National Aeronautics and Space Administration

Small Business Innovation Research (SBIR)

Phase I

Fiscal Year 2022 Solicitation

Completed Proposal Package Due Date and Time:
March 9, 2022 - 5:00 p.m. ET

Contents

Executive Summary

This notice identifies the objectives for the Small Business Innovation Research (SBIR) Program Phase I projects, deadlines, funding information, eligibility criteria for projects and Offerors, and instructions to submit a complete proposal package.

The NASA SBIR program focuses on transforming scientific discovery into products and services through innovations that have potential for infusion into NASA programs and missions, potential for commercialization into NASA relevant commercial markets, and have a societal benefit.

Unlike fundamental research, the NASA SBIR program supports small businesses in the creation of innovative, disruptive technologies and enables the application of research advancements from conception into the market. Different from most other investors, the NASA SBIR Program funds early or "seed" stage research and development that has commercial potential. The program provides equity-free funding at the earliest stages of company and technology development.

NASA requests small business to submit a completed proposal package for the SBIR Program Phase I for fiscal year (FY) 2022. **The SBIR subtopics appear in an integrated list in Chapter 9 and each subtopic will indicate its program of origin.**

NASA uses an electronic submission system called the Electronic Handbook (EHB) and all Offerors must use the EHB for submitting a completed proposal package. The EHB guides firms through the steps for submitting a complete proposal package. All submissions are through a secure connection and most communication between NASA and the firm is through either the EHB or email. For more information see section 3.

1. Program Description

1.1 Legislative Authority and Background

The National Defense Authorization Act for Fiscal Year 2017 (Pub. L. 114–328, §1834(a) Extension of SBIR and STTR programs was amended in the Small Business Act (15 U.S.C. 638) and extended the implementation through September 30, 2022. Policy is provided by the Small Business Administration (SBA) through the combined SBIR/STTR Policy Directive. The main purpose of the legislation is to stimulate technological innovation in the Federal R/R&D sector and increase private sector commercialization in both programs. Accordingly, the NASA SBIR program is in a unique position to meet both goals by transforming scientific discovery and innovation to be used in NASA programs and missions as well as emphasizing private sector commercialization.

The SBIR program is Congressionally mandated and intended to support scientific excellence and technological innovation through the investment of federal research funds to build a strong national economy by stimulating technological innovation in the private sector; strengthening the role of small business in meeting federal research and development needs; increasing the commercial application of federally supported research results; and fostering and encouraging participation by socially and economically disadvantaged and women-owned small businesses.

1.2 Purpose and Priorities

This solicitation includes instructions for Small Business Concerns (SBCs) to submit Phase I completed proposal package to the NASA SBIR program. Furthermore, program background information, eligibility requirements for participants, information on the three program phases, information for submitting completed and responsive proposal packages to NASA specific research subtopics are contained herein. **The fiscal year 2022 solicitation period for Phase I submission of completed proposal packages begins on January 6, 2022 and ends at 5 p.m. Eastern Time on March 9, 2022.**

The NASA SBIR Program does not make awards solely directed toward system studies, market research, routine engineering, development of existing product(s), proven concepts, or modifications of existing products without substantive innovation.

The Space Technology Mission Directorate (STMD) provides overall policy direction for implementation of the NASA SBIR program. The NASA SBIR/STTR Program Management Office (PMO), hosted at the NASA Ames Research Center, operates the program in conjunction with NASA mission directorates and centers. Additionally, the NASA Shared Services Center (NSSC) provides the overall procurement management for the programs.

For the SBIR program, NASA research and technology areas to be solicited are identified annually by the Agency's mission directorates. The directorates identify high-priority research problems and technology needs for their respective programs and projects. The range of problems and technologies is broad, and the list of research subtopics varies in content from year to year to maintain alignment with current interests.

For details on the research subtopic descriptions by Focus Area, see Section 9.

1.3 Three-Phase Program

The NASA SBIR program is carried out in three separate phases. The three phases are described in detail on the NASA SBIR/STTR website: http://sbir.nasa.gov/content/nasa-sbirsttr-basics.

Phase I

This solicitation is only for the preparation and submission of a completed proposal package to describe the Phase I project in how it will demonstrate technical feasibility of the proposed innovation and the potential for infusion within a NASA program or mission and/or use in the commercial market.

Maximum value and period of performance for Phase I:

Phase I Contracts	**SBIR**
Maximum Contract Value	$150,000
Period of Performance	6 months

Phase II

Phase II proposals continue the R&D developed under Phase I to bring the innovation closer to infusion into a NASA program or mission and/or commercialization of the innovation. Phase II will require a more comprehensive proposal, outlining the proposed effort in detail and the commercialization strategy for the effort. Only prior Phase I awardees are eligible to submit a Phase II proposal at the conclusion of the Phase I contract. A separate solicitation will be published for the preparation and submission of Phase II proposals.

Phase II Contracts	**SBIR**
Maximum Contract Value	$750,000*
Maximum Period of Performance	24 months

*Depending on final appropriations, NASA may adjust the maximum contract value for Phase II awards upwards from $750,000 to $1,000,000. Phase I awardees will be notified of maximum value at the time of their Phase II submission and the Phase II solicitation will supersede the information provided above.

Post-Phase II Opportunities for Continued Technology Development

NASA recognizes that Phase I and II awards may not be sufficient in either dollars or time for the firm to complete the total R/R&D and the commercialization activities required to make the project ready for infusion or the commercial marketplace. Therefore, NASA has several initiatives for supporting its small business partners beyond their Phase I and Phase II awards.

Please refer to http://sbir.nasa.gov/content/post-phase-ii-initiatives for eligibility, application deadlines, matching requirements and further information.

Phase III

Phase III is the commercialization of innovative technologies, products, and services resulting from either a Phase I or Phase II contract. This includes further development of technologies for transition into NASA programs, other Government agencies, or the private sector. Phase III contracts are funded from sources other than the SBIR and STTR programs and may be awarded without further competition.

Please refer to https://sbir.nasa.gov/content/post-phase-ii-initiatives#Phase-III for Phase III information.

1.4 Availability of Funds

There is no commitment by NASA to fund any proposal or to make a specific number of awards and NASA may elect to make several or no awards in any specific research subtopic. Number of awards will be based on the level of appropriated funding provided to the program in FY 2022.

It is anticipated the SBIR Phase I completed proposal packages will be selected for negotiation of firm-fixed-price contracts approximately during the month of May 2022 for a period of performance not to exceed six (6) months. Historically, 20% to 22% percent of SBIR Phase I completed proposal packages that are eligible for technical review receive awards.

Under this SBIR Phase I solicitation, NASA will not accept more than 10 completed proposal packages from any one firm to ensure the broadest participation of the small business community. NASA does not plan to award more than five (5) SBIR contracts to any Offeror. See Sections 3.1 and 4.

This solicitation may be released prior to the passage of an appropriations act for FY 2022. Enactment of additional continuing resolutions or an appropriations act may affect the availability or level of funding for this program and may delay the start date of Phase I contracts or impact the maximum contract value levels.

1.5 Eligibility Requirements

1.5.1 Small Business Concern (SBC)

Each Phase I awardee must submit a certification stating that it meets the size, ownership, and other requirements of the SBIR program at the time of a completed proposal package submission, award, and at any other time set forth in SBA's regulations at 13 CFR §§ 121.701-121.705. Socially and economically disadvantaged and women-owned SBCs are particularly encouraged to propose.

1.5.2 SBC Size

A Phase I awardee, combined with its affiliates, must not have more than 500 employees. The SBC must be the primary performer of the proposed research effort.

1.5.3 SBIR Restrictions on Level of Small Business Participation

To be awarded an SBIR Phase I contract, a minimum of two-thirds or 67% of the research or analytical effort must be carried out by the Offeror during Phase I; correspondingly, a maximum of one-third or 33% of the effort may be performed by an outside party such as consultants or subcontractors.

1.5.4 Place of Performance and American-made Products and Equipment

All work shall be performed in the United States. When purchasing equipment or a product under the SBIR/STTR Funding Agreement, purchase only American-made items whenever possible. However, based on a rare and unique circumstance (for example, if a supply, material, or other item or project requirement is not available in the United States), NASA may allow a particular portion of the research or work to be performed or obtained in a country outside of the United States.

Completed proposal packages must clearly indicate if any work will be performed outside the United States, including subcontractor performance, and justification must be provided by downloading and completing the "Request to Use a Foreign Vendor/Purchase of Items from a Foreign Vendor" form found at https://sbir.gsfc.nasa.gov/submissions/learning-support/firm-templates and while completing the budget under section 3.5.

Prior to award, approval by the Contracting Officer for such specific condition(s) must be in writing.

Note: NASA will not approve purchases from or work with countries that appear on the list of Designated Countries. For reference, please see https://www.nasa.gov/oiir/export-control.

1.5.5 Principal Investigator (PI) Employment Requirement

Requirements	**SBIR**
Primary Employment	PI shall be primarily employed with the SBC
Employment Certification	The Offeror must certify in the completed proposal package that the primary employment of the PI will be with the SBC at the time of award and during the conduct of the project and will spend more than one half of his/her time (based on a 40-hour workweek) as an employee of the Awardee or has requested and received a written deviation from this requirement from the Funding Agreement officer
Co-PIs	Not allowed
Deviation Request	Any deviation requests will be reviewed during negotiation of the award and either approved or declined before final award by the Funding Agreement officer
Misrepresentation of Qualifications	Shall result in rejection of the completed proposal package or termination of the contract
Substitution of PIs	Requires a prior approval from NASA after award

Note: NASA considers full-time employment to include salaried employees and employees who regularly work a 40-hour workweek. NASA considers half-time employment to be a 19.9-hour or more workweek. In rare occasions, minor deviations from this requirement may be necessary; however, any minor deviation must be approved in writing prior to the award by the Contracting Officer after consultation with the NASA SBIR/STTR Program Manager/Business Manager.

1.5.6 Restrictions on Venture-Capital-Owned Businesses

At the current time, small businesses owned in majority part by multiple venture capital operating companies, hedge funds, or private equity firms are not eligible to submit a proposal package under this NASA SBIR Phase I solicitation.

1.5.7 Joint Ventures or Limited Partnerships

Both joint ventures and limited partnerships are permitted, provided the entity created qualifies as an SBC in accordance with the definition of an SBC here: http://sbir.nasa.gov/content/nasa-sbirsttr-program-definitions. A statement of how the workload will be distributed, managed, and charged should be included in the completed proposal package. See definitions for Joint Ventures along with examples at 13 CFR 121.103(h).

A copy or comprehensive summary of the joint venture agreement or partnership agreement should be included when uploading the completed proposal package.

1.5.8 Required Benchmark Transition Rate

The Phase I to Phase II transition rate requirement applies to SBIR Phase I Offerors that have received more than 20 (21 or more) Phase I awards over the past 5 fiscal years, excluding the most recent year. These companies must meet the required benchmark rate of transition from Phase I to Phase II. The current transition rate requirement, agreed upon and established by all 11 agencies that have SBIR/STTR programs and published for public comment at 77 FR 63410 in October 2012 and amended at 78 FR 30951 in May 2013, is that an awardee must have received an average of one Phase II for every four Phase I awards received during the most recent 5-year time period (which excludes the most recently completed fiscal year) to be eligible to submit a completed proposal package for a new Phase I (or Direct-to-Phase II) award. That is, the ratio of Phase II to Phase I awards must be at least 0.25.

On June 1 of each year, the SBA assesses SBIR awardees using SBIR award information across all Federal agencies reported on www.sbir.gov to determine if they meet the benchmark requirements. Companies that failed to meet the transition rate benchmark on June 1, 2021, are not eligible to submit a Phase I completed proposal package during the period June 1, 2021, through May 31, 2022. Companies were notified by the SBA if they failed to meet the benchmark and can find their status at any time on www.sbir.gov.

More information on the transition rate requirements is available at https://www.sbir.gov/faqs/performance-benchmarks.

1.6 NASA Technology Available (TAV) for SBIR Use

Offerors have the option of using technology developed by NASA (Technology Available (TAV)) related to the subtopic to which they are proposing. NASA has over 1,400 patents available for licensing in its portfolio, including many patents related to sensors and materials. NASA has over 1,000 available software applications/tools listed in its Software Catalog (https://software.nasa.gov). While NASA scientists and engineers conduct breakthrough research that leads to innovations, the range of NASA's effort does not extend to commercial product development in any of its intramural research areas. Additional work is often necessary to exploit these NASA technologies for either infusion or commercial viability and likely requires innovation on behalf of the private sector. These technologies can be searched via the NASA Technology Transfer Portal, http://technology.nasa.gov, and may be a NASA-owned patent and/or computer software. Use of a TAV requires a patent license or Software Usage Agreement (SUA) from NASA. TAVs are available for use on SBIR projects. NASA provides these technologies "as is" and makes no representation or guarantee that additional effort will result in infusion or commercial viability.

Whether or not a firm proposes the use of a NASA patent or computer software within its proposed effort will not in any way be a factor in the selection for award.

1.6.1 Use of NASA Software

If an Offeror intends to use NASA software, a Software Usage Agreement (SUA), on a nonexclusive, royalty-free basis, is necessary, and the clause at 48 C.F.R. 1852.227-88, Government-Furnished Computer Software and Related Technical Data, will apply to the contract. The SUA shall be requested from the appropriate NASA Center Software Release Authority (SRA), after contract award.

1.6.2 Use of NASA Patent

All Offerors submitting a completed proposal package that include the use of a NASA patent must apply for a nonexclusive, royalty-free evaluation license. After firms have identified a patent to license in the NASA patent portfolio (http://technology.nasa.gov), a link on the patent webpage (“Apply Now to License this Technology”) will direct them to NASA’s Automated Licensing System (ATLAS) to finalize their license with the appropriate field center technology transfer office. The completed evaluation license application must be provided with the proposal following the directions in section 3.5.3. Such grant of nonexclusive evaluation license will be set forth in the successful Offeror’s SBIR contract. The evaluation license will automatically terminate at the end of the SBIR contract. License applications will be treated in accordance with Federal patent licensing regulations as provided in 37 CFR Part 404.

In addition to an evaluation license, if the proposed work includes the making, using, or selling of products or services incorporating a NASA patent, successful awardees will be given the opportunity to negotiate a nonexclusive commercialization license or, if available, an exclusive commercialization license to the NASA patent. Commercialization licenses are also provided in accordance with 37 CFR Part 404.

An SBIR awardee that has been granted a nonexclusive, royalty-free evaluation license to use a NASA patent under the SBIR award may, if available and on a noninterference basis, also have access to NASA personnel knowledgeable about the NASA patent. Licensing Executives located at the appropriate NASA field center will be available to assist awardees requesting information about a patent that was identified in the SBIR contract and, if available and on a noninterference basis, provide access to the inventor or surrogate for the purpose of knowledge transfer.

Note: Access to the inventor for the purpose of knowledge transfer will require the requestor to enter into a Non-Disclosure Agreement (NDA) or other agreement, such as a Space Act Agreement. The awardee may be required to reimburse NASA for knowledge transfer activities. For Phase I completed proposal packages, this is a time-consuming process and is not recommended.

1.7 I-Corps™

NASA has partnered with the National Science Foundation (NSF) to allow Phase I awardees the opportunity to participate in the NSF Innovation Corps (I-Corps™) program. Phase I awardees are encouraged to participate in this training which is designed to lower the market risk inherent in bringing a product or innovation to market, thereby improving the chances for a viable business. The NASA I-Corps program enables small businesses, including startup firms, to increase the odds of accelerating the process of developing their SBIR technologies into a repeatable and scalable business model. The program accomplishes this by putting the firms through a version of the Lean Launchpad/I-Corps process, which includes:

- Developing their business model hypotheses using the Business Model Canvas.
- Testing those hypotheses through the Customer Development Interview process.

The intended results of I-Corps are to enable firms to conduct customer discovery to learn their customers' needs, to obtain a better understanding of their company's value proposition as it relates to those customer needs, and to develop an outline of a business plan for moving forward. For more information on the NASA I-Corps program, see http://sbir.nasa.gov/content/I-Corps.

Offerors who are selected for Phase I contract negotiations will be provided the opportunity to participate in the NASA SBIR/STTR I-Corps program as indicated in Section 3.5.3.9. I-Corps awards will be made separately from the Phase I contract as a grant.

NASA will conduct an abbreviated competition for I-Corps after Phase I Offerors are selected for Phase I SBIR contracts. NASA anticipates awarding approximately 25 grants to SBIR Phase I awardees. The amount of funding is up to $10,000 for the shortened I-Corps version for SBIR firms.

1.8 Technical and Business Assistance (TABA)

The Small Business Act 15 U.S.C. 631, Section 9 (q) Discretionary Technical and Business Assistance permits SBIR Phase I and II awardees to enter into agreements with one or more vendors to provide Technical and Business Assistance (TABA). TABA allows an additional supplement to the award ($6,500 for Phase I) and is aimed at improving the commercialization success of SBIR awardees. TABA may be obtained from entities such as public or private organizations, including an entity established or funded by a U.S. state that facilitates or accelerates the commercialization of technologies or assists in the creation and growth of private enterprises that are commercializing technology.

In accordance with the Small Business Act, NASA may authorize the recipient of a NASA Phase I SBIR award to purchase technical and business assistance services through one or more outside vendors. These services may, as determined appropriate, include access to a network of non-NASA scientists and engineers engaged in a wide range of technologies, assistance with product sales, intellectual property protections, market research, market validation, and development of regulatory plans and manufacturing plans, or access to technical and business literature available through online databases, for the purpose of assisting such concerns in

1. Making better technical decisions concerning such projects;
2. Solving technical problems that arise during the conduct of such projects;
3. Minimizing technical risks associated with such projects; or
4. Commercializing new commercial products and processes resulting from such projects, including intellectual property protections.

For information on how to request TABA at Phase I, please see Section 3.5.3.8, Request for Use of Technical and Business Assistance Funds. Technical and business assistance does not count toward the maximum award amount of your Phase I contract. Approval of technical and business assistance is not guaranteed and is subject to review by the Contracting Officer and the SBIR/STTR Program Management Office. A description of any technical and business assistance obtained under this section and the benefits and results of the technical or business assistance provided will be a required deliverable of your contract.

1.9 Small Business Administration (SBA) Applicant Resources

The SBA oversees the Federal SBIR and STTR programs. The SBA has resources that small businesses can take advantage of in learning about each of the programs and obtaining help in developing a completed proposal package to submit to a Federal SBIR/STTR program. Offerors are encouraged to review the information that is provided at the following links: www.sbir.gov, https://www.sba.gov/local-assistance, and at https://www.sbir.gov/resources.

1.10 NASA Mentor-Protégé Program (MPP)

The purpose of the NASA Mentor-Protégé Program (MPP) is to provide incentives to NASA contractors, performing under at least one active approved subcontracting plan negotiated with NASA, to assist protégés in enhancing their capabilities to satisfy NASA and other contract and subcontract requirements. The NASA MPP established under the authority of Title 42, United States Code (U.S.C.) 2473(c)(1) and managed by the Office of Small Business Programs (OSBP), includes an Award Fee Pilot Program. Under the Award Fee Pilot Program, a mentor is eligible to receive an award fee at the end of the agreement period based upon the mentor’s performance of providing developmental assistance to an active SBIR/STTR Phase II contractor in a NASA Mentor-Protégé agreement (MPA).

The evaluation criterion is based on the amount and quality of technology transfer and business development skills that will increase the protégé’s Technology Readiness Levels (TRLs). TRLs measure technology readiness on a scale of 1 to 9. A mentor should attempt to raise the TRL of the protégé and outline the goals and objectives in the MPA and the award fee plan. A separate award fee review panel set up by NASA OSBP will use the semiannual reports, annual reviews, and the award fee plan in order to determine the amount of award fee given at the end of the performance period of the agreement.

For more information on the Mentor-Protégé Program, please visit https://www.nasa.gov/osbp/mentor-protege-program.

1.11 Fraud, Waste and Abuse and False Statements

Fraud is described as “any false representation about a material fact or any intentional deception designed to deprive the United States unlawfully of something of value or to secure from the United States a benefit, privilege, allowance, or consideration to which an individual or business is not entitled.”
Note: The Federal Government reserves the right to decline any completed proposal packages that include plagiarism and false claims.

Note: Knowingly and willfully making any false, fictitious, or fraudulent statements or representations may be a felony under the Federal Criminal False Statement Act (18 U.S.C., section 1001), punishable by a fine and imprisonment of up to 5 years in prison. The Office of the Inspector General (OIG) has full access to all completed proposal packages submitted to NASA.

Pursuant to NASA policy, any company representative who observes crime, fraud, waste, abuse, or mismanagement or receives an allegation of crime, fraud, waste, abuse, or mismanagement from a Federal employee, contractor, grantee, contractor, grantee employee, or any other source will report such observation or allegation to the OIG. NASA contractor employees and other individuals are also encouraged to report crime, fraud, waste, and mismanagement in NASA's programs to the OIG. The OIG offers several ways to report a complaint:

NASA OIG Hotline: 1-800-424-9183 (TDD: 1-800-535-8134)

NASA OIG Cyber Hotline: http://oig.nasa.gov/cyberhotline.html

Or by mail:
NASA Office of Inspector General
P.O. Box 23089
L'Enfant Plaza Station
Washington, DC 20026

1.12 NASA Procurement Ombudsman Program

The NASA Procurement Ombudsman Program is available under this solicitation as a procedure for addressing concerns and disagreements concerning the terms of the solicitation, the processes used for evaluation of completed proposal packages, or any other aspect of the SBIR procurement. The clause at NASA Federal Acquisition Regulation (FAR) Supplement (NFS) 1852.215-84 (“Ombudsman”) is incorporated into this solicitation.

The cognizant ombudsman is:

Jason Detko
Deputy Assistant Administrator for Procurement
Office of Procurement
NASA Headquarters
Washington, DC 20546-0001
Telephone: 202-358-4483
Fax: 202-358-3082
Email: agency-procurementombudsman@nasa.gov

Offerors are advised that, in accordance with NFS 1852.215-84, the ombudsman does not participate in any way with the evaluation of completed proposal packages, the source selection process, or the adjudication of formal contract disputes. Therefore, before consulting with the ombudsman, Offerors must first address their concerns, issues, disagreements, and/or recommendations to the Contracting Officer for resolution. Offerors are further advised that the process set forth in this solicitation provision (and described at NFS 1852.215-84) does not augment their right to file a bid protest or otherwise toll or elongate the period in which to timely file such a protest.

1.13 General Information

1.13.1 Questions About This Solicitation and Means of Contacting NASA SBIR Program

To ensure fairness, questions relating to the intent and/or content of research subtopics in this solicitation cannot be addressed during the open solicitation period. Only questions requesting clarification of completed proposal package instructions and administrative matters will be addressed.

The cutoff date and time for receipt of Phase I solicitation procurement-related questions is March 2, 2022, at 5:00 p.m. ET.

Offerors that have questions requesting clarification of completed proposal package instructions and administrative matters should refer to the NASA SBIR/STTR website or contact the NASA SBIR/STTR helpdesk.

1. NASA SBIR/STTR website: http://sbir.nasa.gov

2. Help Desk: The NASA SBIR/STTR Help Desk can answer any questions regarding clarification of completed proposal package instructions and any administrative matters. The Help Desk may be contacted by:

    a. Email: sbir@reisystems.com
    b. The requestor must provide the name and telephone number of the person to contact, the organization name and address, and the specific questions or requests.

1.14 Definitions

A comprehensive list of definitions related to the programs is available at http://sbir.nasa.gov/content/nasa-sbirsttr-program-definitions. These definitions include those from the combined SBIR/STTR policy directives as well as terms specific to NASA. Offerors are strongly encouraged to review these prior to submitting a completed proposal package.

2. Registrations, Certifications and Other Completed Proposal Package Information

2.1 Small Business Administration (SBA) Firm Registry

All SBCs that are applying to any SBIR solicitation are required to register with the SBIR Firm Registry that is managed by the SBA. In addition, all SBCs must update their commercialization status through the SBIR Firm Registry. Information related to the steps necessary to register with the SBIR Firm Registry can be found at https://www.sbir.gov/registration.

After an SBC registers with SBA and/or updates their commercialization information, the Offeror needs to obtain a portable document format (PDF) copy of the SBC registration. In addition, the SBC must provide their unique SBC Control ID (assigned by SBA upon completion of the Company Registry registration) and must upload the PDF copy of the SBC registration in the EHB. Offerors should complete the Firm Certifications form in the EHB and will be provided instructions how to complete at time of submission. Firm Certifications are applicable across all completed proposal packages submitted by the SBC for the specific solicitation and the EHB will provide guidance on how to complete these certifications.

2.2 System for Award Management (SAM) Registration

Offerors are required to register with SAM prior to submitting a completed proposal package. To be eligible for SBIR awards, firms must be registered under the applicable North American Industry Classification System (NAICS) codes for the SBIR Phase I and II awards (codes 541713 or 541715). Offerors without an active SAM registration by the due date for a completed proposal package will be ineligible for award. Offerors who started the registration process but did not complete the registration by the due date for a completed proposal package will be ineligible for award.

Offerors who are not registered should consider applying for registration immediately upon receipt of this solicitation. Typically, SAM registration and updates to SAM registration have required a processing period of several weeks.

Offerors and contractors may obtain information on SAM registration and annual confirmation requirements at https://www.sam.gov/SAM/pages/public/index.jsf ***or by calling 866-606-8220.***

SAM is the primary repository for contractor information required for the conduct of business with NASA. It is maintained by the Department of Defense. To be registered in SAM, all mandatory information, including the Unique Entity Identifier (UEI), an existing Data Universal Numbering System (DUNS) or DUNS+4 number and a Commercial and Government Entity (CAGE) code, must be validated in SAM.

- By **April of 2022**, the federal government will stop using the DUNS number to uniquely identify entities. At that point, entities doing business with the federal government will use a Unique Entity Identifier (UEI) created in SAM.gov. They will no longer have to go to a third-party website to obtain their identifier. This transition allows the government to streamline the entity identification and validation process, making it easier and less burdensome for entities to do business with the federal government.
    - If your entity is registered in SAM.gov today, your Unique Entity ID (UEI) has already been assigned and is viewable in SAM.gov. This includes inactive registrations. The Unique Entity ID is currently located below the DUNS Number on your entity registration record. Remember, you must be signed in to your SAM.gov account to view entity records. To learn how to view your Unique Entity ID (UEI) go to this help article.

  - Refer to the Guide to Getting a Unique Entity ID if you want to get a Unique Entity ID (UEI) for your organization.

- The DUNS number is a 9-digit number assigned by Dun and Bradstreet Information Services to identify unique business entities. The DUNS+4 is similar but includes a 4-digit suffix that may be assigned by a parent (controlling) business concern. To obtain a DUNS number, please follow instructions at http://www.dnb.com.

- The CAGE code is assigned by the Defense Logistics Information Service (DLIS) to identify a commercial or Government entity. If an SBC does not have a CAGE code, one will be assigned during the SAM registration process.

Note: It is recommended to list Purpose of Registration as "All Awards" on your SAM Registration.

2.3 Certifications

Offerors must complete the Firm and Proposal Certifications section in the Electronic Handbook (EHB), answering "Yes" or "No" to certifications as applicable. Firms should carefully read each of the certification statements. The Federal Government relies on the information to determine whether the business is eligible for a SBIR program award. A similar certification will be used to ensure continued compliance with specific program requirements at time of award and during the life of the Funding Agreement. The definitions for the terms used in this certification are set forth in the Small Business Act, SBA regulations (13 CFR Part 121), the SBIR/STTR Policy Directives, and any statutory and regulatory provisions referenced in those authorities.

For Phase I awards, in addition to the final invoice certification and as a condition for payment of the final invoice, a life cycle certification shall be completed in the EHB. The life cycle certification is preset in the EHB, and it shall be completed along with the final invoice certification before uploading the final invoice in the Department of Treasury's Invoice Processing Platform (IPP).

If the Contracting Officer believes that the business may not meet certain eligibility requirements at the time of award, the business is required to file a size protest with the SBA, who will determine eligibility. At that time, SBA will request further clarification and supporting documentation to assist in the eligibility determination. Additionally, the Contracting Officer may request further clarification and supporting documentation regarding eligibility to determine whether a referral to SBA is required.

2.4 Federal Acquisition Regulation (FAR) and NASA Certifications and Clauses

SAM contains required certifications Offerors may access at https://www.acquisition.gov/browsefar as part of the required registration (see FAR 4.1102). Offerors must complete these certifications to be eligible for award.

Offerors should be aware that SAM requires all Offerors to provide representations and certifications electronically via the website and to update the representations and certifications as necessary, but at least annually, to keep them current, accurate, and complete. NASA will not enter into any contract wherein the contractor is not compliant with the requirements stipulated herein.

In addition, there are clauses that Offerors will need to be aware of if selected for a contract. For a complete list of FAR and NASA clauses see Appendix D.

2.5 Software Development Standards

Offerors proposing projects involving the development of software may be required to comply with the requirements of NASA Procedural Requirements (NPR) 7150.2A, NASA Software Engineering Requirements, available online at https://nodis3.gsfc.nasa.gov/npg_img/N_PR_7150_002C_/N_PR_7150_002C_.pdf.

2.6 Human and/or Animal Subject

Offerors should be aware of the requirement that an approved protocol by a NASA review board is required if the proposed work includes human or animal subject. An approved protocol shall be provided to the Contracting Officer prior to the initiation of any human and/or animal subject research. Offerors shall identify the use of human or animal subject in the Proposal Certifications form. For additional information, contact the NASA SBIR/STTR Program Support Office at sbir@reisystems.com . Reference 14 CFR 1230 and 1232.

Note: Due to the complexity of the approval process, use of human and/or animal subjects is not allowed for Phase I contracts.

2.7 HSPD-12

Firms that require access to Federally controlled facilities or access to a Federal information system (Federally controlled facilities and Federal information system are defined in FAR 2.101(b)(2)) for 6 consecutive months or more must adhere to Homeland Security Presidential Directive 12 (HSPD-12), Policy for a Common Identification Standard for Federal Employees and Contractors, and Federal Information Processing Standards Publication (FIPS PUB) Number 201, Personal Identity Verification (PIV) of Federal Employees and Contractors, which require agencies to establish and implement procedures to create and use a Government-wide secure and reliable form of identification no later than October 27, 2005. See https://nvlpubs.nist.gov/nistpubs/FIPS/NIST.FIPS.201-2.pdf.

This is in accordance with FAR clause 52.204-9, Personal Identity Verification of Contractor Personnel, which states in part that the contractor shall comply with the requirements of this clause and shall ensure that individuals needing such access shall provide the personal background and biographical information requested by NASA.

Note: Additional information regarding PIV credentials can be found at https://csrc.nist.gov/Projects/PIV.

3. Proposal Preparation Instructions and Requirements

3.1 Multiple Proposal Submissions

Each proposal submitted must be based on a unique innovation, must be limited in scope to just one subtopic, and shall be submitted only under that one subtopic within each program. An Offeror shall not submit more than 10 proposals to the SBIR program. An Offeror may submit more than one unique proposal to the same subtopic; however, an Offeror shall not submit the same (or substantially equivalent) proposal to more than one subtopic. Submitting substantially equivalent proposals to several subtopics may result in the rejection of all such proposals. To enhance SBC participation, NASA does not plan to select more than 5 SBIR proposals from any one Offeror under this solicitation.

Note: Offerors are advised to be thoughtful in selecting a subtopic to ensure the proposal is responsive to the NASA need as defined by the subtopic. The NASA SBIR/STTR program will NOT move a proposal between subtopics or programs.

3.2 Understanding the Patent Landscape

Offerors should indicate in the proposal that a comprehensive patent review has been completed to ensure that there is no existing patent or perceived patent infringement based on the innovation proposed. The U.S. Patent and Trade Office (USPTO) has an online patent search tool that can found at https://www.uspto.gov/patents-application-process/search-patents.

3.3 Proprietary Information in the Proposal Submission

Information contained in unsuccessful proposals will remain the property of the applicant. The Federal Government may, however, retain copies of all proposals. Public release of information in any proposal submitted will be subject to existing statutory and regulatory requirements. If proprietary information is provided by an applicant in a proposal, which constitutes a trade secret, commercial or financial information, it will be treated in confidence, to the extent permitted by law, provided that the proposal is clearly marked by the applicant as follows:

(A) The following “italicized” legend must appear on the title page of the proposal:

> *This proposal contains information that shall not be disclosed outside the Federal Government and shall not be duplicated, used, or disclosed in whole or in part for any purpose other than evaluation of this proposal, unless authorized by law. The Government shall have the right to duplicate, use, or disclose the data to the extent provided in the resulting contract if award is made as a result of the submission of this proposal. The information subject to these restrictions is contained on all pages of the proposal except for pages [insert page numbers or other identification of pages that contain no restricted information]. (End of Legend);* and

(B) The following legend must appear on each page of the proposal that contains information the applicant wishes to protect:

> *Use or disclosure of information contained on this sheet is subject to the restriction on the title page of this proposal.*

Information contained in unsuccessful proposals will remain the property of the applicant. However, the Government will retain copies of all proposals in accordance with its records retention schedule.

3.4 Release of Certain Proposal Information

In submitting a proposal, the Offeror agrees to permit the Government to disclose publicly the information contained in the Contact Information form and Proposal Summary form, which includes the Technical Abstract and Briefing Chart. Other proposal data is considered to be the property of the Offeror, and NASA will protect it from public disclosure to the extent permitted by law, including requests submitted under the Freedom of Information Act (FOIA).

3.5 Requirements to Submit a Phase I Completed Proposal Package

3.5.1 General Requirements

NASA uses an electronic submission system called the Electronic Handbook (EHB) and all Offerors must use the EHB for submitting a completed proposal package. The EHB guides firms through the steps for submitting a complete proposal package. All submissions are through a secure connection and most communication between NASA and the firm is through either the EHB or email. To access the EHB go to https://sbir.gsfc.nasa.gov/submissions/login.

Completed proposals packages contain a Technical Proposal as described in section 3.5.3.5 below. A Technical Proposal must clearly and concisely:

1. Describe the proposed innovation relative to the current state of the art;
2. Address the scientific, technical, and commercial merit and feasibility of the proposed innovation as well as its relevance and significance to NASA interests as described in section 9 of this solicitation; and
3. Provide a preliminary strategy that addresses key technical, market, and business factors pertinent to the successful development and demonstration of the proposed innovation and its transition into products and services for NASA mission programs, the NASA relevant commercial markets, and other potential markets and customers.

3.5.2 Format Requirements

Note: The Government administratively screens all elements of a completed proposal package and will decline any proposal package that does not conform to the following formatting requirements.

Page Limitations and Margins

Note: Technical proposal uploads with any page(s) going over the required page limit will not be accepted.
A Phase I technical proposal shall not exceed a total of 19 standard 8.5- by 11-inch (21.6- by 27.9-cm) pages which will include all 10 parts of the technical proposal including all graphics and table of contents.

Margins must be 1.0 inch (2.5 cm). Offerors must ensure that the margins are in compliance before uploading the Phase I technical proposal.

The additional EHB forms required for completed proposal package submission will not count against the 19-page limit.

Suggested Page Limits for Proposal Sections

Within each section is a suggested page limit for each part of the technical proposal. These are guidelines and are not strict requirements. Offerors are still required to meet the total page limit requirements as described above.

Type Size

No type size smaller than 10 point shall be used for text or tables, except as legends on reduced drawings. Completed proposal packages prepared with smaller font sizes will be declined during the administrative review and will not be considered.

Header/Footer Requirements

Headers must include firm name, proposal number, and project title. Footers must include the page number and proprietary markings if applicable. Margins can be used for header/footer information.

Classified Information
NASA will reject any proposal package that contains classified information.

Project Title
The proposal project title shall be concise and descriptive of the proposed effort. The title should not use acronyms or words like "development of" or "study of." The NASA research subtopic title must not be used as the proposal title.

3.5.3 Completed Proposal Package

Each completed proposal package submitted shall contain the following items:

1. Proposal Contact Information
2. Proposal Certifications, electronically endorsed
3. Proposal Summary (must not contain proprietary data)
4. Proposal Budget (including letters of commitment for Government resources and subcontractors/consultants and foreign vendor form, if applicable)
5. Technical Proposal
6. Briefing Chart (must not contain proprietary data)
7. NASA Evaluation License Application, only if TAV is being proposed
8. Technical and Business Assistance (TABA) request (optional)
9. I-Corps Interest Form
10. Firm-Level Forms (completed once for all proposals submitted to a single solicitation)
    a. Firm Certifications
    b. Audit Information
    c. Prior Awards Addendum
    d. Commercial Metrics Survey (CMS)
11. Electronic Endorsement by the designated small business representative and Principal Investigator (PI) is completed before the deadline

Note: Letters expressing general technical interest or letters of funding support commitments (for Phase I) are not required or desired and will not be considered during the review process. However, if submitted, such letter(s) will count against the proposal page limit.

Note: The EHB will not allow the upload of relevant technical papers, product samples, videotapes, slides, or other ancillary items, and they will not be considered during the review process.

3.5.3.1 Proposal Contact Information Form

The Offeror shall provide complete information for each contact person and submit the form as required in the EHB. ***Note: Contact Information is public information and may be disclosed.***

3.5.3.2 Proposal Certifications Form

The Offeror shall provide complete information for each item and submit and electronically endorse the form as required in the EHB.

3.5.3.3 Proposal Summary Form

The Offeror shall provide complete information for each item and submit the form as required in the EHB.

Note: The Proposal Summary, including the Technical Abstract, is public information and may be disclosed. Do not include proprietary information in this form.

3.5.3.4 Proposal Budget Form

The Offeror must complete the Proposal Budget form following the instructions provided. The total requested funding for the Phase I effort shall not exceed $150,000 or $156,500 (if requesting $6,500 for TABA, see section 1.8 and 3.5.3.8).

Note:

- ***The Government is not responsible for any monies expended by the firm before award of any contract.***
- ***NASA and the Office of Management and Budget (OMB) has issued a policy that requires a review of any request to purchase materials or supplies from foreign vendors. Due to the short timeframe to issue a Phase I contract, NASA is strongly encouraging Offerors to consider purchasing materials and supplies from domestic vendors only. If a foreign vendor is proposed, the Phase I contract may be delayed or not awarded.***

In addition, the following information must be submitted in the Proposal Budget form, as applicable:

Proposal Budget Requirements for Use of Government Resources

In cases where an Offeror seeks to use Government resources as described in Part 8 of the technical proposal instructions, the Offeror shall provide the following:

1. Statement, signed by the appropriate Government official at the affected Federal department or agency, verifying that the resources should be available during proposed period of performance.
2. Signed letter on company letterhead from the SBC's designated small business representative explaining why the SBIR research project requires the use of Government resources (such as, but not limited to, Federal services, equipment, or facilities, etc.) including data that verifies the absence of non-Federal facilities or personnel capable of supporting the research effort, a statement confirming that the facility proposed is not a Federal laboratory, if applicable, and the associated cost estimate.

Note: Use of Federal laboratories/facilities for Phase I contracts is highly discouraged as these arrangements will in most cases cause significant delays in making the final award. Approval for use of Federal facilities and laboratories for a Phase I technical proposal requires a strong justification at time of submission and will require approval by the Contracting Officer during negotiations if selected for award.

See Part 8 of the Technical Proposal instructions for additional information on use of Government resources.

Use of Subcontractors and Consultants

Offerors that propose using subcontractors or consultants must submit the following:

1. ***List of consultants by name with the number of hours and hourly costs identified for each consultant.***
2. ***Breakdown of subcontractor budget should mirror the SBC's own breakdown in the Proposal Budget form and include breakdowns of direct labor, other direct costs, and profit, as well as indirect rate agreements.***

3. ***A signed letter of commitment is required for each subcontractor and/or consultant. For educational institutions, the letter must be from the institution's Office of Sponsored Programs.***

Subject to the restrictions set forth in section 1.5 and below, the SBC may establish business arrangements with other entities or individuals to participate in performance of the proposed R/R&D effort. Subcontractors' and consultants' work have the same place-of-performance restrictions as stated in section 1.5.4.

The following restrictions apply to the use of subcontractors/consultants, and the formula below must be used in preparing budgets with subcontractors/consultants:

The proposed subcontracted business arrangements, including consultants, must not exceed 33 percent of the research and/or analytical work [as determined by the total cost of the proposed subcontracting effort (to include the appropriate overhead (OH) and general and administrative expenses (G&A) in comparison to the total effort funded by the government (total contract price including cost sharing, if any, less profit, if any)].

Occasionally, deviations from this SBIR requirement may occur, and must be approved in writing by the Funding Agreement officer after consultation with the NASA SBIR PMO.

Example:	Total price to include profit	$99,500
	Profit	$3,000
	Total price less profit	$99,500 - $3,000 = $96,500
	Subcontractor cost	$29,500
	G&A	5%
	G&A on subcontractor cost	$29,500 x 5% = $1,475
	Subcontractor cost plus G&A	$29,500 + $1,475 = $30,975
	Percentage of subcontracting effort*	**$30,975/$96,500 = 32.1%**
	***Subcontractor cost plus G&A/Total price less profit**	

For an SBIR Phase I, this is acceptable because it is below the limitation of 33 percent.

See Part 9 of the Technical Proposal for additional information on the use of subcontractors and consultants.

Travel in Phase I

Due to the intent and short period of performance of the Phase I contracts, along with their limited budget, travel during the Phase I contract is highly discouraged unless it is required to successfully complete the proposed effort. If the purpose of the meeting cannot be accomplished via videoconference or teleconference, the Offeror must provide a rationale for the trip in the proposal budget form. All travel must be approved by the Contracting Officer and concurred by the Technical Monitor.

3.5.3.5 Technical Proposal

This part of the submission should not contain any budget data and **must consist of all 10 parts listed below in the given order. All 10 parts of the technical proposal must be numbered and titled. A completed proposal package omitting any part will be considered nonresponsive to this solicitation and declined without further consideration. Parts that are not applicable must be included and marked "Not applicable."**

The completed proposal package shall provide all information needed for a complete evaluation. Evaluators will not seek additional information. Any pertinent references or publications should be noted in Part 5 of the technical proposal.

The required table of contents is provided below:

Part 1: Table of Contents *(Suggested page limit – 0.5 page and counts toward the 19-page limit)*

The technical proposal must begin with a brief table of contents indicating the page numbers of each of the parts of the completed proposal package (see below for an example).

Phase I Table of Contents

Part 1: Table of Contents……………………………………………………………………………………Page X
Part 2: Identification and Significance of the Innovation…………………………………………Page X
Part 3: Technical Objectives……………………………………………………………………………Page X
Part 4: Work Plan……………………………………………………………………………………………Page X
Part 5: Related R/R&D………………………………………………………………………………………Page X
Part 6: Key Personnel and Bibliography of Directly Related Work……………………………Page X
Part 7: The Market Opportunity…………………………………………………………………………Page X
Part 8: Facilities/Equipment………………………………………………………………………………Page X
Part 9: Subcontractors and Consultants………………………………………………………………Page X
Part 10: Related, Essentially Equivalent, and Duplicate Proposals and Awards………….Page X

Part 2: Identification and Significance of the Proposed Innovation *(Suggested page limit – 5 pages)*
Succinctly describe:

- The proposed innovation.
- The relevance and significance of the proposed innovation to an interest, need, or needs, within a subtopic described in section 9.
- The proposed innovation relative to the current state of the art.

Part 3: Technical Objectives *(Suggested page limit – 1 page)*
State the specific objectives of the Phase I R/R&D effort as it relates to the problem statement(s) posed in the subtopic description and the types of innovations being requested.

Indicate the proposed deliverables at the end of the Phase I effort and how these align with the proposed subtopic deliverables described within a subtopic found in section 9.

Note: All Offerors submitting completed proposal packages who are planning to use NASA TAV including Intellectual Property (IP) must describe their planned developments with the IP. The NASA Evaluation License Application should be added as an attachment in the Proposal Certifications form (see section 1.6).

Part 4: Work Plan *(Suggested page limit – 5 pages)*
Include a detailed description of the Phase I R/R&D plan to meet the technical objectives. The plan shall indicate what will be done, where it will be done, and how the R/R&D will be carried out. Discuss in detail the methods planned to achieve each task or objective. The plan shall also include task descriptions, schedules, resource allocations, estimated task hours for each key personnel, and planned accomplishments (including project milestones). Offerors shall ensure that the estimated task hours provided in the work plan for key personnel are consistent with the hours reported in the Proposal Budget form. If the Offeror is a joint venture or limited partnership, a statement of how the workload will be distributed, managed, and charged must be included here.

Part 5: Related R/R&D *(Suggested page limit – 1 page)*

Describe significant current and/or previous R/R&D that is directly related to the technical proposal including any conducted by the PI or by the Offeror. Describe how it relates to the proposed effort and any planned coordination with outside sources. The Offeror must persuade reviewers of his or her awareness of key recent R/R&D conducted by others in the specific subject area.

Part 6: Key Personnel and Bibliography of Directly Related Work *(Suggested page limit – 2.5 pages)*
Identify all key personnel involved in Phase I activities whose expertise and functions are essential to the success of the project. Provide biographical information, including directly related education and experience. Where the resume/vitae are extensive, summaries that focus on the most relevant experience or publications are desired and may be necessary to meet completed proposal package size limitation.

The PI is considered key to the success of the effort and must make a substantial commitment to the project. The following requirements are applicable:

Functions: The functions of the PI are planning and directing the project, leading it technically and making substantial personal contributions during its implementation, serving as the primary contact with NASA on the project, and ensuring that the work proceeds according to contract agreements. Competent management of PI functions is essential to project success. The Phase I completed proposal package shall describe the nature of the PI's activities and the amount of time that the PI will personally apply to the project. The amount of time the PI proposes to spend on the project must be acceptable to the Contracting Officer.

Qualifications: The qualifications and capabilities of the proposed PI and the basis for PI selection are to be clearly presented in the completed proposal package. NASA has the sole right to accept or reject a PI based on factors such as education, experience, demonstrated ability and competence, and any other evidence related to the specific assignment.

Eligibility: This part shall also establish and confirm the eligibility of the PI and shall indicate the extent to which existing projects and other proposals recently submitted or planned for submission in fiscal year 2022 commit the time of the PI concurrently with this proposed activity. Any attempt to circumvent the restriction on PIs working more than half time for an academic or a nonprofit organization by substituting an ineligible PI will result in the proposal package being declined.

Part 7: The Market Opportunity *(Suggested page limit – 1 page)*
The purpose of this section is for Phase I Offerors to describe the potential commercialization opportunities for the innovation. The SBIR program is mandated to move funded innovations into commercial markets including both federal markets and private sector commercial markets. In addition, Offerors who start to address the market opportunities early will be better positioned to address additional commercialization metrics under future SBIR efforts including Phase II and Phase III.

Phase I Offerors should address each of the following:

- Discuss the business economics and market drivers in the target industry.
- How has the market opportunity been validated?
- Describe your customers and your basic go-to-market strategy to achieve the market opportunity.
- Describe the competition.
- How do you expect the competitive landscape may change by the time your innovation enters the market?
- What are the key risks in bringing your innovation to market?
- Describe your commercialization approach.

- Discuss the potential economic benefits associated with your innovation and provide estimates of the revenue potential, detailing your underlying assumptions.
- Describe the resources you expect will be needed to implement your commercialization approach.

Part 8: Facilities/Equipment *(Suggested page limit – 1 page)*
Describe the types, location, and availability of physical facilities necessary to carry out the work proposed.

Describe the types, location, and availability of equipment necessary to carry out the work proposed. Items of equipment to be purchased must be fully justified under this section. **When purchasing equipment or a product under the SBIR funding agreement, the small business should purchase only American-made items whenever possible.**

Government-furnished laboratory equipment, facilities, or services (collectively, “Government resources”) the Offeror shall describe in this part why the use of such Government resources is necessary and not reasonably available from the private sector. See sections 3.5.3.4 and 5.13 for additional requirements when proposing use of such Government resources. The narrative description of resources should support the proposed approach and documentation in the Proposal Budget form.

Note: Use of Federal laboratories/facilities for Phase I contracts is highly discouraged. Approval for use of Federal facilities and laboratories for a Phase I completed proposal package requires the Contracting Officer approval during negotiations if selected for award.

Part 9: Subcontractors and Consultants *(Suggested page limit – 1 page)*
The Offeror must describe all subcontracting or other business arrangements and identify the relevant organizations and/or individuals with whom arrangements are planned. The expertise to be provided by the entities must be described in detail, as well as the functions, services, and number of hours. Offerors are responsible for ensuring that all organizations and individuals proposed to be utilized are available for the time periods proposed. Subcontract costs shall be documented in the Subcontractors/Consultants section of the Proposal Budget form and supporting documentation should be uploaded for each (appropriate documentation is specified in the form). The narrative description of subcontractors and consultants in the technical proposal should support the proposed approach and documentation in the Proposal Budget form.

Note: Offerors who do not plan to have a subcontractor or consultants need to indicate this in the EHB.

Part 10: Related, Essentially Equivalent, and Duplicate Proposals and Awards *(Suggested page limit – 1 page)*
WARNING: While it is permissible with proper notification to submit identical proposals or proposals containing a significant amount of essentially equivalent work for consideration under numerous Federal program solicitations, it is unlawful to enter into funding agreements requiring essentially equivalent work.

If an Offeror elects to submit identical proposals or proposals containing a significant amount of essentially equivalent work under other Federal program solicitations, a statement must be included in each proposal indicating the following:

1. The name and address of the agencies to which proposals were submitted or from which awards were received.
2. Date of proposal submission or date of award.
3. Title, number, and date of solicitations under which proposals were submitted or awards received.
4. The specific applicable research subtopics for each proposal submitted or award received.

5. Titles of research projects.
6. Name and title of principal investigator or project manager for each proposal submitted or award received.

Offerors are at risk for submitting essentially equivalent proposals and therefore are strongly encouraged to disclose these issues to the soliciting agency to resolve the matter prior to award.

A summary of essentially equivalent work information, as well as related research and development on proposals and awards, is also required on the Proposal Certifications form (if applicable).

3.5.3.6 Briefing Chart

The 1-page briefing chart is required to assist in the ranking and advocacy of technical proposals prior to selection and contains the following sections with summary information:

- Identification and Significance of Innovation
- Technical Objectives
- Proposed Deliverables
- NASA Applications
- NASA Relevant Commercial Market Applications
- Graphic

It shall not contain any proprietary data or ITAR-restricted data. An electronic form will be provided during the submissions process. For more inforamtin on ITAR see https://www.sbir.gov/tutorials/itar/.

Note: The briefing chart is public information and may be disclosed. Do not include proprietary information in this form.

3.5.3.7 NASA Evaluation License Application, only if TAV is being proposed

If you have applied for TAV by following the instructions found at http://technology.nasa.gov, upload the application of the TAV request with your completed proposal package.

3.5.3.8 Request for Use of Technical and Business Assistance (TABA) Funds at Phase I

Offerors may request Phase I TABA and can choose their own TABA vendor. NASA does not have a TABA preferred vendor. All requests for Phase I TABA must be submitted in the Phase I completed proposal package submission. However, Offerors are not required to request TABA at Phase I, and there is no prerequisite that an Offeror must use Phase I TABA funding to obtain a Phase II award or request TABA funding at Phase II.

Requests for TABA funding are not reviewed under the technical evaluation of the completed proposal package, and the request for TABA funds will not be part of the decision to make an award. All TABA requests will be reviewed after a completed proposal package is selected for award and during the contract negotiation process.

Offerors selected for Phase I contract negotiations can receive up to $6,500 as a TABA supplement to the Phase I award.

Although an Offeror can use TABA funding for services they choose, NASA is encouraging Offerors to use the limited amount of $6,500 Phase I TABA funds for the following activities:

1. Development of a Phase II TABA Needs Assessment – If a Phase I Offeror plans to request TABA funding at Phase II, the Offeror should secure a TABA vendor that can provide services to support the development of a Phase II TABA needs assessment. The goal of the TABA Needs Assessment is to determine and define the types of TABA services and costs the Offeror would need if the project was selected for a future Phase II award. The Offeror could request up to $50,000 for these Phase II TABA services.

2. Development of a Phase II Commercialization and Business Plan – Offerors that are planning to submit a future proposal for Phase II funding will be required to submit a commercialization and business plan that meets the requirements of a future Phase II submission. NASA is encouraging Offerors to use Phase I TABA funding to secure a TABA vendor that can help develop the required elements of the commercialization and business plan so that NASA can evaluate a firm's ability to commercialize the innovation and provide a level of confidence regarding the firm's future and financial viability.

If requesting Phase I TABA funding, Offerors are required to provide the following TABA information by following the directions found in the Budget forms in the EHB:

The following information must be provided for each TABA vendor

- Name of vendor
- Contact information of the vendor
- Vendor DUNS number
- Vendor website address
- Description of vendor(s) expertise and knowledge of providing technical and business assistance services to develop and complete a TABA Needs Assessment for a future Phase II submission, to develop a Commercialization Plan for a future Phase II submission, or other TABA services. If requesting TABA for other services, the Offeror must describe the vendor(s) expertise in providing the requested services
- Itemized list of services and costs the TABA vendor will provide. **This applies to all vendors.**
- Describe the deliverables the TABA vendor will provide and a plan to submit a deliverable summarizing the outcome of the TABA services with expected supporting information.
- TABA costs reflected in the budget forms.

Note: All TABA vendors must be a legal business in the United States and NASA will review the U.S. Government-wide System for Award Management (SAM) excluded parties list to ensure the proposed TABA vendor can receive Federal funds. NASA will consider TABA requests that are missing any requested TABA information (e.g., DUNS number, etc.) as incomplete and will not review the TABA request or provide TABA approval under the award.

NASA reserves the right to withhold funds requested for TABA until a formal review and approval of the requested vendor is completed.

In addition to the review of the TABA request in the completed proposal package, NASA may also consider additional information, such as a review the vendor's website, Duns and Bradstreet reports, and SAM.gov, to verify the existence of the vendor(s) and to assess the capability of the vendor(s).

NASA will only approve TABA funding if the completed proposal package is selected for a Phase I award and the Offeror adequately demonstrates the existence and capability of the selected vendor(s) as determined at the sole discretion of NASA. Notification of the approval or denial of TABA funding will be provided to the Offeror prior to award.

Any TABA funding **will be in addition to the Phase I contract award value, is not subject to any profit or fee by the requesting firm, and cannot be used in the calculation of indirect cost rates or general and administrative expenses (G&A).** The TABA cost(s) and service(s) to be provided by each vendor will be based on the original Phase I period of performance. Requests for TABA funding outside of the Phase I period of performance or after a completed proposal package submission will not be considered.

Schedule of Deliverables and Payments for TABA—Offerors that are approved to receive TABA under a Phase I award will be reimbursed for TABA expenses. Reimbursement for TABA will be based on the awardee providing a TABA end-of-contract report at the end of the contract period of performance. Reimbursement will not be provided for any amounts incurred over the TABA funding amount approved by the Government prior to award.

For additional TABA information see https://www.sbir.gov/node/2088581.

3.5.3.9 I-Corps Interest Form

A complete proposal package will require Offerors to complete a short I-Corps interest form (see section 1.7 for additional information on the I-Corps program) as part of their submission. This form is found in the EHB and NASA uses this form to determine the level of interest from Phase I Offerors to participate in the NASA I-Corps program. Offerors are encouraged to complete the form in its entirety.

Based on the initial level of interest in the I-Corps program, NASA plans to open the opportunity to all Phase I awardees to ensure a successful cohort of teams participate in the program. Phase I awardees will receive information from the SBIR/STTR PMO during contract negotiations describing the process to provide a 5-page proposal to participate in the I-Corps program. Directions for completing the proposal including due dates, training dates, and available grant funding will be provided via email.

Additional details on the program can be found at http://sbir.nasa.gov/content/I-Corps.

The Government reserves the right to limit the number of Offerors to participate in the I-Corps program based on the assessment of the I-Corps proposals and funding availability.

3.5.3.10 Firm Level Forms

All form submissions shall be completed electronically within the EHB and do not count toward the 19-page limit for the technical proposal. For many of these forms, Offerors can view sample forms located in the NASA SBIR/STTR Resources section: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

A. Firm Certifications

Firm certifications that are applicable across all completed proposal package submissions submitted to this solicitation must be completed via the Firm Certifications section of the Proposal Submissions Electronic Handbook (EHB). The Offeror shall answer “Yes” or “No” as applicable. An example of the certifications can be found in the NASA SBIR/STTR Resources section: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. An electronic form will be provided during the submissions process.

Note: The designated firm administrator, typically the first person to register your firm, is the only individual authorized to update the certifications.

B. Audit Information

Although firms are not required to have an approved accounting system, knowledge that a firm has an approved accounting system facilitates NASA’s determination that rates are fair and reasonable. To assist NASA, the SBC shall complete the questions in the Audit Information form regarding the firm’s rates and upload the Federal agency audit report or related information that is available from the last audit. There is a separate Audit Information section in the Proposal Budget form that shall also be completed. If your firm has never been audited by a federal agency, then answer "No" to the first question and you do not need to complete the remainder of the form. An electronic form will be provided during the submissions process.

The Contracting Officer will use this Audit Information to assist with negotiations if the completed proposal package is selected for award. The Contracting Officer will advise Offerors what is required to determine reasonable cost and/or rates in the event the Audit Information is not adequate to support the necessary determination on rates.

Note: The designated firm administrator, typically the first person to register your firm, is the only individual authorized to update the audit information.

C. Prior Awards Addendum

If the SBC has received more than 15 Phase II awards in the prior 5 fiscal years, submit the name of the awarding agency, solicitation year, phase, date of award, Funding Agreement/contract number, and subtopic title for each Phase II. If your firm has received any SBIR or STTR Phase II awards, even if it has received fewer than 15 in the last 5 years, it is still recommended that you complete this form for those Phase II awards your firm did receive. This information will be useful when completing the Commercialization Metrics Survey (CMS) and in tracking the overall success of the NASA SBIR and STTR programs. Any NASA Phase II awards your firm has received will be automatically populated in the electronic form, as well as any Phase II awards previously entered by the SBC during prior submissions (you may update the information for these awards). An electronic form will be provided during the submissions process.

Note: The designated firm administrator, typically the first person to register your firm, is the only individual authorized to update the addendum information.

D. Commercialization Metrics Survey (CMS)

NASA has instituted a comprehensive commercialization survey/data-gathering process for firms with prior NASA SBIR/STTR awards to allow NASA to track the overall commercialization success of its SBIR and STTR programs. The Commercialization Metrics Survey is a required part of the completed proposal package submissions process and must be completed via the Proposal Submissions EHB electronic form. Companies with no SBIR/STTR awards or awards within the last 3 to 5 years will not be penalized under past performance for the lack of past SBIR/STTR commercialization.

If an Offeror has received any Phase III awards resulting from work on any NASA SBIR or STTR awards, provide the related Phase I or Phase II contract number, name of Phase III awarding agency, date of award, Funding Agreement number, amount, project title, and period of performance. The survey will also ask for firm financial, sales, and ownership information, as well as any commercialization success the firm has had because of SBIR or STTR awards. This information must be updated annually during completed proposal package submission via the EHB.

Note: Information received from Offerors via the survey is kept confidential and will not be made public except in broad aggregate, with no firm-specific attribution. Password protected documents may not be submitted in response to the survey.

4. Method of Selection and Evaluation Criteria

All Phase I proposals will be evaluated and judged on a competitive basis. Proposals will be initially screened to determine responsiveness. Proposals passing this initial screening will be technically evaluated by engineers or scientists to determine the most promising technical and scientific approaches. Each proposal will be judged on its own merit. NASA is under no obligation to fund any proposal or any specific number of proposals in a given topic. It also may elect to fund several or none of the proposed approaches to the same topic or subtopic.

4.1 Evaluation Process and Evaluation Criteria

NASA conducts a multi-stage review process of all completed proposal packages to determine if the proposal package can be moved forward to be evaluated and ranked on a competitive basis:

1. **Administrative Review.** All complete proposal packages received by the published deadline will undergo an administrative review to determine if the proposal package meets the requirements found in section 3, Proposal Preparation Instructions and Requirements and section 6 Submission of Proposals. A complete proposal package that is found to be noncompliant with the requirements in sections 3 and 6 will be declined and no further evaluations will occur. The Offeror will be notified of NASA's decision to eliminate the proposal package from consideration and the reason(s) for the decision. Incomplete proposal packages will be automatically declined, and no further evaluations will occur.

2. **Technical Responsiveness.** Complete proposal packages that pass the administrative review will be screened to determine technical responsiveness to the subtopic of this solicitation. Complete proposal packages that are determined to be nonresponsive to the subtopic will be declined and no further evaluations will occur. The Offeror will be notified that NASA declined the complete proposal package and will receive written feedback.

   Note: Offerors are advised to be thoughtful in selecting a subtopic to ensure the technical proposal is responsive to the NASA need as defined by the subtopic. The NASA SBIR program will NOT evaluate a technical proposal under a subtopic that was not selected by the firm and will not switch a complete proposal package from one subtopic to another during the award period of performance, or between Phase I and Phase II or to another program such as Small Business Technology Transfer (STTR).

3. **Technical Evaluation**. Complete proposal packages determined to be responsive to the administrative requirements and technically responsive to the subtopic of this solicitation, as evidenced by the technical abstract and technical proposal, will be fully evaluated by Subject Matter Experts to determine the most promising technical and scientific approaches.

   Factor 1: Scientific/Technical Merit and Feasibility
   The proposed R/R&D effort will be evaluated on:
   - The technical approach and the anticipated agency and commercial benefits that may be derived from the research.
   - The adequacy of the proposed effort, and its relationship to the fulfillment of requirements of the research subtopic.
   - The soundness and technical merit of the proposed approach and its incremental progress toward subtopic solution.
   - The proposal should describe an innovative and feasible technical approach to the identified NASA problem area/subtopic. Specific objectives, approaches, and plans for developing and verifying the innovation must demonstrate a clear understanding of the problem and the current state of

the art. The degree of understanding and significance of the risks involved in the proposed innovation must be presented.

Factor 2: Experience, Qualifications, and Facilities
The qualifications of the proposed Principal Investigators/Project Managers, supporting staff and consultants and subcontractors, if any, will be evaluated for consistency with the research effort and their degree of commitment and availability.

The proposed necessary instrumentation or facilities required to accomplish the proposed technical approach will be evaluated to determine if they are adequate. In addition, any proposed reliance on external sources, such as Government-furnished equipment or facilities (section 3.5.3.4 and part 8 of the technical proposal), will be evaluated for reasonableness.

Factor 3: Effectiveness of the Proposed Work Plan
The proposed work plan should describe the methods planned to achieve each objective or task in detail. The work plan will be evaluated for comprehensiveness, its proposed effective use of available resources and approach to labor distribution. In addition, the work plan's proposed schedule for meeting the Phase I objectives will be evaluated to make sure they are reasonable and consistent with the proposed technical approach.

Factor 4: Commercial Potential
The evaluation factor will consider: the Offeror's record of commercializing SBIR or other research; the existence of Phase II funding commitments from private sector or non-SBIR funding sources; the existence of Phase III follow-on commitments for the subject of the research; and the presence of other indicators of the commercial potential of the idea.

In addition, the evaluation will consider whether the Offeror's proposal has demonstrated a knowledge of whether NASA mission programs and/or other Government agency programs and/or non-Government markets/programs could be applied to the proposed innovation. If known, Offerors should indicate if there are any existing and projected commitments for funding of the innovation beyond Phase I and II (this can include investment, sales, licensing, and other indicators of commercial potential).

4. Price Evaluation.
Utilizing the procedures set forth in FAR 15.404-1, the Offeror's budget proposal form will be evaluated to determine whether the offeror's proposed pricing is fair and reasonable. NASA will only make an award when the price is fair and reasonable and approved by the NASA Contracting Officer.

If a proposal is selected for award, the Contracting Officer will review all the evaluations for the proposal and will address any pricing issues identified during negotiation of the final award.

4.2 Scoring of Factors and Weighting to Determine the Most Highly Rated Proposals

Factors 1, 2, and 3 will be scored numerically and Factor 4 will be assigned an adjectival rating (Excellent, Very Good, Good, Fair, or Poor). Factor 1 is worth 50 points and Factors 2 and 3 are each worth 25 points. The sum of the scores for Factors 1, 2, and 3 will constitute the Technical Merit score.

The most highly technical rated proposals will be eligible for prioritization. To determine the most highly rated technical proposals, the Technical Merit score (Factors 1, 2 and 3) is significantly more important than the Commercial Potential rating (Factor 4).

4.3 Prioritization

For the most highly rated proposals, NASA will prioritize those proposals that offer the best solutions to the technical needs as defined in the subtopics to make recommendations to the Source Selection Official (SSO). In making such a determination, NASA may consider a variety of additional programmatic balance factors such as portfolio balance across NASA Programs, Centers and Mission Directorates, available funding, first-time awardees/participants, historically underrepresented communities including minority and women-owned small businesses, geographic distribution, and/or balance across ideation/point solutions/market stimulation when making recommendations.

4.4 Selection

Those proposals recommended for negotiations will be forwarded to the SBIR/STTR PMO for analysis and presented to the Mission Directorates and SSO for review. The SSO has the final authority for choosing the specific proposals for contract negotiation. Each completed proposal package selected for negotiation by the SSO will be evaluated by the Contracting Officer to determine eligibility for an award. The terms and conditions of the contract will be negotiated based on the SBIR Small Business Act (15 U.S.C. 638), FAR and NASA FAR requirements, and a responsibility determination made. The Contracting Officer will advise the SSO on matters pertaining to cost reasonableness, responsibility, and known past performance issues.

The list of completed proposal packages selected for negotiation will be posted on the NASA SBIR/STTR website (http://sbir.nasa.gov). All firms will receive a formal notification letter. A Contracting Officer will negotiate an appropriate contract to be signed by both parties before work begins.

Under this solicitation, NASA will not accept more than 10 completed proposal packages from any one firm to ensure the broadest participation of the small business community. NASA does not plan to award more than 5 SBIR contracts to any Offeror.

4.5 I-Corps Evaluation Process

For awardees invited to submit an I-Corps proposal pursuant to sections 1.7 and 3.5.3.9, NASA will provide a programmatic assessment of firms based on the following criteria:

- Proposed team members demonstrate a commitment to the requirements of the I-Corps program.
- The proposed team includes the proper composition and roles as described in the I-Corps proposal requirements.
- The I-Corps proposal defines that the small business is at a stage that fits the goals of the program and aligns with the NASA SBIR program goals.
- The I-Corps proposal demonstrates that there is potential for commercialization in both NASA and NASA Relevant Commercial markets.

Based on the assessment of the above criteria the NASA SBIR/STTR PMO will provide a recommendation of I-Corps proposals to receive grants to the SSO. The SSO will make the final selections for I-Corps. NASA anticipates a total of approximately 25 SBIR firms will be selected for participation in the I-Corps program for Phase I.

4.6 Technical and Business Assistance (TABA)

NASA conducts a separate review of all Phase I Offeror requests for TABA after the SSO makes the final selection of projects to enter negotiation for a Phase I contract. The SBIR/STTR PMO conducts the initial evaluation of the TABA request to determine if the request meets the requirements found in sections 1.8 and 3.5.3.8. The Contracting Officer makes the final determination to allow TABA funding under the contract.

The review of Phase I TABA requests will include the following:

- A review to determine if the awardee will use the funding to develop a Phase II TABA Needs Assessment and a Phase II Commercialization and Business Plan and/or if there are additional services being requested.
- Verification of TABA vendors by reviewing the vendor information and websites.
- A review of the vendor(s) expertise and knowledge in providing technical and business assistance services to develop and complete a TABA Needs Assessment, a Commercialization and Business Plan, or other proposed TABA services.
- A review of the costs to be provided to the TABA vendor(s).
- Proposed plans to submit a deliverable summarizing the outcome of the TABA services with expected supporting information.
- Verification that TABA costs are reflected in the budget forms.
- There is no evidence of Fraud, Waste and Abuse for these funds.

4.7. Access to Proprietary Data by Non-NASA Personnel

4.7.1 Non-NASA Reviewers

In addition to utilizing Government personnel in the review process, NASA, at its discretion and in accordance with 1815.207-71 of the NASA FAR Supplement, may utilize individuals from outside the Government with highly specialized expertise not found in the Government. Qualified experts outside of NASA (including industry, academia, and other Government agencies) may assist in performing evaluations as required to determine or verify the merit of a completed proposal package. Offerors should not assume that evaluators are acquainted with the Offeror, key individuals, or with any experiments or other information. Any decision to obtain an outside evaluation shall take into consideration requirements for the avoidance of organizational or personal conflicts of interest and any competitive relationship between the prospective contractor or subcontractor(s) and the prospective outside evaluator. Any such evaluation will be under agreement with the evaluator that the information (data) contained in the completed proposal package will be used only for evaluation purposes and will not be further disclosed.

4.7.2 Non-NASA Access to Confidential Business Information

In the conduct of completed proposal package processing and potential contract administration, the Agency may find it necessary to provide access to the completed proposal package to other NASA contractor and subcontractor personnel. NASA will provide access to such data only under contracts that contain an appropriate NFS 1852.237-72 Access to Sensitive Information clause that requires the contractors to fully protect the information from unauthorized use or disclosure.

4.8 Notification and Feedback to Offerors

After Phase I selections for negotiation have been made, a notification will be sent to the designated small business representative identified in the completed proposal package according to the processes described below.

Note: Due to the competitive nature of the program and limited funding, recommendations to fund or not fund a completed proposal package will be final. Any notification or feedback provided to the Offeror is not an opportunity to reopen selection decisions or obtain additional information regarding the final decision. Offerors are encouraged to use the written feedback to understand the outcome and review of their completed proposal package and to develop plans to strengthen future proposals.

4.8.1 Phase I Feedback

NASA uses a two-stage process to notify Phase I Offerors of the outcome of their completed proposal package.

1. At the time of the public selection announcement, the designated small business representative will receive an email indicating the outcome of the completed proposal package.

2. NASA will automatically email proposal feedback to the designated small business representative within 60 days of the announcement of selection for negotiation. If you have not received your feedback within 60 days after the announcement, contact the NASA SBIR/STTR Program Support Office at sbir@reisystems.com. **Due to the sensitivity of this feedback, NASA will only provide feedback to the designated small business representative and will not provide this to any other parties.**

5. Considerations

5.1 Requirement for Contracting

Upon award of a Funding Agreement, the Awardee will be required to make certain legal commitments through acceptance of numerous clauses in Phase I Funding Agreements. The outline that follows is illustrative of the types of clauses to which the contractor would be committed. This list is not a complete list of clauses to be included in Phase I Funding Agreements and is not the specific wording of such clauses. Copies of complete terms and conditions are available by following the links in appendix D.

(1) Standards of Work. Work performed under the Funding Agreement must conform to high professional standards.
(2) Inspection. Work performed under the Funding Agreement is subject to Government inspection and evaluation at all times.
(3) Examination of Records. The Comptroller General (or a duly authorized representative) must have the right to examine any pertinent records of the Awardee involving transactions related to this Funding Agreement.
(4) Default. The Federal Government may terminate the Funding Agreement if the contractor fails to perform the work contracted.
(5) Termination for Convenience. The Funding Agreement may be terminated at any time by the Federal Government if it deems termination to be in its best interest, in which case the Awardee will be compensated for work performed and for reasonable termination costs.
(6) Disputes. Any dispute concerning the Funding Agreement that cannot be resolved by agreement must be decided by the contracting officer with right of appeal.
(7) Contract Work Hours. The Awardee may not require an employee to work more than 8 hours a day or 40 hours a week unless the employee is compensated accordingly (for example, overtime pay).
(8) Equal Opportunity. The Awardee will not discriminate against any employee or applicant for employment because of race, color, religion, sex, or national origin.
(9) Equal Opportunity for Veterans. The Awardee will not discriminate against any employee or application for employment because he or she is a disabled veteran or veteran of the Vietnam era.
(10) Equal Opportunity for People with Disabilities. The Awardee will not discriminate against any employee or applicant for employment because he or she is physically or intellectually disabled.
(11) Officials Not to Benefit. No Federal Government official may benefit personally from the SBIR/STTR Funding Agreement.
(12) Covenant Against Contingent Fees. No person or agency has been employed to solicit or secure the Funding Agreement upon an understanding for compensation except bona fide employees or commercial agencies maintained by the Awardee for the purpose of securing business.
(13) Gratuities. The Funding Agreement may be terminated by the Federal Government if any gratuities have been offered to any representative of the Government to secure the award.
(14) Patent Infringement. The Awardee must report each notice or claim of patent infringement based on the performance of the Funding Agreement.
(15) American Made Equipment and Products. When purchasing equipment or a product under the SBIR/STTR Funding Agreement, purchase only American-made items whenever possible.

To simplify making contract awards and to reduce processing time, all contractors selected for Phase I contracts will ensure that:

1. All information in your completed proposal package is current (e.g., your address has not changed, the proposed PI is the same, etc.). If changes have occurred since submittal of your completed proposal package, notify the Contracting Officer immediately.
2. Your firm is registered with System for Award Management (SAM) (section 2.2).
3. Your firm complies with the FAR 52.222-37 Employment Reports on Special Disabled Veterans, Veterans of the Vietnam Era, and Other Eligible Veterans (VETS-4212) requirement (See Appendix D). Confirmation that a VETS-4212 report has been submitted to the Department of Labor, and is current, shall be provided to the Contracting Officer within 10 business days of the notification of selection for negotiation.
4. Your firm HAS NOT proposed a Co-Principal Investigator.
5. Your firm will provide timely responses to all communications from the NSSC Contracting Officer.
6. All proposed cost is supported with documentation, such as a quote, previous purchase order, published price lists, etc. All letters of commitment are dated and signed by the appropriate person with contact information. If a university is proposed as a subcontractor or a RI, the signed letter shall be on the university letterhead from the Office of Sponsored Programs. If an independent consultant is proposed, the signed letter should not be on a university letterhead. If the use of Government facilities or equipment is proposed, your firm shall submit a signed letter from the Government facility authorizing the use of the facility and stating the availability and the cost, if any, together with a signed letter from your firm justifying the need to use the facility.

From the time of completed proposal package notification of selection for negotiation until the award of a contract, all communications shall be submitted electronically to NSSC-SBIR-STTR@nasa.gov.

Note: Costs incurred prior to and in anticipation of award of a contract are entirely the risk of the contractor if a contract is not subsequently awarded. A notification of selection for negotiation is not to be misconstrued as an award notification to commence work.

5.2 Awards

5.2.1 Anticipated number of Awards

NASA does not estimate an exact number of anticipated Phase I contract awards; however, the table below reflects the historical information for the program.

Year	Number of SBIR Phase I Proposals Reviewed	Number of SBIR Phase I Awards	Percentage of SBIR Phase I Awards
2021	1503	305	20.2%
2020	1603	352	21.9%
2019	1420	314	22.1%

5.2.2 Award Conditions

NASA awards are electronically signed by a NASA Contracting Officer and transmitted electronically to the organization via email. NSSC will distribute the NASA SBIR award with the following items.

Phase I:

- SF26—Contract Cover Sheet
- Contract Terms and Conditions—to include reference to the completed proposal package and budget
- Attachment 1: Contract Distribution List
- Attachment 2: Template of the Final Summary Chart
- Attachment 3: IT Security Management Plan Template

- Attachment 4: Applicable Documents List
- Negotiation Confirmation
- Phase I Frequently Asked Questions (FAQs)

5.2.3 Type of Contract

NASA SBIR Phase I awards are made as firm fixed price contracts.

5.2.4 Model Contracts

Examples of the NASA SBIR contracts can be found in the NASA SBIR/STTR Resources section: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. ***Note: Model contracts are subject to change.***

5.3 Reporting and Required Deliverables

An IT Security Management Plan is required at the beginning of the contract. Contractors interested in doing business with NASA and/or providing IT services or solutions to NASA should use the list found at the website of the Office of the Chief Information Officer (OCIO) as a reference for information security requirements: https://www.nasa.gov/content/security-requirements-policies. An example of an IT Security Management Plan can be found in the NASA SBIR/STTR Resources section: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. For more information, see NASA FAR Supplement clause 1852.204-76

All contracts shall require the delivery of technical reports that present (1) the work and results accomplished; (2) the scientific, technical, and commercial merit and feasibility of the proposed innovation and project results; (3) the proposed innovation's relevance and significance to one or more NASA interests (section 9); and (4) the strategy for development and transition of the proposed innovation and project results into products and services for NASA mission programs and other potential customers. Deliverables may also include the demonstration of the proposed innovation and/or the delivery of a prototype or test unit, product, or service for NASA testing and utilization if requested under Phase I.

The technical reports and other deliverables are required as described in the contract and are to be provided to NASA. These reports shall document progress made on the project and activities required for completion. Periodic certification for payment will be required as stated in the contract. A final report must be submitted to NASA upon completion of the Phase I R/R&D effort in accordance with applicable contract provisions.

A final New Technology Summary Report (NTSR) is due at the end of the contract, and New Technology Report(s) (NTR) are required if technology(ies) is/are developed under the award prior to submission of the final invoice. For additional information on NTSR and NTR requirements and definitions, see section 5.9.

If TABA is requested, Phase I contracts will require TABA deliverables that summarize the outcome of the TABA services with expected supporting information.

Report deliverables shall be submitted electronically via the EHB. For any reports that require an upload, NASA requests the submission in PDF or Microsoft Word format.

Note: To access contract management in the EHB, you will be required to have an identity in the NASA Access Management System (NAMS). This is the Agency's centralized system for requesting and maintaining accounts for NASA IT systems and applications. The system contains user account information, access requests, and account maintenance processes for NASA employees, contractors, and remote users such as educators and foreign users. A basic background check and completion of NASA IT Security Training is required for this account. Instructions to create an identity in NAMS will be provided during contract negotiations.

It is recommended that you begin this process immediately upon notification, as this access will be required to submit deliverables and invoices.

5.4 Payment Schedule

All NASA SBIR contracts are firm-fixed-price contracts. The exact payment terms will be included in the contract.

Although invoices are submitted electronically through the Department of Treasury's Invoice Processing Platform (IPP), as a condition for payment, invoice certifications shall be completed in the EHB for each individual invoice. The certification is preset in the EHB, and it shall be completed before uploading each invoice in IPP. Upon completion of the certification, a link to IPP is automatically provided in the EHB.

If TABA is requested, Phase I awardees will be required to submit TABA vendor invoices for reimbursement per the payment schedule in section 3.5.3.8.

5.5 Profit or Fee

Contracts may include a reasonable profit. The reasonableness of proposed profit is determined by the Contracting Officer during contract negotiations. Reference FAR 15.404-4.

5.6 Cost Sharing

Cost sharing is permitted for completed proposal packages under this program solicitation; however, cost sharing is not required. Cost sharing will not be an evaluation factor in consideration of your completed proposal package or will not be used in the determination of the percentage of Phase I work to be performed on the contract.

5.7 Rights in Data Developed Under SBIR Funding Agreements

The SBIR program provides specific rights for data developed under SBIR awards. Please review the full text at the following FAR 52.227-20 Rights in Data-SBIR Program and PCD 21-02 FEDERAL ACQUISITION REGULATION (FAR) CLASS DEVIATION – PROTECTION OF DATA UNDER THE SMALL BUSINESS INNOVATIVE RESEARCH/SMALL TECHNOLOGY TRANSFER RESEARCH (SBIR/STTR) PROGRAM

5.8 Copyrights

The contractor may copyright and publish (consistent with appropriate national security considerations, if any) material developed with NASA support. NASA receives a royalty-free license for the Federal Government and requires that each publication contain an appropriate acknowledgment and disclaimer statement.

5.9 Invention Reporting, Election of Title, Patent Application Filing, and Patents

Awardees under the SBIR program are required to provide New Technology Reports (NTR) for any new subject inventions, and the New Technology Summary Reports (NTSR) for the interim and final contract periods. Please review full text at the following https://www.sbir.gov/sites/default/files/SBA_SBIR_STTR_POLICY_DIRECTIVE_OCT_2020_v2.pdf to understand these requirements.

5.10 Government-Furnished and Contractor-Acquired Property

In accordance with the SBIR/STTR Policy Directive, the Federal Government may transfer title to property provided by the SBIR Participating Agency to the awardee, or acquired by the awardee for the purpose of fulfilling the contract, where such transfer would be more cost effective than recovery of the property.

5.11 Essentially Equivalent Awards and Prior Work

If an award is made pursuant to a proposal or completed proposal package submitted under a SBIR solicitation, the firm will be required to certify with every invoice that it has not previously been paid nor is currently being paid for essentially equivalent work by any agency of the Federal Government. **Failure to report essentially equivalent or duplicate efforts can lead to the termination of contracts and/or civil or criminal penalties.**

5.12 Additional Information

5.12.1 Precedence of Contract Over this Solicitation

This program solicitation reflects current planning. If there is any inconsistency between the information contained herein and the terms of any resulting SBIR contract, the terms of the contract take precedence over the solicitation.

5.12.2 Evidence of Contractor Responsibility

The Government may request the Offeror to submit certain organizational, management, personnel, and financial information to establish responsibility of the Offeror. Contractor responsibility includes all resources required for contractor performance (e.g., financial capability, workforce, and facilities).

5.13 Use of Government Resources

Federal Departments and Agencies

Use of SBIR funding for unique Federal/non-NASA resources from a Federal department or agency that does not meet the definition of a Federal laboratory as defined by U.S. law and in the SBA Policy Directive on the SBIR program requires a waiver from the SBA. Completed proposal packages requiring waivers must include an explanation of why the waiver is appropriate. NASA will provide the Offeror’s request, along with an explanation to SBA, during the negotiation process. NASA cannot guarantee that a waiver can be obtained from SBA. Specific instructions to request use of Government Resources are in sections 3.5 of the solicitation.

Note: NASA facilities qualify as Federal laboratories.

Support Agreements for Use of Government Resources

Note: Use of Federal laboratories/facilities for Phase I contracts is highly discouraged as these arrangements will in most cases cause significant delays in making the final award. Approval for use of Federal facilities and laboratories for a Phase I technical proposal requires a strong justification at time of submission and will require approval by the Contracting Officer during negotiations if selected for award.

All Offerors selected for award who require the use of any Federal facility shall, within 20 business days of notification of selection for negotiations, provide to the NSSC Contracting Officer an agreement by and between the Contractor and the appropriate Federal facility/laboratory, executed by the Government official authorized to approve such use. The agreement must delineate the terms of use, associated costs, and facility responsibilities and liabilities. Having a signed agreement for use of Government resources is a requirement for award.

For proposed use of NASA resources, a NASA SBIR/STTR Support Agreement template is available in the Resources section (http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html) and must be executed before a contractor can use NASA resources. Offerors shall only include a signed letter of commitment from an authorized NASA point of contact in the completed proposal packages. NASA expects selected Offerors to finalize and execute their NASA SBIR Support Agreement during the negotiation period with the NSSC.

Contractor Responsibilities for Costs

In accordance with FAR Part 45, it is NASA's policy not to provide services, equipment, or facilities (resources) (capital equipment, tooling, test, and computer facilities, etc.) for the performance of work under SBIR contracts. Generally, any contractor will furnish its own resources to perform the proposed work on the contract.

In all cases, the contractor shall be responsible for any costs associated with services, equipment, or facilities provided by NASA or another Federal department or agency, and such costs shall result in no increase in the price of this contract.

Note: The SBIR/STTR Support Agreement has been updated to include additional requirements related to NASA IT Security. The new additions are found under Section C. Part 3 of the Terms and Conditions of the Support Agreement and are below.

> 3. If Contractor’s use of NASA resources includes use of or access to NASA Information Technology (IT) resources, the Contractor will at all times remain in compliance with and adhere to all NASA IT security requirements and processes, including those set forth in the Contractor’s IT Security Plan. The Contractor’s failure to do so may result in NASA’s unilateral termination of this Use Agreement.

6. Submission of Proposals

6.1 How to Apply for SBIR Phase I

NASA uses electronically supported business processes for the SBIR program. An Offeror must have internet access and an email address. Paper submissions are not accepted.
To apply for a NASA SBIR Phase I contract all SBCs are required to follow the steps found below.

6.1.1 Electronic Submission Requirements via the EHB

NASA uses an electronic submission system called the Electronic Handbook (EHB) and all Offerors must use the EHB for submitting a completed proposal package. The EHB guides firms through the steps for submitting a complete proposal package. All submissions are through a secure connection and most communication between NASA and the firm is through either the EHB or email. To access the EHB go to https://sbir.gsfc.nasa.gov/submissions/login.

New SBCs must register in the EHB to begin the submission process. Returning firms can use the same account they have used for previous submissions unless the business name has changed. Firms are encouraged to start the EHB registration process early to allow sufficient time to complete the submissions process.

It is recommended that the designated small business representative, or an authorized representative designated by the designated small business representative, be the first person to register for the SBC. The SBC's Employer Identification Number (EIN)/Taxpayer Identification Number is required during registration.

Note: The designated small business representative, typically the first person to register your firm, will become the firm administrator and will be the only individual authorized to update and change the firm-level forms in the EHB.

For successful completed proposal package submission, SBCs shall complete all forms online, upload their required documents in an acceptable format, and have the designated small business representative and Principal Investigator (PI) electronically endorse the proposal package within the EHB system.

6.1.2 Deadline for Phase I Completed Proposal Package

A complete proposal package for Phase I shall be received no later than 5:00 p.m. ET on Wednesday, March 9, 2022, via the EHB. See Section 3. Proposal Preparation Instructions and Requirements.

Offerors are responsible for ensuring that all files constituting the complete proposal package be uploaded prior to the deadline. **If a complete proposal package is not received by the 5:00 p.m. ET deadline, the proposal package will be determined to be incomplete and will not be evaluated.** Offerors are strongly encouraged to start the submission process early to allow sufficient time to upload their complete proposal package. An Offeror that waits to submit a proposal package near the deadline is at risk of not completing the required uploads and endorsements of their completed proposal package by the required deadline, resulting in the rejection of the proposal package.

6.1.3 Complete Proposal Package Submission

Firms will upload all components of a complete proposal package using the Proposal Submissions module in the EHB. Directions are found within the EHB to assist users. All transactions via the EHB are encrypted for security purposes.

A complete proposal package consists of online forms and associated documentation that must be submitted in PDF format via the EHB. Below is what a completed proposal package includes. See section 3 for additional information on how to complete each of these sections.

1. Proposal Contact Information
2. Proposal Certifications
3. Proposal Summary
4. Proposal Budget and Associated forms
5. Technical Proposal
6. Briefing Chart
7. NASA Evaluation License Application (only if TAV is being proposed)
8. I-Corps Interest Form
9. Technical and Business Assistance (TABA) Request, if applicable
10. Firm-Level Forms (completed once for all completed proposal packages submitted to a single solicitation)
    a. Firm Certifications
    b. Audit Information
    c. Prior Awards Addendum
    d. Commercialization Metrics Survey (CMS)
11. Electronic Endorsement by the designated small business representative and Principal Investigator (PI)

Firms cannot submit security/password-protected PDF files, as reviewers may not be able to open and read these files. Proposal packages containing security/password-protected PDF files will be declined and not considered.

Offerors are responsible for virus checking all files prior to submission. NASA may reject any completed proposal package that contains a file with a detected virus.

You may upload a complete proposal package multiple times, with each new upload replacing the previous version, but only the final uploaded and electronically endorsed version will be considered for review. If you have already completed a prior upload and endorsed the proposal package, any new uploads will require a re-endorsement of the new completed proposal package.

Before you can submit the final completed proposal package, the EHB will ask you to download the entire completed proposal package and certify that you have reviewed it to ensure that you have met the requirements in this solicitation and have uploaded the correct documentation.

A proposal package that is missing the final endorsements will be considered an incomplete proposal package and will be declined and will not be reviewed.

Note: Embedded animation or video, as well as reference technical papers for "further reading," will not be considered for evaluation.

6.1.4 Acknowledgment of a Completed Proposal Package Receipt

NASA will acknowledge receipt of electronically submitted and completed proposal package upon endorsement by the designated small business representative by sending an email to the designated small business representative email address as provided on the completed proposal package cover sheet, as well as to the user who created the completed proposal package, if different. ***If a completed* proposal package *acknowledgment is not received after***

submission, the Offeror should immediately contact the NASA SBIR/STTR Program Support Office at sbir@reisystems.com.

6.1.5 Withdrawal of Completed Proposal Packages

Prior to the close of submissions, completed proposal packages may be withdrawn via the Proposal Submissions module in the EHB. In order to withdraw a completed proposal package after the deadline, the designated small business representative must send written notification via email to sbir@reisystems.com.

6.1.6 Service of Protests

Protests, as defined in section FAR 33.101 of the Federal Acquisition Regulation, that are filed directly with an agency, and copies of any protests that are filed with the Government Accountability Office (GAO), shall be served on the Contracting Officer (addressed as follows) by obtaining written and dated acknowledgment of receipt from:

Theresa Stanley
NASA Shared Services Center
Building 1111, Jerry Hlass Road
Stennis Space Center, MS 39529
Agency-SBIR-STTRSolicitation@mail.nasa.gov

The copy of any protest shall be received in the office designated above within one day of filing a protest with the GAO.

7. Proposal, Scientific and Technical Information Sources

7.1 NASA Organizational and Programmatic Information

General sources relating to organizational and programmatic information at NASA is available via the following websites:

NASA Budget Documents, Strategic Plans, and Performance Reports:
http://www.nasa.gov/about/budget/index.html
NASA Organizational Structure: http://www.nasa.gov/centers/hq/organization/index.html
NASA SBIR/STTR Programs: http://sbir.nasa.gov

Information regarding 2020 NASA Technology Taxonomy and the NASA Strategic Integration Framework can be obtained at the following websites:

Office of the Chief Technologist	
2020 NASA Technology Taxonomy	https://www.nasa.gov/offices/oct/taxonomy/index.html

NASA Mission Directorates	
Aeronautics Research	http://www.aeronautics.nasa.gov/
Human Exploration and Operations	http://www.nasa.gov/directorates/heo/home/
Science	http://nasascience.nasa.gov
Space Technology	http://www.nasa.gov/directorates/spacetech/home/index.html

NASA Centers	
Ames Research Center (ARC)	http://www.nasa.gov/centers/ames/home/index.html
Armstrong Flight Research Center (AFRC)	http://www.nasa.gov/centers/armstrong/home/index.html
Glenn Research Center (GRC)	http://www.nasa.gov/centers/glenn/home/index.html
Goddard Space Flight Center (GSFC)	http://www.nasa.gov/centers/goddard/home/index.html
Jet Propulsion Laboratory (JPL)	http://www.nasa.gov/centers/jpl/home/index.html
Johnson Space Center (JSC)	http://www.nasa.gov/centers/johnson/home/index.html
Kennedy Space Center (KSC)	http://www.nasa.gov/centers/kennedy/home/index.html
Langley Research Center (LaRC)	http://www.nasa.gov/centers/langley/home/index.html
Marshall Space Flight Center (MSFC)	http://www.nasa.gov/centers/marshall/home/index.html
Stennis Space Center (SSC)	http://www.nasa.gov/centers/stennis/home/index.html
NASA Shared Services Center (NSSC)	https://www.nssc.nasa.gov/

7.2 United States Small Business Administration (SBA)

The SBA oversees the Federal SBIR and STTR programs. The SBA has resources that small businesses can take advantage of in learning about the program and obtaining help in developing a proposal or a completed proposal package to a Federal SBIR/STTR program. Offerors are encouraged to review the information that is provided at the following links: www.sbir.gov, https://www.sba.gov/local-assistance, and at https://www.sbir.gov/resources.

The SBA issues a SBIR/STTR Policy Directive which provides guidance to all Federal Agencies that have a SBIR/STTR program. The Policy Directives for the SBIR/STTR programs may be obtained from the SBA at www.sbir.gov or at the following address:

U.S. Small Business Administration
Office of Technology – Mail Code 6470

409 Third Street, S.W.
Washington, DC 20416
Phone: 202-205-6450

7.3 National Technical Information Service

The National Technical Information Service (NTIS) is an agency of the Department of Commerce and is the Federal Government's largest central resource for Government-funded scientific, technical, engineering, and business-related information. For information regarding various NTIS services and fees, call or write:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Phone: 703-605-6000
URL: http://www.ntis.gov

8. Submission Forms

Note: Previews of all forms and certifications are available via the NASA SBIR/STTR Resources section, located at http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

8.1 SBIR Phase I Checklist

For assistance in completing your Phase I completed proposal package, use the following checklist to ensure your submission is complete.

1. The technical proposal and innovation are submitted for one subtopic only.
2. The entire completed proposal package is submitted consistently with the requirements outlined in section 3.
    a. Proposal Contact Information
    b. Proposal Certifications
    c. Proposal Summary
    d. Proposal Budget
        i. Including letters of commitment for Government resources and subcontractors/consultants (if applicable)
        ii. Foreign Vendor form (if applicable) – Note: NASA and the Office of Management and Budget (OMB) has issued a policy that requires a review of any request to purchase materials or supplies from foreign vendors. Due to the short timeframe to issue a Phase I contract, NASA is strongly encouraging Offerors to consider purchasing materials and supplies from domestic vendors only. If a foreign vendor is proposed, the Phase I contract may be delayed or not awarded.
    e. Technical Proposal including all 10 parts as stated in section 3.
    f. Briefing Chart
    g. NASA Evaluation License Application (only if TAV is being proposed)
    h. I-Corps Interest Form
    i. Technical and Business Assistance (TABA) Request, if applicable
    j. Firm-Level Forms (completed once for all completed proposal packages submitted to a single solicitation)
        i. Firm Certifications
        ii. Audit Information
        iii. Prior Awards Addendum
        iv. Commercialization Metrics Survey (CMS)
            1. Foreign Vendor form (if applicable)
    k. Electronic Endorsement by the designated small business representative and Principal Investigator (PI)
3. **The technical proposal shall not exceed a total of 19 standard 8.5- by 11-inch pages with one-inch margins and shall follow the format requirements (section 3.5.2).**
4. The technical proposal contains all 10 parts in order (section 3.5.3).
5. Any additional required letters/documentation.
    a. A letter of commitment from the appropriate Government official if the research or R&D effort requires use of Government resources (sections 3.5 and 5.13).
    b. Letters of commitment from subcontractors/consultants.
    c. If the firm is an eligible joint venture or a limited partnership, a copy or comprehensive summary of the joint venture agreement or partnership agreement is included.

  d. NASA Evaluation License Application if proposing the use of NASA technology (TAV).
  e. Supporting documentation of budgeted costs.

6. Proposed funding does not exceed $150,000 (section 1.4), and if requesting TABA, the cost for TABA does not exceed $6,500 (sections 1.8 and 3.5.3.8).
7. Proposed project duration does not exceed six (6) months (section 1.4).
8. Completed proposal package is electronically endorsed by the designated small business representative and the Principal Investigator (PI) by the published deadline.
9. **Complete proposal packages and all endorsements shall be received no later than 5:00 p.m. ET on March 9, 2022 (section 6.1.2).**

9. Research Subtopics for SBIR

Introduction

The SBIR subtopics are organized into groupings called Focus Areas. Focus Areas are a way of grouping NASA interests and related technologies with the intent of making it easier for Offerors to understand related needs across the Agency and thus identify subtopics where their research and development capabilities may be a good match. In addition, there are some SBIR subtopics that may be closely aligned with the NASA STTR program. Offerors should consider both programs when planning to apply. To find the NASA SBIR and STTR solicitations, click this link: https://sbir.nasa.gov/solicitations.

Notes:

Offerors are advised to be thoughtful in selecting a subtopic to ensure the technical proposal is responsive to the NASA need as defined by the subtopic. The NASA SBIR program will NOT move a completed proposal package between SBIR subtopics other programs such as STTR.

NASA uses a Subtopic numbering convention for the SBIR program and maintains this from year to year. The mapping is as follows:

For SBIR Subtopics:
A – Aeronautics Research Mission Directorate (ARMD)
H – Human Exploration and Operations Mission Directorate (HEOMD)
S – Science Mission Directorate (SMD)
Z – Space Technology Mission Directorate (STMD)

Offerors should think of the subtopic lead mission directorates and lead/participating centers as potential customers for their technical proposals. Multiple mission directorates and centers may have interests across the subtopics within a Focus Area.

Related subtopic pointers are identified in the subtopic headers when applicable to assist Offerors with identifying related subtopics that also potentially seek related technologies for different customers or applications. As stated in section 3, an Offeror shall not submit the same (or substantially equivalent) completed proposal packages to more than one subtopic. It is the Offeror's responsibility to select which subtopic to propose to.

Focus Area 1 In-Space Propulsion Technologies

NASA is interested in technologies for advanced in-space propulsion systems to reduce travel time, increase payload mass, reduce acquisition costs, reduce operational costs, and enable new science capabilities for exploration and science spacecraft. The future will require demanding propulsive performance and flexibility for more ambitious missions requiring high duty cycles, more challenging environmental conditions, and extended operation. This focus area seeks innovations for NASA propulsion systems in chemical, electric, nuclear thermal and advanced propulsion systems related to human exploration and science missions. Propulsion technologies will focus on a number of mission applications including ascent, descent, orbit transfer, rendezvous, station keeping, proximity operations and deep space exploration.

Z10.01 Cryogenic Fluid Management (SBIR)

Lead Center: GRC
Participating Center(s): JSC, MSFC

Scope Title: Cryogenic Fluid Management (CFM)

Scope Description:

This subtopic seeks technologies related to cryogenic propellant (e.g., hydrogen, oxygen, methane) storage and transfer to support NASA's space exploration goals. This includes a wide range of applications, scales, and environments consistent with future NASA missions. Such missions include but are not limited to upper stages, ascent and descent stages, refueling elements or aggregation stages, nuclear thermal propulsion, and in situ resource utilization. This subtopic solicits proposals in the following areas, in order of priority:

1. High-pressure-ratio compressor for on-orbit gas transfer: Design and develop concepts for a high-pressure-ratio compressor for supercritical xenon and helium, capable of increasing low-pressure fluid to 3,000 psia with continuous flow of up to 15 g/s, allowing for on-orbit transfer of gases for applications of refueling. The temperature range of the xenon is 17 to 40 °C. The compressor must be capable of surviving launch-load vibrations, be able to function accurately in microgravity and vacuum environment (10^{-5} torr) and be able to maintain gas cleanliness to Level A/10 for nonvolatile residue. For Phase I, the main deliverable should be a compressor design and performance analysis. For Phase II, the main deliverable should be a working engineering model of the compressor and the compressor itself.
2. Cryogenic flight-weight valves (minimum Cv >50, goal to Cv of ~100) for low-pressure (<50 psi) liquid oxygen/methane/hydrogen with low internal leakage (~1 sccm, goal of <0.1 sccm) and external leakage (~3 sccm, goal of <0.1 sccm) over multiple cycles (>500 cycles with a goal of 5,000 cycles) to maximize the lifetime of the valve. Proposals can include metallic or nonmetallic sealing elements. Proposals should address the whole valve subsystem, including actuation and actuation mechanisms, with the goal of minimizing mass in Phase II. Phase I deliverable should be proof of concept of the valve with test data using liquid nitrogen, while the Phase II deliverable should be the valve.
3. Subgrid computational fluid dynamics (CFD) of the film condensation process for 1g and low gravity (lunar or Martian) to be implemented into commercial industry standard CFD codes. The subgrid model should capture the formation and growth of the liquid layer as well as its movement along a wall boundary and should implement the volume of fluid (VOF) scheme. The condensation subgrid model should be validated against experimental data (with a target accuracy of 25%), with a preference for condensation data without a noncondensable. Emphasis should be placed on cryogenic fluid data, but noncryogenic data is acceptable. Phase I should be focused on simplified geometries (vertical plates/walls), while Phase II should be focused on complicated geometries

(e.g., full cylindrical tank). The subgrid model and implementation scheme should be the final deliverable.

4. Development of heat flux sensors capable of measuring heat fluxes between 0.1 and 5.0 W/m^2 for cryogenic applications. The sensors should have a target uncertainty of 2% full scale or less at temperatures as high as 300 K and at least as low as 77 K with a goal of 20 K. Proposers should target a demonstration of sensor operability in the 77-K temperature range in Phase I with a full demonstration of calibration and uncertainty in Phase II. Deliverable for Phase II should be the calibrated heat flux sensor.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.1 Cryogenic Systems

Desired Deliverables of Phase I and Phase II:

- Hardware
- Software
- Prototype

Desired Deliverables Description:
Phase I proposals should at minimum deliver proof of the concept, including some sort of testing or physical demonstration, not just a paper study. Phase II proposals should provide component validation in a laboratory environment, preferably with hardware deliverable to NASA.

State of the Art and Critical Gaps:
CFM is a crosscutting technology suite that supports multiple forms of propulsion systems (nuclear and chemical), including storage, transfer, and gauging, as well as liquefaction of ISRU-produced propellants. The Space Technology Mission Directorate (STMD) has identified that CFM technologies are vital to NASA's exploration plans for multiple architectures, whether hydrogen/oxygen or methane/oxygen systems, including chemical propulsion and nuclear thermal propulsion. Several recent Phase II projects have resulted from CFM subtopics, most notably for cryocoolers, liquid acquisition devices, phase separators, broad area cooling, and composite tanks.

Relevance / Science Traceability:
STMD strives to provide the technologies that are needed to enable exploration of the solar system, both manned and unmanned systems; CFM is a key technology to enable exploration. Whether liquid oxygen/liquid hydrogen or liquid oxygen/liquid methane is chosen by Artemis as the main in-space propulsion element to transport humans, CFM will be required to store propellant for up to 5 years in various orbital environments. Transfer will also be required, whether to engines or other tanks (e.g., depot/aggregation), to enable the use of cryogenic propellants that have been stored. In conjunction with ISRU, oxygen will have to be produced, liquefied, and stored; liquefaction and storage are both CFM functions for the surface of the Moon or Mars. ISRU and CFM liquefaction drastically reduces the amount of mass that must be landed.

References:
No references for this subtopic.

Z10.04 Materials, Processes, and Technologies for Advancing In-Space Electric Propulsion Thrusters (SBIR)

Lead Center: GRC
Participating Center(s): JPL

Scope Title: High-Temperature, High-Voltage Electric Propulsion Harness Assembly

Scope Description:
Electric propulsion (EP) for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. This subtopic seeks to address ongoing challenges with EP performance repeatability, hardware reliability, and total life-cycle cost. Critical NASA EP needs have been identified in the scope area detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state of the art (SOA) and quantitatively (not just qualitatively) describe anticipated improvements over relevant SOA materials, processes, and technologies that substantiate NASA investment.

In EP systems, power, commands, and telemetry are relayed between the power processing unit (PPU) and the thruster via dedicated electrical harness assemblies. These harnesses must support the voltage and current needs of the thruster, survive in-space conditions and the operational thermal environment, and not incur unacceptable line loss, radiated emissions, and mass and volume impacts to the spacecraft. Harnesses must also have sufficient flexibility and abrasion resistance, especially for thrusters that are integrated onto actuated gimbals. Individual EP technologies may have specific needs that must be addressed; for example, low-inductance harnesses are preferred in Hall-effect thrusters to reduce thruster discharge oscillations and to promote system stability.

Thermal management of EP systems is a persistent challenge and can be severe in both high-power (>10 kW) and high-power-density (e.g., compact subkilowatt) thrusters. This solicitation seeks advancements in cable and connector materials and designs to support harness assembly solutions addressing all of the following gridded ion and Hall-effect propulsion system needs:

- Voltages (after derating) up to 600-800 VDC (for Hall-effect thrusters) or up to 1.8-2.1 kVDC (for gridded ion thrusters).
- Operating temperatures of at least 350 °C, survival temperatures down to at least -60 °C, and the ability to survive at least 10,000 on-off thermal cycles.
- Direct currents (after derating) up to 10-15 A (for compact <1-kW systems) or up to 25-200 A (for >10-kW systems).
- Deratings consistent with NASA Technical Standard MSFC-STD-3012A (Appendix A) for connectors and wiring.
- Low outgassing materials consistent with the guideline (i.e., maximum total mass loss (TML) of 1% and maximum collected volatile condensable material (CVCM) deposition of 0.1%) in NASA Technical Standard MSFC-SPEC-1443B.
- Features (e.g., venting of connectors and backshells) to mitigate Paschen or corona discharges due to materials or trapped volume outgassing at operating temperatures.
- Features to support harness shielding and grounding.
- Available lengths, flexibility (e.g., bend radius), and abrasion resistance comparable to or better than SOA.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.2 Electric Space Propulsion

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I:

1. Final report containing test data characterizing key properties that address the critical gaps as well as the design and test plan for an EP harness assembly solution to be implemented in Phase II.
2. Material samples that can be used for independent verification of claimed improvements over SOA.

Phase II:

1. Final report containing test data verifying key functional and environmental requirements of the EP harness assembly design, including a functional demonstration in an operating thruster environment (in which partnering with EP developers may be necessary).
2. Prototype harness assembly that can be used for independent verification of claimed improvements over SOA.

State of the Art and Critical Gaps:
Recent NASA EP harnesses have utilized stranded, plated copper wiring with multilayer, crosslinked fluoropolymer (e.g., polytetrafluoroethylene (PTFE) and ethylene tetrafluoroethylene (ETFE)) insulation consistent with MIL-W-22759/SAE Standard AS22759D. Commercial off-the-shelf (COTS) wiring rated to 600 VDC and 1,000 VDC exists but is limited to temperatures below ~260 °C. Meanwhile, COTS electrical connectors (such as MIL-SPEC circular connectors) typically have even lower temperature limits.

Temperature derating requirements for electrical connectors mating to SOA EP thrusters have been challenging for recent NASA missions and have complicated mechanical retention and strain relief at the interface. Custom connector solutions or extensive component testing to relax derating requirements are possible approaches, but they are unattractive as increased development costs would be incurred for each mission. Harness material and design improvements that increase the maximum allowable harness temperature would improve the thermal margin for derating purposes on SOA thrusters and facilitate the development of thrusters with higher powers or power densities relative to SOA.

SOA EP harnesses frequently employ custom insulation wraps on COTS wiring to support high thruster operating voltages. Such wraps can be mechanically fragile and complicate harness handling and installation. Harness material and design improvements that increase the voltage rating are desirable to improve system reliability and to reduce life-cycle costs.

Relevance / Science Traceability:
Both NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. SMD spacecraft need the ability to rendezvous with, orbit, and conduct in situ exploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; mission priorities are outlined in the decadal surveys for each of the SMD divisions (https://science.nasa.gov/about-us/science-strategy/decadal-surveys). For HEOMD, higher power EP is a key element in supporting sustained crewed exploration of cislunar space and Mars.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in EP systems related to such missions. The roadmap for such in-space propulsion technologies is covered under the 2020 NASA Technology Taxonomy (https://www.nasa.gov/offices/oct/taxonomy/index.html), with supporting information archived in the 2015 NASA Technology Roadmap TA-2 (https://www.nasa.gov/offices/oct/home/roadmaps/index.html).

References:

1. Goebel, D. M., and Katz, I., “Fundamentals of Electric Propulsion: Ion and Hall Thrusters,” https://descanso.jpl.nasa.gov/SciTechBook/SciTechBook.html

2. NASA Technical Standard MSFC-STD-3012A, “Electrical, Electronic, and Electromechanical (EEE) Parts Management and Control Requirements for MSFC Space Flight Hardware,” https://standards.nasa.gov/standard/msfc/msfc-std-3012
3. NASA Technical Standard MSFC-SPEC-1443B, “Outgassing Test for Nonmetallic Materials Associated with Sensitive Optical Surfaces in a Space Environment,” https://standards.nasa.gov/standard/msfc/msfc-spec-1443
4. NASA Technical Handbook NASA-HDBK-4007 (Change 3), “Spacecraft High-Voltage Paschen and Corona Design Handbook,” https://standards.nasa.gov/standard/nasa/nasa-hdbk-4007
5. U.S. Military Specification MIL-W-22759/SAE Standard AS22759D, “Wire, Electrical, Fluoropolymer-Insulated, Copper or Copper Alloy.”
6. Clark, S. D., et al., “BepiColombo Electric Propulsion Thruster and High Power Electronics Coupling Test Performances,” IEPC-2013-133, http://electricrocket.org/IEPC/e2cbw2a1.pdf
7. Pinero, L. R., “The Impact of Harness Impedance on Hall Thruster Discharge Oscillations,” IEPC-2017-023, http://electricrocket.org/IEPC/IEPC_2017_23.pdf

Scope Title: Advanced Thermal Management for Hall-Effect Thrusters

Scope Description:
Electric propulsion (EP) for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. This subtopic seeks to address ongoing challenges with EP performance repeatability, hardware reliability, and total life-cycle cost. Critical NASA EP needs have been identified in the scope area detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state of the art (SOA) and quantitatively (not just qualitatively) describe anticipated improvements over relevant SOA materials, processes, and technologies that substantiate NASA investment.

As Hall-effect thrusters are scaled up in power for next-generation missions with large payloads (including human crews), thermal management poses a major design challenge. Compact subkilowatt thrusters for small spacecraft also typically operate with high power density and face similar challenges. To protect critical components such as electromagnets, technological advances are needed to improve the efficiency with which heat can be radiated or conducted away from temperature-sensitive areas of the thruster.

NASA is soliciting proposals for high-emissivity coatings that are compatible with high thruster operating temperatures (300 to 400 °C) and remain compliant with the material outgassing guideline (i.e., maximum total mass loss (TML) of 1% and maximum collected volatile condensable material (CVCM) deposition of 0.1%) in NASA Technical Standard MSFC-SPEC-1443B. Development of discharge channels and anodes made from intrinsically high-emittance materials is also encouraged. Plasma-facing materials and coatings must be able to survive for >20,000 hr of thruster operation while maintaining their thermal performance.

Other approaches of interest include novel radiator geometries that can either be easily attached to existing thrusters or integrated into the design of existing thruster components. Heat pipes integrated into a standard Hall-effect thruster design are also of interest. The solutions must be compatible with expected maximum local temperature in a high-power thruster at the implementation location (e.g., 400 to 600 °C in the vicinity of the inner magnet coil) as well as elevated saturation temperatures that do not produce excessive vessel pressure.

Novel radiator geometries, integral heat pipes, and/or channels for pumped fluid loops also open the design space to additively manufactured implementation of these features. Hiperco® is a typical material that these features could be additively manufactured from, but other magnetic materials may also be considered. Whatever solutions are presented, a reduction of at least 50 to 100 °C in peak inner coil temperatures is desired.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.2 Electric Space Propulsion

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Phase I:

1. Final report containing data from small-scale or coupon testing of the proposed heat rejection technology and a design and test plan for scaling up the technology to a Hall-effect thruster in Phase II.
2. If applicable, material samples that can be used for independent verification of claimed improvements over the SOA (e.g., this would apply to surface coatings).

Phase II:

1. Final report containing test data verifying thermal performance of the novel or improved heat rejection technology, demonstrated in an operating Hall-effect thruster environment (in which partnering with EP developers may be necessary).
2. If applicable, hardware prototypes delivered to NASA to enable testing of the new technology on additional laboratory thrusters (e.g., this would apply to bolt-on radiators, coatings, etc.).

State of the Art and Critical Gaps:
High-emissivity coatings (such as black oxide) have been tested on high-power Hall-effect thruster components, but adhesion over >1,000 thermal cycles and during extended thruster operation remains challenging. Coatings exist that can radiate away heat efficiently while still having low absorptivity of radiated power from the background environment (Conversano et al. 2019). Exterior-facing thruster surfaces may be constructed from carbon to facilitate radiative heat loss (Reilly et al. 2016). The dominant heat load in the thruster arises from plasma impacting the discharge channel and anode (Reilly et al. 2016), so improving the ability of these surfaces to radiate could have significant benefits. A smaller heat load is generated within the magnetic coils, but the thermal conductivities of the coil bobbins, ferromagnetic cores, and potting material are usually low, making the coils a problem area thermally. SOA thrusters are designed to maintain good thermal contact between internal components to maximize heat conduction from the interior to the exterior (Myers et al. 2016), but novel solutions such as heat pipes could dramatically improve heat transport efficiency. Radiators extending from the thruster body have been used for heat rejection in recent NASA Hall thruster designs (Myers et al. 2016, Conversano et al. 2019).

Relevance / Science Traceability:
Both NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. SMD spacecraft need the ability to rendezvous with, orbit, and conduct in situ exploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; mission priorities are outlined in the decadal surveys for each of the SMD divisions (https://science.nasa.gov/about-us/science-strategy/decadal-surveys). For HEOMD, higher-power EP is a key element in supporting sustained crewed exploration of cislunar space and Mars.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in EP systems related to such missions. The roadmap for such in-space propulsion technologies is covered under the 2020 NASA Technology Taxonomy (https://www.nasa.gov/offices/oct/taxonomy/index.html), with supporting information archived in the 2015 NASA Technology Roadmap TA-2 (https://www.nasa.gov/offices/oct/home/roadmaps/index.html).

References:

1. Goebel, D.M., and Katz, I, “Chapter 7: Hall Thrusters,” Fundamentals of Electric Propulsion: Ion and Hall Thrusters, https://descanso.jpl.nasa.gov/SciTechBook/SciTechBook.html
2. Myers, J., Kamhawi, H., Yim, J., and Clayman, L., “Hall Thruster Thermal Modeling and Test Data Correlation,” 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, July, 2016, AIAA-2016-4535.
3. Conversano, R. W., Reilly, S. W., Kerber, T. V., Brooks, J. W., and Goebel, D. M., “Development of and Acceptance Test Preparations for the Thruster Component of the Ascendant Sub-kW Transcelestial Electric Propulsion System (ASTRAEUS),” 36th International Electric Propulsion Conference, Vienna, Austria, September, 2019.
4. Mazouffre, S., Echegut, P., and Dudeck, M., “A Calibrated Infrared Imaging Study on the Steady State Thermal Behavior of Hall Effect Thrusters,” Plasma Sources Sci. Technol., 16, 13-22, 2006.
5. Reilly, S., Sekerak, M., and Hofer, R., “Transient Thermal Analysis of the 12.5 kW HERMeS Hall Thruster,” 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, July, 2016, AIAA-2016-5024.
6. Reilly, S., and Hofer, R. “Thermal Analysis of the 100-kW Class X3 Hall Thruster,” 47th International Conference on Environmental Systems, Charleston, South Carolina, July, 2017, IECS-2017-345.
7. Martinez, R. A., Dao, H., and Walker, Mitchel L. R., “Power Deposition into the Discharge Channel of a Hall Effect Thruster,” J. Prop. Power, 30, 209-220, 2014.
8. NASA Technical Standard MSFC-SPEC-1443B, “Outgassing Test for Nonmetallic Materials Associated with Sensitive Optical Surfaces in a Space Environment,” https://standards.nasa.gov/standard/msfc/msfc-spec-1443

Scope Title: Cost-Effective Carbon-Based Electrodes for High-Power, High-Performance Gridded Ion Thrusters

Scope Description:

Electric propulsion (EP) for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. This subtopic seeks to address ongoing challenges with EP performance repeatability, hardware reliability, and total life-cycle cost. Critical NASA EP needs have been identified in the scope area detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state of the art (SOA) and quantitatively (not just qualitatively) describe anticipated improvements over relevant SOA materials, processes, and technologies that substantiate NASA investment.

Gridded ion thruster technology offers high efficiency, high specific-impulse capabilities, and has been used successfully to support NASA science missions as well as commercial Earth-orbiting applications. The primary life limiter for these devices is typically erosion of the accelerator electrode due to bombardment by charge-exchange ions. While NASA gridded ion thrusters have achieved the necessary lifetimes in the past by operating at derated current densities, there is interest in operation at higher thrust and power densities that would increase mission capture and allow for more compact thruster designs. Higher power and current densities result in increased erosion rates of the accelerator electrode, such that the refractory metals used on previous designs may no longer be sufficient to meet demanding lifetime requirements.

Carbon-based electrodes have shown promise by offering significantly higher erosion resistance compared to refractory metals. Innovative solutions are desired that would result in manufacturing processes for carbon-based electrodes that are cost-effective relative to prior efforts, making them competitive with SOA electrode manufacturing using refractory metals. These solutions must be capable of producing carbon-based electrodes with the following geometries, operating voltages, and thermal properties:

- Screen and accelerator electrode thicknesses of ~0.33 mm and ~0.50 to 0.75 mm, respectively.

- Screen and accelerator electrode open area fractions of ~70% and ~25%, respectively.
- Screen and accelerator aperture diameters of ~2 mm and ~1.25 mm, respectively.
- Gap between the screen and accelerator electrode of ~0.50 to 0.75 mm.
- A shallow spherical dome (i.e., dished) geometry for both screen and accelerator electrodes.

Note: Dome and flat geometries are both of interest to NASA. However, a dome geometry ensures sufficient electrode stiffness and first-mode natural frequency to withstand expected structural loading during launch as well as maintaining required electrode gaps and avoiding buckling due to compressive stresses caused by nonuniform temperature distributions along electrodes. Manufacturing solutions capable of producing only flat electrodes will also be considered but must demonstrate that structural loading during launch and potential buckling during operation will not be issues.

- Extensibility to beam extraction (i.e., perforated) diameters of 40 cm or larger.
- Tight tolerances on apertures' locations (<0.1 mm) to facilitate proper alignment of apertures between screen and accelerator electrodes.
- Minimum voltage standoff capability between screen and accelerator electrodes of 2 kV.
- Peak operating temperatures of 450 °C.
- Coefficients of thermal expansion less than or equal to that of molybdenum (4.8×10^{-6} K^{-1}).

Proposals are desired that offer solutions which are applicable for manufacturing of carbon-based screen and accelerator electrodes. However, proposals that focus only on carbon-based accelerator electrodes will be considered if such solutions are shown to be compatible with screen electrodes made with heritage refractory metals.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.2 Electric Space Propulsion

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Phase I:

1. A final report detailing the material properties and the manufacturing processes for the carbon-based electrodes, as well as an evaluation of the extensibility of the processes to sizes of interest (i.e., 40-cm perforated diameter or larger).
2. A scaled-down sample of each carbon-based electrode (either screen and accelerator or accelerator only, depending on the approach) representative of typical electrode thickness and open area fraction to be delivered to NASA for independent assessment and tests.

Phase II:

1. A final report detailing final manufacturing processes and an updated evaluation of the extensibility of these processes to sizes of interest (i.e., 40-cm perforated diameter or larger).
2. Carbon-based screen and accelerator electrodes (or accelerator electrode only, depending on the approach) at least 30 cm in diameter that can be hot-fire tested with a gridded ion thruster (in which partnering with EP developers may be necessary).

State of the Art and Critical Gaps:
While extensive research and development of carbon-based electrodes have resulted in solutions that were technically adequate, the complexity and associated costs of manufacturing have been prohibitive toward

widespread adoption into ion thruster technology. The material used for electrodes has historically been refractory metals, whose thermal and mechanical properties allow the electrodes to withstand the temperatures and launch loads they will experience while offering adequate erosion resistance. Fabrication using refractory metals such as molybdenum typically involves chemical etching to produce the apertures within the electrodes. Carbon-based solutions have been developed previously by several organizations and include carbon-carbon, amorphous graphite, and pyrolytic graphite (PG). Fabrication techniques for carbon-based electrodes have been rather varied and complex and have included methods such as chemical vapor deposition and carbonization. Apertures in carbon-based electrodes have been created using laser drilling, electric discharge machining (EDM), or machining. As such, innovative solutions are desired that would result in manufacturing processes for carbon-based electrodes that are less complex and/or more cost-effective than prior efforts.

Relevance / Science Traceability:
Both NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. SMD spacecraft need the ability to rendezvous with, orbit, and conduct in situ exploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; mission priorities are outlined in the decadal surveys for each of the SMD divisions (https://science.nasa.gov/about-us/science-strategy/decadal-surveys). For HEOMD, higher power EP is a key element in supporting sustained crewed exploration of cislunar space and Mars.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in EP systems related to such missions. The roadmap for such in-space propulsion technologies is covered under the 2020 NASA Technology Taxonomy (https://www.nasa.gov/offices/oct/taxonomy/index.html), with supporting information archived in the 2015 NASA Technology Roadmap TA-2 (https://www.nasa.gov/offices/oct/home/roadmaps/index.html).

References:

1. Goebel, D. M., and Katz, I., "Fundamentals of Electric Propulsion: Ion and Hall Thrusters," https://descanso.jpl.nasa.gov/SciTechBook/SciTechBook.html
2. Sangregorio, M., Xie, K., Wang, N., Guo, N., and Zang, Z., "Ion engine grids: Function, main parameters, issues, configurations, geometries, materials and fabrication methods," Chinese Journal of Aeronautics Vol. 31, No. 8, 2018, pp. 1635-1649.
3. Snyder, J. S., "Review of Carbon-based Grid Development Activities for Ion Thrusters," 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA-2003-4715, Huntsville, AL, July 20-23, 2003.
4. Haag, T., "Mechanical Design of Carbon Ion Optics," 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA-2005-4408, Tucson, AZ, July 10-13, 2005.
5. De Pano, M. K., Hart, S. L., Hanna, A. A., and Schneider, A. C., "Fabrication and Vibration Results of 30-cm Pyrolytic Graphite Ion Optics," 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA-2004-3615, Fort Lauderdale, FL, July 11-14, 2004.
6. Polk, J. E., Goebel, D. M., Snyder, J. S., Schneider, A. C., Johnson, L. K., and Sengupta, A., "A high power ion thruster for deep space missions," Review of Scientific Instruments, Vol. 83, No. 7, 2012, pp. 073306-1–073306-14.
7. Wallace, N. C., and Corbett, M., "Optimization and Assessment of the Total Impulse Capability of the T6 Ion Thruster," 30th International Electric Propulsion Conference, IEPC-2007-231, Florence, Italy, September 17-20, 2007.
8. Wang, J., Polk, J., Brophy, J., and Katz, I., "Three-Dimensional Particle Simulations of NSTAR Ion Optics," 27th International Electric Propulsion Conference, IEPC-2001-085, Pasadena, CA, October 15-19, 2001.
9. Christensen, J. A., Freick, K. J., Hamel, D. J., Hart, S. L., Norenberg, K. T., Haag, T. W., Patterson, M. J., Rawlin, V. K., Sovey, J. S., Anderson, J. R., Becker, R. A., and Polk, J. E., "Design and Fabrication of

a Flight Model 2.3 kW Ion Thruster for the Deep Space 1 Mission," 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA-1998-3327, Cleveland, OH, July 13-15, 1998.

Scope Title: High-Power Electric Propulsion Thrusters for Mars-Class Missions

Scope Description:
Electric propulsion (EP) for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. This subtopic seeks to address ongoing challenges with EP performance repeatability, hardware reliability, total life-cycle cost, and future needs.

Critical NASA EP needs have been identified in the scope area detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state of the art (SOA) and quantitatively (not just qualitatively) describe anticipated improvements over relevant SOA materials, processes, and technologies that substantiate NASA investment.

Megawatt-class EP has been identified as a key NASA need for enabling sustained human Mars exploration missions. This solicitation seeks solutions that would advance the technical maturation of high-power EP thrusters. NASA is interested in thruster technologies that meet both of the following requirements:

1. Expected operability at ≥100 kW of electrical power, with scalability or clustering approaches capable of supporting ≥1 MW of electrical power.
2. Present technology readiness level (TRL) of ≥4 at the thruster level per NASA NPR 7123.1C Appendix E, in which TRL 4 is defined in this solicitation’s context as a low-fidelity laboratory thruster with test performance demonstrating agreement with analytical predictions for a relevant environment.

To remain within the scope of SBIR awards, proposals addressing component-level or subcomponent-level innovations are desired with a clearly defined path toward thruster-level integration and ground demonstration. Proposals shall address the following:

- Justified compliance with the thruster-level power and TRL requirements listed above.
- Key performance parameters, both SOA and anticipated, relative to the baseline metrics in Table 1.3 of the National Academies’ "Space Nuclear Propulsion for Human Mars Exploration" 2021 report.
- Critical technical challenges identified to date associated with maturing the thruster technology (including interfacing with other elements of a complete EP subsystem) and how the proposed solution addresses one or more of the critical challenges.
- Anticipated compliance with the desired SBIR deliverables (Technological Details section, below).
- Anticipated compliance with the expected TRL range at completion of the project (Technological Details section, below).

Note: The expected TRL range at completion of the project addresses the TRL of the proposed component-level or subcomponent-level innovations. When integrated and demonstrated with a thruster during Phase II, the proposed innovations must support a thruster-level TRL ≥4.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.2 Electric Space Propulsion

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype

- Hardware

Desired Deliverables Description:
Phase I:

1. Final report containing:
    - Design and test plan (to be implemented in Phase II) for thruster-level integration and demonstration of the proposed innovation.
    - Data from proof-of-concept or breadboard testing of the proposed innovation, along with comparisons to SOA and predicted performance.

Phase II:

1. Final report containing test data verifying the performance of the proposed innovation, including a functional demonstration in an operating thruster environment.

State of the Art and Critical Gaps:
Chapter 3 of the National Academies' "Space Nuclear Propulsion for Human Mars Exploration" 2021 report provides an overview of SOA technologies and critical gaps for high-power EP thrusters.

Relevance / Science Traceability:
Both NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. SMD spacecraft need the ability to rendezvous with, orbit, and conduct in situ exploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; mission priorities are outlined in the decadal surveys for each of the SMD divisions (https://science.nasa.gov/about-us/science-strategy/decadal-surveys). For HEOMD, higher-power EP is a key element in supporting sustained crewed exploration of cislunar space and Mars.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in EP systems related to such missions. The roadmap for such in-space propulsion technologies is covered under the 2020 NASA Technology Taxonomy (https://www.nasa.gov/offices/oct/taxonomy/index.html), with supporting information archived in the 2015 NASA Technology Roadmap TA-2 (https://www.nasa.gov/offices/oct/home/roadmaps/index.html).

References:

1. NASA, "Appendix E: Technology Readiness Levels," NPR 7123.1C (NASA Systems Engineering Processes and Requirements), https://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_7123_001C_&page_name=AppendixE
2. National Academies of Sciences, Engineering, and Medicine, Space Nuclear Propulsion for Human Mars Exploration, Washington, DC: The National Academies Press, 2021, https://www.nap.edu/catalog/25977/space-nuclear-propulsion-for-human-mars-exploration

Z10.05 Rotating Detonation Rocket Engines (RDRE) (SBIR)

Lead Center: MSFC
Participating Center(s): GRC

Scope Title: Rotating Detonation Rocket Engine (RDRE) Injector Response, Recovery, and Operation Dynamics

Scope Description:

RDRE injectors require further study and novel solutions to combat major challenges that this high-performance engine cycle experiences. Technology development efforts are needed to better understand how to reduce backflow potential of combustion products as the high-pressure detonation passes over the injector orifices. A high impulsive diodicity for injector elements represents one means by which this may be achieved. Recovery dynamics at various equivalent pressure-drop conditions may hold the key to minimizing deflagration losses. This is particularly the case for liquid/gas and liquid/liquid bipropellants. It is well known that recovery of propellants to reach the chamber at the same time and equivalently participate in the detonation process is where most detonation benefits would come from. Finally, new element schemes that effectively stand off the detonation from the injector face as well as evenly distribute and mix propellant without losing unburnt propellant from the critical region are desired. Standing off the detonation from the injector face would reduce the overall pressure gradient that the injector orifices would experience and thus reduce backflow significantly. Each of these tasks is needed, among others, to reduce overall operating pressures to meet more reasonable liquid engine system requirements.

An ultra-high-performance detonation injector solution that attempts to resolve these challenges or address similar challenges is needed. Computational fluid dynamics modeling (CFD) and analysis in conjunction with cold-flow test, and finally hot-fire testing, would be highly desirable depending on the phase of the work. Solutions that resolve these challenges would afford NASA and the industry partner a feasible path forward to radically improving combustion device performances, enabling future mission architectures, including Moon to Mars.

This subtopic seeks innovative engineering solutions to the problem of injector response and detonation dynamics in the RDRE cycle with applicable propellants. Liquid/gas and liquid/liquid propellant phases are of primary interest, with particular interest in using cryogenic phase propellant. Methane, hydrogen, RP-1, hypergolics, and their subsequent phases are of primary interest to NASA. Gas/gas phase injection is not acceptable unless both liquid oxygen and fuel are in cryogenic states and both being used to regeneratively cool hardware.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.4 Advanced Propulsion

Desired Deliverables of Phase I and Phase II:

- Hardware
- Analysis
- Research
- Prototype

Desired Deliverables Description:
Phase I is multifaceted and could include multiple development pathways. A feasibility study that demonstrates proof of concept for the given application is needed. This can be accomplished with CFD or other type of analysis that shows high diodicity injector schemes can be effectively employed in detonation engines. Further demonstration of manufacturing practicality of complex injector geometries will also be required. One way to do this would be to produce subscale injector orifices, potentially using additive manufacturing techniques. Conventional machining techniques could also be used to produce single-element flow specimens of various geometries. These orifices and specimens could then be subjected to a shock or simulated detonation. The injector's response and recovery dynamics would then be measured. Visualization and measurement of backflow or backflow resistance would be very helpful in this regard. Cold-flow testing using water or air as propellant simulants would be the norm. New techniques for production, postprocessing, and operation of injector orifices would be ancillary but a major addition to the work as it would demonstrate reduction of cost and schedule for hardware development.

Phase I requires small-scale laboratory demonstration using cold-flow experiments and/or modeling efforts to show proof of concept. Proof of concept could include demonstration of elevated diodicity potential for specific injector element geometries over a baseline comparison case. Metrics by which diodicity can be assessed include geometries that produce diodicity of >1.4. However, there are schemes that could reach a diodicity of >10x factor. Efforts to understand propellant rates of recovery are also critical.

Phase II would entail cold-flow testing with simulated shock/detonation conditions in a laboratory setting and/or heat sink/regenerative hot-fire testing that assesses injector response, recovery, and performances such as C*, thrust, and/or visual diagnostics of combustion emissions that allow for the deduction of combustion efficiency. Thrust measurements are desired as well.

State of the Art and Critical Gaps:
Propulsion system performance advancement is virtually at a standstill. In fact, industry is now sacrificing combustion performance and specific impulse improvements for manufacturability. RDREs represent a potential for dramatic improvement in ease of manufacturing, combustion device specific-impulse performance, and advancing U.S. space access capability. High-efficiency propulsion system concepts such as the RDRE are being investigated across the United States, and interest has never been higher. Thus, this work seeks to radically improve and expand the design and test capability of RDREs toward making space access more feasible and cost effective.

Relevance / Science Traceability:
The research requested through this solicitation is relevant to many current NASA projects and programs, particularly for future use with HLS (Human Landing System), SLS (Space Launch System), and the Moon to Mars agency architecture. There is also direct applicability to RDRE ARDVARC (Additive Rotating Detonation Variant Rocket Chamber), RAMFIRE (Reactive Additive Manufacturing for Fourth Industrial Revolution Exploration Systems), LLAMA (Long Life Additive Manufacturing Assembly, and ALPACA (Advanced Lander Performance Additive Chamber Assembly) programs at NASA Marshall Space Flight Center.

References:

1. B. R. Bigler, J. W. Bennewitz, S. A. Danczyk, and W. A. Hargus, “Rotating Detonation Rocket Engine Operability Under Varied Pressure Drop Injection,” J. Spacecr. Rockets, pp. 1–10, 2020, doi: 10.2514/1.a34763.
2. D. Lim, “Experimental Studies of Liquid Injector Response and Wall Heat Flux in a Rotating Detonation Rocket Engine,” Purdue University Graduate School, 2019.
3. G. S. Gill and W. H. Nurick, “Liquid Rocket Engine Injectors,” NASA Spec Publ SP-8089, 1976.
4. J. Hulka, “Design and Fabrication of Additively-Manufactured Injector Elements for an RS-25 Preburner,” 2019.

Scope Title: Methodologies for Improving Rotating Detonation Rocket Engine (RDRE) Exhaust Thrust Capturing (Nozzle Design Optimization) and Mitigation of Losses

Scope Description:
Innovative methods by which RDRE exhaust products can be optimally captured to produce ideal thrust at minimum hardware mass are desired. The traditional RDRE nozzle typically involves the use of an aerospike-like plug nozzle in the center body and cowl or outer body nozzle. It is not fully understood how to optimally capture the thrust of an RDRE given that the exit flow has kinetic energy losses from the oscillatory exhaust. Methods by which these losses can be recovered would be of interest. Furthermore, methods by which the oscillatory outlet flow could be minimized would also be highly desirable.

In addition to the expansion section described above, novel methods for chamber and subsequent throat design are of interest. It is well known that an abrupt area contraction causes deleterious impacts to the detonation's stability and thus causes a decrease in detonative performance, which is thought to cause a decrease in global engine performance. Further investments into geometries that do not hinder detonation performance but also increase specific impulse are desired.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.4 Advanced Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Phase I requires CFD modeling or equivalent analysis/experimental work that demonstrates loss minimization and thrust maximization in addition to attempts that reduce overall hardware mass and scale. The primary goal is to better understand how to design a coupled chamber and nozzle configuration for RDREs that will ideally produce thrust with minimized losses. Methodologies that investigate and assess how to best accomplish this end are a priority. One potential means by which this could be accomplished includes creation of a program that utilizes the method of characteristics to design a plug/outer nozzle configuration at specific design conditions.

Phase I requires modeling efforts to show proof of concept and a down selected geometry to manufacture and test. Proof of concept could include full CFD simulation or simpler analysis methodology over a baseline comparison case. The baseline could be a standard-practice straight annulus with plug nozzle designed using Bykovskii's relations [1,2]. Novel methods for reducing loss mechanisms will also need to be shown. These may include protruding channel geometries into the annulus that may act as stators.

Phase II would entail heat sink/regenerative hot-fire testing that assesses performances such as C*, thrust, and/or visual diagnostics of combustion emissions that allow for the deduction of combustion efficiency.

State of the Art and Critical Gaps:
Propulsion system performance advancement is virtually at a standstill. In fact, industry is now sacrificing combustion performance and specific impulse improvements for manufacturability. RDREs represent a potential for dramatic improvement in ease of manufacturing, combustion device specific-impulse performance, and advancing U.S. space access capability. High-efficiency propulsion system concepts such as the RDRE are being investigated across the United States, and interest has never been higher. Thus, this work seeks to radically improve and expand the design and test capability of RDREs toward making space access more feasible and cost effective.

Relevance / Science Traceability:
The research requested through this solicitation is relevant to current NASA projects and programs, particularly for future use with HLS (Human Landing System), SLS (Space Launch System), and the Moon to Mars agency architecture. Advancement of liquid propulsion system specific impulse is also heavily dependent on nozzle design for the RDRE cycle.

References:

1. K. Goto, J. Nishimura, A. Kawasaki, K. Matsuoka, J. Kasahara, A. Matsuo, I. Funaki, D. Nakata, M. Uchiumi, and K. Higashino, “Propulsive performance and heating environment of rotating detonation engine with various nozzles,” J. Propuls. Power, vol. 35, no. 1, pp. 213–223, 2019.

2. S. Yetao, L. Meng, and W. Jianping, “Continuous detonation engine and effects of different types of nozzle on its propulsion performance,” Chinese J. Aeronaut., vol. 23, no. 6, pp. 647–652, 2010.
3. M. Fotia, T. A. Kaemming, J. Hoke, and F. Schauer, “Study of the experimental performance of a rotating detonation engine with nozzled exhaust flow,” in 53rd AIAA Aerospace Sciences Meeting, 2015, p. 631.
4. T. Smith, A. Pavli, and K. Kacynski, “Comparison of theoretical and experimental thrust performance of a 1030:1 area ratio rocket nozzle at a chamber pressure of 2413 kN/sq m (350 psia),” in 23rd Joint Propulsion Conference, 1987, p. 2069.

Focus Area 2 Power, Energy and Storage

Power is a ubiquitous technology need across many NASA missions, and new technologies are sought to improve and/or enable the generation, storage, and distribution of electrical power for both human and robotic missions. In space power, mission applications include planetary surface power, large-scale spacecraft prime power, and small-scale robotic probe power. Applicable technology development is sought for: 1) efficient means of transmitting, connecting, and managing kilowatt-class power over long distances on planetary surfaces, 2) high-voltage, radiation tolerant switches and components that are needed to optimize mass and efficiency for new high power missions, and 3) components and systems to enable space-rated fuel cells in both primary generation and secondary energy storage applications. Finally, various power generation and storage technologies are sought for extreme-environment planetary science missions. An overarching objective is to mature technologies from analytical or experimental proof-of-concept (TRL3) to breadboard demonstration in a relevant environment (TRL5). Successful efforts will transition into NASA Projects where the prototype deliverables will be incorporated into ground testbeds or flight demonstrations. Note that there are similar power technology development needs at higher power levels for electrified aircraft propulsion which is covered in Focus Area 18 – Air Vehicle Technologies.

S13.07 Energy Storage for Extreme Environments (SBIR)

Lead Center: GRC
Participating Center(s): JPL

Scope Title: Energy Storage for Extreme Environments

Scope Description:
NASA's Planetary Science Division is working to implement a balanced portfolio, within the available budget and based on a decadal survey, that will continue to make exciting scientific discoveries about our solar system. This balanced suite of missions shows the need for low-mass/-volume energy storage that can effectively operate in extreme environments for future NASA Science Missions.

Future science missions will require advanced primary and secondary battery systems capable of operating at temperature extremes and improved specific energy. Advancements to battery energy storage capabilities that address operation for one of the listed missions (Venus, deep space, or lunar) combined with high specific energy and energy density (cell-level goals: >250 Wh/kg and >500 Wh/L for secondary; >800 Wh/kg and >1,000 Wh/L for primary) are of interest. For deep space missions, operation to -200 °C and an operational duration of 30 to 60 days for environments such as Europa, Enceladus, and Titan are required. For Venus surface missions, operation from 460 to 500 °C and an operational duration of 30 to 60 days are required. For lunar surface applications, operation at a temperature range of -230 to +120 °C and during14-day eclipses for lunar night survival and operations are required. Novel battery-pack-level designs and technologies that enhance battery reliability and safety as well as support improved thermal management are also of interest. Combinations of cell-level improvements and/or battery-system-level improvement for enhanced temperature capability will be considered.

Furthermore, missions that incorporate non-rechargeable (primary) batteries will benefit from instrumentation or modeling that can effectively determine state of charge to a high degree of accuracy and/or state of health: particularly those missions that use cell chemistries with discharge voltage profiles that are a weak function of state of charge or state of health, such as lithium carbon monofluoride (Li-CFx) cells. Technologies of interest include: (1) radiation-hardened (to 1 Mrad total ionizing dose) coulomb integration application-specific integrated circuits (ASICs) or hybrid circuits, with >1% accuracy over 1 to 20 A, operating over 24 to 36 V; (2) computational models that can predict state of charge/state of health for primary cells; and (3) nondestructive instrumentation that can detect state of charge/state of health for primary and secondary cells.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.2 Energy Storage

Desired Deliverables of Phase I and Phase II:

- Prototype
- Research

Desired Deliverables Description:
Research should be conducted to demonstrate technical feasibility in a final report for Phase I and show a path toward a Phase II, and when possible, deliver a demonstration unit for NASA testing at the completion of the Phase II contract. Phase II emphasis should be placed on developing and demonstrating the technology under relevant test conditions. Additionally, a path should be outlined that shows how the technology could be commercialized or further developed into science-worthy systems.

State of the Art and Critical Gaps:
State-of-the-art primary and rechargeable cells are limited in both capacity and temperature range. Typical primary Li-SO_2 and Li-$SOCl_2$ operate within a maximum temperature range of -40 to 80 °C but suffer from capacity loss, especially at low temperatures. At -40 °C, the cells will provide roughly half the capacity available at room temperature. Similarly, rechargeable Li-ion cells operate within a narrow temperature range of -20 to 40 °C and suffer from capacity loss at lower temperatures. The lower limit of temperature range of rechargeable cells can be extended using low-temperature electrolytes, but with limited rate capability and concerns about lithium plating on charge. There is currently a gap that exists for high-temperature batteries, primary and rechargeable, that can operate at Venus atmospheric temperatures. In addition, there is a gap in the ability to accurately predict or measure the amount of usable capacity of primary battery cells, particularly after a long mission cruise with exposure to varying temperatures and ionizing radiation dose. This solicitation is aimed at the development of cells that can maintain performance at extreme temperatures to minimize or eliminate the need for strict thermal management of the batteries (which adds complexity and mass to the spacecraft) as well as instrumentation or modeling to predict state of charge/state of health of primary batteries for deep space missions.

Relevance / Science Traceability:
These batteries are applicable over a broad range of science missions. Low-temperature batteries are needed for potential NASA decadal missions to ocean worlds (Europa, Enceladus, Titan) and the icy giants (Neptune, Uranus). These batteries are also needed for science missions on the lunar surface. Low-temperature batteries developed under this subtopic would enhance these missions and could be potentially enabling if the missions are mass or volume limited. There is also significant interest in a Venus surface mission that will require primary and/or rechargeable batteries that can operate for 60+ days on the surface of Venus. A high-temperature battery that can meet these requirements is enabling for this class of missions.

References:

1. NASA Science: https://science.nasa.gov/
2. Solar Electric Propulsion: https://www1.grc.nasa.gov/space/sep/

S16.01 Photovoltaic Power Generation and Conversion (SBIR)

Lead Center: GRC
Participating Center(s): JPL

Scope Title: Photovoltaic Energy Conversion

Scope Description:
This subtopic is seeking photovoltaic cell and blanket technologies that lead to significant improvements in overall solar array performance for missions in areas of scientific interest including high-intensity, high-temperature (HIHT) such as near the Sun and at the inner planets; low-intensity, high-temperature (LIHT) like in the Venus atmosphere; low-intensity, low-temperature (LILT) at the outer planets, including at distances up to Saturn; and high-radiation environments like that near the inner moons of Jupiter. Additionally, sought are solar power systems that can provide high power in compactly stowed volumes for small spacecraft. The subtopic goal is to demonstrate a significant improvement of performance versus state-of-the-art solar cell and array technologies for specific Science Mission locations.

These improvements may be achieved by optimizing the cell technology to operate in a specific environment (HIHT/LIHT/LILT), increasing end of life (EOL) performance, increasing photovoltaic cell efficiency above 35% at 1 AU, development of cells (including encapsulation) for mission-specific environments, and/or decreasing solar cell module/blanket stowed volume. Missions at distances of greater than 1 AU may include an inner-planetary flyby, as such technologies that optimize solar cell string length to account for the changes in power generation are also of interest.

Advances in photovoltaic energy conversion may include but are not limited to, the following: (1) photovoltaic cell and blanket technologies capable of LILT operation applicable to outer planetary (low solar intensity) missions; (2) photovoltaic cell and blanket technologies capable of HIHT operation applicable to inner-planetary missions; (3) photovoltaic cell and blanket technologies that enhance and extend performance in lunar applications including orbital, surface, and transfer; and (4) solar cell and blanket technologies to support missions in high-radiation, LILT environments near Jupiter and its moons.

All proposals relevant to the scope described above would be eligible to be considered for award. For proposals featuring technologies intended for use in planetary science applications, this year a preference will be given to those proposals that would benefit in situ studies of icy ocean worlds, especially low-intensity low-temperature photovoltaic systems.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.1 Power Generation and Energy Conservation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I deliverables include detailed reports with proof of concept and key metrics of components tested and verified.

Phase II deliverables include detailed reports with relevant test data along with proof-of-concept hardware and components developed.

State of the Art and Critical Gaps:
State-of-the-art (SOA) photovoltaic array technology consists of high efficiency, multijunction cell technology on thick honeycomb panels and, as of late, lightweight blanket deployable systems. There are very limited demonstrated technologies for HIHT and LILT missions. A current solution for high-radiation intensity involves adding thick cover glass to the cells, which increases the overall system mass.

Significant improvements in overall performance are needed to address the current gaps between the SOA and many mission requirements for photovoltaic cell efficiency >30%, array mass specific power >200 W/kg, decreased stowed volume, long-term operation in radiation environments, high-power arrays, and a wide range of environmental operating conditions.

Little work has been done to optimize solar cell and array technologies for these unique NASA missions, and programs have adapted SOA technologies through engineering methods and acceptance of decreased performance.

Relevance / Science Traceability:
These technologies are relevant to any space science, Earth science, planetary surface, or other science mission that requires affordable high-efficiency photovoltaic power production for orbiters, flyby craft, landers, and rovers. Specific requirements can be found in the References but include many future Science Mission Directorate (SMD) missions. Specific requirements for orbiters and flybys to outer planets include: LILT capability (>38% at 10 AU and <140 °C), radiation tolerance (6×10^{15} 1 MeV e/cm^2), high power (>50 kW at 1 AU), low mass (3× lower than the standard operating procedure (SOP)), low volume (3× lower than SOP), long life (>15 years), and high reliability. These technologies are relevant and align with any Space Technology Mission Directorate (STMD) or Human Exploration and Operations Mission Directorate (HEOMD) mission that requires affordable high-efficiency photovoltaic power production.

Expands Plans for Moon Exploration: More Missions, More Sciences: https://www.nasa.gov/feature/nasa-outlines-new-lunar-science-human-exploration-missions

NASA Science Missions: https://science.nasa.gov/missions-page?field_division_tid=All&field_phase_tid=3951

References:

1. Solar Power Technologies for Future Planetary Science Missions: https://solarsystem.nasa.gov/resources/548/solar-power-technologies-for-future-planetary-science-missions/
2. NASA outlines New Lunar Science, Human Exploration Missions: https://www.nasa.gov/feature/nasa-outlines-new-lunar-science-human-exploration-missions
3. NASA Science Missions: https://science.nasa.gov/missions-page

Z1.05 Lunar and Planetary Surface Power Management and Distribution (SBIR)

Lead Center: GRC
Participating Center(s): GSFC, JSC

Scope Title: Innovative Ways to Transmit Power over Long Distances for Lunar and Mars Missions

Scope Description:
The Global Exploration Roadmap (January 2018) and the Space Policy Directive (December 2017) detail NASA's plans for future human-rated space missions. A major factor in this effort involves establishing bases on the lunar surface and eventually Mars. Surface power for bases is envisioned to be located remotely from the habitat modules and must be efficiently transferred over significant distances. The International Space Station (ISS) has the largest and highest power (100 kW) space power distribution system, with eight interleaved microgrids providing power functions similar to a terrestrial power utility. Planetary bases will be similar to the ISS, with expectations of storage, science, and habitation modules and multiple power sources, but at higher power levels and with longer distribution networks providing interconnection. In order to enable high-power (>100 kW) and longer distribution systems on the surface of the Moon or Mars, NASA is in need of innovative technologies in the areas of lower mass/higher efficiency power electronic regulators, switchgear, connectors, wireless sensors, power scavenging, and power management control. The technologies of interest would need to operate in extreme temperature environments, including lunar night, and could experience temperature changes ranging from -153 to 123 °C for lunar applications and -125 to 80 °C for Mars bases. In addition to temperature extremes, technologies would need to withstand (have minimal degradation from) lunar dust/regolith, Mars dust storms, and space radiation levels.

While this subtopic would directly address the lunar and Mars base initiatives, technologies developed could also benefit other NASA Mission Directorates, including SMD (Science Mission Directorate) and ARMD (Aeronautics Research Mission Directorate). Specific projects that could find value in the technologies developed herein include Gateway, In-Situ Resource Utilization (ISRU), Advanced Modular Power Systems (AMPS), In-Space Electric Propulsion (ISP), planetary exploration, and Electrified Aircraft Propulsion Technology. The power levels may be different, but the technology concepts could be similar, especially when dealing with temperature extremes and the need for electronics with higher power density and efficiency.

Specific technologies of interest would need to address the lunar or Mars environment and include:

- Application of wide-bandgap electronics in direct current (DC)-to-DC isolating converters with wide-temperature (-70ºC to 150ºC), high-power-density (>2 kW/kg), high-efficiency (>96%) power electronics and associated drivers for voltage regulation.
- Distribution components of a three-phase/1,200-Hz permanent magnet alternator, 480-VAC to 650-VDC power management and distribution with direct drive to Hall thrusters. Key components of the distribution include rotary alternators and alternating current (AC) transmission, including alternator voltage, step-up/step-down transformers, and rectifiers.

NOTE: See Subtopic Z13.02, Mechanisms for Extreme Environments, to propose power connection/termination-related technologies that are impervious to environmental dust and enable robotic deployment, such as robotically enabled high-voltage connectors and/or near-field wireless power transfer in the 1- to 10-kW range.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.3 Power Management and Distribution

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Typically, deliverables under Phase I proposals are geared toward a technology concept with associated analysis and design. A final report usually suffices in summarizing the work, but a prototype is preferred. Phase II hardware prototypes will have opportunities for infusion into NASA technology testbeds and commercial landers.

State of the Art and Critical Gaps:
While high-power terrestrial distribution systems exist, there is no equivalent to a lunar or planetary base. Unique challenges must be overcome in order to enable a realistic power architecture for these future applications, especially when dealing with the environmental extremes that will be encountered. Operability in environments subject to temperature swings will be a critical requirement for any technology developed, from power converters to cabling or power-beaming concepts. In addition, proposals will have to consider lunar regolith and Mars dust storms. To enable a new Mars transportation capability for human exploration, new technology development must be started soon to address the unique needs of a mixed alternating current/direct current (AC/DC) space-rated power system to prove feasibility and provide realistic performance metrics for detailed vehicle design concepts and mission trade studies.

Relevance / Science Traceability:
This subtopic would directly address a remaining technology gap in the lunar and Mars surface mission concepts and Mars human transportation needs. There are potential infusion opportunities with SMD (Science Mission Directorate), Commercial Lander Payload Services (CLPS), HEOMD (Human Exploration and Operations Mission Directorate), and Flexible Lunar Architecture for Exploration (FLARE). In addition, technologies developed could benefit other NASA missions, including Gateway. The power levels may be different, but the technology concepts could be similar, especially when dealing with temperature extremes.

References:

1. The Global Exploration Roadmap, January 2018: https://www.nasa.gov/sites/default/files/atoms/files/ger_2018_small_mobile.pdf
2. Space Policy Directive-1, Reinvigorating America's Human Space Exploration Program, December 11, 2017: https://www.federalregister.gov/documents/2017/12/14/2017-27160/reinvigorating-americas-human-space-exploration-program

Z1.06 Radiation-Tolerant High-Voltage, High-Power Electronics (SBIR)

Lead Center: GSFC
Participating Center(s): GRC, JPL, LaRC

Scope Title: Radiation-Tolerant High-Voltage, High-Power Electronics

Scope Description:
NASA’s directives for space exploration and habitation require high-performance, high-voltage transistors and diodes capable of operating without damage in the natural galactic cosmic ray space radiation environment and induced neutron environment. Recently, significant progress has been made in the research community in understanding the mechanisms of heavy-ion-radiation-induced single-event effect (SEE) degradation and catastrophic failure of wide bandgap (WBG) power transistors and diodes. This subtopic seeks to facilitate movement of this understanding into the successful development of radiation-hardened gallium nitride high-voltage transistors and gallium nitride and/or silicon carbide rectifiers to meet NASA mission power needs reliably in the space environment. These needs include:

- High-voltage, high-power solutions: Taxonomy Area (TX) 03.3.4 (Power Management and Distribution (PMAD) - Advanced Electronic Parts) calls out the need for development of radiation-hardened high-voltage components for power systems. NASA has a core need for diodes and transistors that meet the following specifications:
    - Diodes: Minimum 1200 V, 40 A, with fast recovery <50 ns. Forward voltage drop should not exceed 150% of that in state-of-the-art (SOA) unhardened diodes.

  - Transistors: Minimum 650 V, 40 A, with <24-mohm on-state drain-source resistance.
- High-voltage, low-power solutions: In support of TX 8.1.2 (Sensors and Instruments - Electronics), radiation-hardened high-voltage transistors are needed for low-mass, low-leakage, high-efficiency applications such as lidar Q-switch drivers, mass spectrometers, and electrostatic analyzers. High-voltage, fast-recovery diodes are needed to enhance performance of a variety of heliophysics and planetary science instruments.
  - Transistors: Minimum 1000 V, <50-ns turn-on and turn-off times.
  - Diodes: 2 kV to 5 kV, <50-ns recovery time. Forward voltage drop should not exceed 150% of that in SOA unhardened diodes.
- High-voltage, low- to medium-power solutions: In support of peak-power solar tracking systems for planetary spacecraft and small satellites, transistors and diodes are needed to increase buck converter efficiencies through faster switching speeds.
  - Transistors: Minimum 600 V, <50-ns turn-on and turn-off times, current ranging from low to >20 A.

Successful proposal concepts should result in the fabrication of GaN transistors and/or GaN or SiC diodes that meet or exceed the above performance specifications without susceptibility to damage due to the galactic cosmic ray heavy-ion space radiation environment (SEEs resulting in permanent degradation or catastrophic failure) and the fission reactor environment. These diodes and/or transistors will form the basis of innovative high-efficiency, low-mass, and low-volume systems and therefore must significantly improve upon the electrical performance available from existing heavy-ion SEE radiation-tolerant devices. Lower TRL (technology readiness level) semiconductor technologies are not solicited at this time.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.3 Power Management and Distribution

Desired Deliverables of Phase I and Phase II:

- Hardware
- Prototype
- Analysis

Desired Deliverables Description:
Phase I deliverables must state the initial SOA for the proposed technology and justify the expected final performance metrics. Well-developed plans for validating the tolerance to heavy-ion radiation must be included, and the expected total ionizing dose tolerance should be indicated and justified, or test plans included. Target radiation performance levels will depend upon the device structure due to the interaction of the high electric field with the ionizing particle.

Heavy-ion SEE susceptibility:

- For vertical-field power devices: No heavy-ion-induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface-incident linear energy transfer (LET) of 40 MeV-cm2/mg and sufficient energy to maintain a rising LET level throughout the epitaxial layer(s).
- For all other devices: No heavy-ion-induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface-incident LET of 75 MeV-cm2/mg and sufficient energy to penetrate to the substrate interface prior to the ions reaching their maximum LET value (Bragg peak).

Induced radiation effect susceptibility:

- All devices should maintain performance requirements at neutron dose levels of 10^{11} to 10^{13} cm^{-2} total 1-MeV neutron equivalent fluence, and between 100 and 1,000 krad(Si) total ionizing gamma-ray dose under worst-case bias conditions.

Deliverables in Phase II shall include prototype and/or production-ready semiconductor devices (diodes and/or transistors); and device electrical and radiation performance characterization (device electrical performance specifications, heavy-ion SEE test results, and neutron and gamma total-dose radiation analyses or test results).

State of the Art and Critical Gaps:
High-voltage silicon power devices are limited in current ratings and have limited power efficiency and higher losses than do commercial WBG power devices. Efforts to space-qualify WBG power devices to take advantage of their tremendous performance advantages revealed that they are very susceptible to damage from the high-energy, heavy-ion space radiation environment (galactic cosmic rays), which cannot be shielded against. Higher voltage devices are more susceptible to these effects. Space-qualified GaN transistors are currently available, but these are limited to 300 V. Recent radiation testing of 600-V and higher GaN transistors has shown failure susceptibility at about 50% of the rated voltage, or less. Silicon carbide power devices have undergone several-generation advances commercially, improving their overall reliability, but catastrophically fail at less than 50% of their rated voltage.

Specific needs in STMD (Space Technology Mission Directorate) and SMD (Science Mission Directorate) areas have been identified for spacecraft PMAD, and science instrument power applications and device performance requirements to meet these needs are included in this subtopic nomination. In all cases, there is no alternative solution that can provide the mass and power savings sought to enable game-changing capability. Current PPUs (power processing units) and instrument power systems rely on older silicon technology with many stacked devices and efficiency penalties. In NASA's move to do more with less (smaller satellites), and its lunar/planetary habitation objectives requiring up to 100 kW power production, the technology sought by this subtopic is truly enabling.

State-of-the-art, currently available heavy-ion SEE-tolerant silicon power devices include a Schottky diode capable of 600 V, 30 A, and 27-ns recovery time, and a power MOSFET (metal-oxide semiconductor field-effect transistor) capable of 650 V, 28 A, with on-state resistance of 116 mohm and >50 ns turn-off time. Commercial (non-SEE tolerant) GaN and SiC offerings are available that meet the electrical performance needs indicated in this subtopic, but that cannot meet the heavy-ion SEE requirements indicated.

Relevance / Science Traceability:
Power transistors and diodes form the building blocks of numerous power circuits for spacecraft and science instrument applications. This subtopic therefore feeds a broad array of space technology hardware development activities by providing SEE (heavy-ion) and total-dose radiation-hardened SOA device technologies that achieve higher voltages with lower power consumption and greater efficiency than is presently available.

TX 03.3.4, Power Management and Distribution (PMAD) – Advanced Electronic Parts, calls out the need for development of radiation-hardened high-voltage components for power systems. This subtopic serves as a feeder to the subtopic Lunar and Planetary Surface Power Distribution, in which WBG circuits for PMAD applications are solicited. The solicited developments in this subtopic will also feed systems development for the NASA Kilopower project due to the savings in size/mass combined with radiation hardness.

TX 08.1.2, Sensors and Instruments – Electronics: Radiation-hardened high-voltage transistors are needed for low-mass, low-leakage, high-efficiency applications such as lidar Q-switch drivers, mass spectrometers, and electrostatic analyzers. These applications are aligned with science objectives including Earth science lidar needs, Jovian moon exploration, and Saturn missions. Finally, mass spectrometers critical to planetary and asteroid research and in the search for life on other planets such as Mars require high-voltage power systems and will thus benefit from mass and power savings from this subtopic's innovations.

References:

Partial listing of relevant references:

1. S. J. Pearton, A. Haque, A. Khachatrian, A. Ildefonso, L. Chernyak, and F. Ren, "Review—Opportunities in Single Event Effects in Radiation-Exposed SiC and GaN Power Electronics," *ECS Journal of Solid State Science and Technology*, vol. 10, p. 075004, 2021.
2. E. Mizuta et al., "Single-Event Damage Observed in GaN-on-Si HEMTs for Power Control Applications," *IEEE Transactions on Nuclear Science,* vol. 65, pp. 1956-1963, 2018.
3. M. Zerarka et al., "TCAD Simulation of the Single Event Effects in Normally-OFF GaN Transistors After Heavy Ion Radiation," *IEEE Transactions on Nuclear Science,* vol. 64, pp. 2242-2249, 2017.
4. C. Abbate et al., "Experimental Study of Single Event Effects Induced by Heavy Ion Irradiation in Enhancement Mode GaN Power HEMT," *Microelectronics Reliability,* vol. 55, pp. 1496-1500, 2015.
5. J. M. Lauenstein, M. C. Casey, R. L. Ladbury, H. S. Kim, A. M. Phan, and A. D. Topper, "Space Radiation Effects on SiC Power Device Reliability," in *2021 IEEE International Reliability Physics Symposium (IRPS)*, pp. 1-8, 2021.
6. J. A. McPherson, C. W. Hitchcock, T. P. Chow, W. Ji, and A. A. Woodworth, "Ion-Induced Mesoplasma Formation and Thermal Destruction in 4H-SiC Power MOSFET Devices," IEEE *Transactions on Nuclear Science*, vol. 68, pp. 651-658, 2021.
7. D. R. Ball et al., "Ion-Induced Energy Pulse Mechanism for Single-Event Burnout in High-Voltage SiC Power MOSFETs and Junction Barrier Schottky Diodes," *IEEE Transactions on Nuclear Science,* vol. 67, no. 1, pp. 22-28, 2020.
8. R. A. Johnson, A. F. Witulski, D. R. Ball, K. F. Galloway, A. L. Sternberg, R. A. Reed, et al., "Unifying Concepts for Ion-Induced Leakage Current Degradation in Silicon Carbide Schottky Power Diodes," *IEEE Transactions on Nuclear Science*, vol. 67, pp. 135-139, 2020.
9. S. Kuboyama et al., "Thermal Runaway in SiC Schottky Barrier Diodes Caused by Heavy Ions," *IEEE Transactions on Nuclear Science,* vol. 66, pp. 1688-1693, 2019.
10. C. Shuang, Y. Qingkui, D. Guanghua, G. Jinlong, W. He, Z. Hongwei, et al., "Leakage Current Degradation in SiC Junction Barrier Schottky Diodes under Heavy Ion Microbeam," in *2019 IEEE 26th International Symposium on Physical and Failure Analysis of Integrated Circuits (IPFA)*, pp. 1-4, 2019.
11. A. Akturk, J. M. McGarrity, N. Goldsman, D. Lichtenwalner, B. Hull, D. Grider, et al., "Terrestrial Neutron-Induced Failures in Silicon Carbide Power MOSFETs and Diodes," *IEEE Transactions on Nuclear Science*, vol. 65, pp. 1248-1254, 2018.
12. A. Javanainen, K. F. Galloway, C. Nicklaw, A. L. Bosser, V. Ferlet-Cavrois, J.-M. Lauenstein, et al., "Heavy Ion Induced Degradation in SiC Schottky Diodes: Bias and Energy Deposition Dependence," *IEEE Transactions on Nuclear Science*, vol. 64, pp. 415-420, 2017.
13. A. Javanainen, M. Turowski, K. F. Galloway, C. Nicklaw, V. Ferlet-Cavrois, A. Bosser, et al., "Heavy-Ion-Induced Degradation in SiC Schottky Diodes: Incident Angle and Energy Deposition Dependence," *IEEE Transactions on Nuclear Science*, vol. 64, pp. 2031-2037, 2017.

Z1.08 Space-Rated Fuel Cell Technologies (SBIR)

Lead Center: GRC

Participating Center(s): JSC

Scope Title: Reversible Proton Exchange Membrane (PEM) Cells for High-Pressure Oxygen and Hydrogen

Scope Description:

Objective: Develop a PEM cell design that stably and efficiently operates in both electrolysis and fuel cell modes at high pressures with pure oxygen and hydrogen.

NASA needs energy storage technologies with very high specific energies (W·hr/kg) to maximize the intended science and exploration payloads. Packaged state-of-the-art lithium ion battery systems have a packaged specific energy of ~180 W·hr/kg. Regenerative fuel cell systems have the theoretical potential to more than double this specific energy, depending on the mission specifics and mission energy requirements. Current regenerative fuel cell (RFC) energy storage systems include a significant balance of plant to manage the discrete stack architecture necessitated by the water management requirements of the hydrogen-oxygen-water reaction triad. Detailed research into potential electrolyte chemistries for high-efficiency/low-mass RFC systems strongly indicates that the PEM technology includes the necessary ionic conductivity to support required reaction rates as well as the mechanical durability to survive the high pressures and dynamic thermal and mechanical environments. A unitized fuel cell that supports both the power-producing fuel cell reaction and the energy-storing electrolysis reaction has the potential to reduce the complexity of the RFC balance of plant. Recent developments by academia, Government, and industry have produced these unitized PEM cells for use in hydrogen/air systems. NASA operates in environments without access to air and must use pure oxygen. This call seeks to leverage the existing developments in the unitized PEM cell design that support high-pressure unitized PEM cell operation in air to utilize pure oxygen. As this application is critically limited by available power and mass, preference is given to solutions with lower parasitic power and mass.

- Working fluids: Oxygen, hydrogen, water.
- Operational life: >170 cycles (~10-yr life + flight qualification testing).
- Minimum round-trip efficiency: >48% based on higher heating value (HHV) when measured at 500 mA/cm^2 in fuel cell mode, 1,500 mA/cm^2 in electrolysis mode.
- Operation in fuel cell mode:
    - Minimum = 3 hr.
    - Target = 366 hr.
- Operation in electrolysis mode:
    - Minimum = 3 hr.
    - Target = 366 hr.
- Maximum time to cycle between modes: 3 min (lower preferred).
- Process fluid pressure range (oxygen and hydrogen):
    - Minimum = 35 to 250 psia.
    - Target = 35 to 2,500 psia.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.2 Energy Storage

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype
- Hardware
- Analysis

Desired Deliverables Description:
Phase I Deliverables:

1. Final report.
2. Testing up to 250 psia with both reactants.
3. Engineering data package including supporting analyses, design drawings, test plans, and reports.

Phase II:

1. Final report.
2. Testing up to 2,500 psia with both reactants.
3. Engineering data package including supporting analyses, design drawings, test plans, and reports.

4. Prototype reversible fuel cell stack of at least 5 cells with an active area of at least 50 cm^2 for testing at a NASA center.

State of the Art and Critical Gaps:
Current regenerative fuel cell designs utilize discrete (separate) electrochemical stacks for the fuel cell and electrolysis reactions. A unitized cell has the possibility of significantly reducing the mass of a system by eliminating up to a third of the system components by incorporating both reactions within a single electrochemical stack. The Department of Energy has supported development of unitized cells for hydrogen/air systems. However, these cell designs utilize catalysts and other materials unsuitable for the H_2/O_2 systems required by space applications.

Relevance / Science Traceability:
This technology would support any lunar or Mars mission that requires an energy storage system with a specific energy higher than the ~180 W·hr/kg offered by packaged lithium ion battery systems. This includes Science Mission Directorate (SMD) lunar sensor arrays or crewed lunar outposts.

References:
The literature contains many papers on the challenges associated with reversible PEM cells. These challenges include catalyst selectivity, amphiphilic/hydrophilic/hydrophobic surface treatments, and fluid versus electrode reversibility. Since the bulk of the recent research in this area was funded by the Department of Energy (DOE), see the DOE Reversible Fuel Cell Targets (https://www.hydrogen.energy.gov/pdfs/20001-reversible-fuel-cell-targets.pdf) for the current terrestrial performance and life targets.

Scope Title: High-Efficiency Reversible Dehumidification Technology

Scope Description:
Objective: Develop a desiccant material or other technical solution to manage dew point of bulk gases and recover separated water for later use.

Water management is a major concern on the lunar surface, and operational systems on the lunar surface need to conserve water whenever possible. Power-limited in situ resource utilization (ISRU) and regenerative fuel cell (RFC) energy storage systems generate water-saturated hydrogen and oxygen gases that need to be dehumidified prior to storing the gases. Nonregenerative desiccants or technologies that require dumping absorbed water overboard constitute unacceptable water-loss rates for ISRU and RFC systems. As this application is critically limited by available power and mass, preference is given to solutions with lower parasitic power and mass.

- Bulk fluid 1: Oxygen, saturated with water (noncondensing) at flow rates up to 50 SLPM.
- Bulk fluid 2: Hydrogen, saturated with water (noncondensing) at flow rates up to 100 SLPM.
- Target dew point: <-40 °C.
- Recovery rate (%): >99.3% per cycle.
- Operational life: >100 cycles (~6-yr life + flight qualification testing).
- Process fluid pressure range: 35 to 2,500+ psia.
- Process fluid temperature range: 4 to 85 °C.

Special notes:

- Desiccant materials to be compatible with bulk fluids.
- No slipstreams (any fluids that leave the system through a slipstream represent a loss of system capacity).
- Cannot release particulates to the system that could contaminate the electrochemical hardware.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 03 Aerospace Power and Energy Storage
Level 2: TX 03.2 Energy Storage

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype
- Hardware

Desired Deliverables Description:
Phase I Deliverables:

1. Final report.
2. Engineering data package including supporting analyses, design drawings, test plans, and reports.

Phase II Deliverables:

1. Final report.
2. Engineering data package including supporting analyses, design drawings, test plans, and reports.
3. Two prototype sets of hydrogen and oxygen humidification control system for testing at a NASA Center.

State of the Art and Critical Gaps:
Based on current research, there exists a gap for regenerative humidity regulation solutions for hydrogen and oxygen gas systems with long-term operation that exclude venting water or gases overboard.

Relevance / Science Traceability:
This technology can apply to any NASA mission that produces hydrogen and oxygen from water. Examples include ISRU and power applications and, to a much lesser extent, life support applications.

References:

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2. C.A. O’Meara, I.J. Jakupca, P.J. Smith, “Status of Regenerative Fuel Cell Technologies for Lunar Surface Applications,” 2020 Conference on Advanced Power Systems for Deep Space, October 2020, NASA Document ID 20205008316.

Focus Area 3 Autonomous Systems for Space Exploration

The exploration of space requires the best of the nation's technical community to provide the technologies that will enable human and robotic exploration beyond Low Earth Orbit (LEO): to establish a lunar presence, to visit asteroids, to extend human reach to Mars, and for increasingly ambitious missions. Examples of such missions include robotic platforms like the Europa Lander or crewed missions with extended periods of dormancy such as Gateway. Gateway represents a vital component of NASA’s Artemis program, which will serve as a multi-purpose orbital lunar outpost that provides essential support for a long-term human return to the lunar surface. It will serve as a staging point for deep space exploration. Autonomous Systems technologies provide the means of migrating mission control from Earth to spacecraft, habitats, and robotic explorers. This is enhancing for missions in the Earth-Lunar neighborhood and enabling for deep space missions. Long light-time delays, for example up to 42 minutes round-trip between Earth and Mars, require time-critical control decisions to be closed on-board autonomously, rather than through round-trip communication to Earth mission control. For robotic explorers this will be done through automation, while for human missions this will be done through astronaut-automation teaming.

Long-term crewed spacecraft and habitats, such as the International Space Station, are so complex that a significant portion of the crew's time is spent keeping it operational even under nominal conditions in low-Earth orbit, while still requiring significant real-time support from Earth. The considerable challenge is to migrate the knowledge and capability embedded in current Earth mission control, with tens to hundreds of human specialists ready to provide instant knowledge, to on-board automation that teams with astronauts to autonomously manage spacecraft and habitats. For outer planet robotic explorers, the opportunity is to autonomously and rapidly respond to dynamic environments in a timely fashion.

Specific innovations being sought in this solicitation are described below:

- Deep neural nets and neuromorphic processing have substantial benefit for in-space autonomy and cognition. Advances in signal and data processing for neuromorphic processors promise to enable artificial intelligence and machine learning for autonomous spacecraft operations.
- Intelligent autonomous agent cognitive architectures are sought after as an onboard spacecraft capability. Their open, modular framework has the potential to enable decision-making under uncertainty and learn in a manner that the performance of the system is assured and improves over time.
- Onboard fault management capabilities, such as onboard sensing, computing, algorithms, and models are a critical element of health management for future spacecraft. Offboard components that contribute to onboard fault management are also relevant.
- Improvements in autonomous systems performance are needed, in the context of multi-agent Cyber-Physical-Human (CPH) teams with either some independence under general human direction or complete independence. This capability will help to address the need for integrated data uncertainty management and a robust representation of “trustworthy and trusted” autonomy in space.
- The control and coordination of swarms such as planetary rovers, flyers, and in-space vehicles in dynamic environments is emerging as a critical technological need for future space missions.
- Gateway is seeking capabilities using autonomy and artificial intelligence for operations and health management individually and/or jointly under crewed and un-crewed conditions.

Please refer to the description and references of each subtopic for further detail to guide development of proposals within this technically diverse focus area.

H6.22 Deep Neural Net and Neuromorphic Processors for In-Space Autonomy and Cognition (SBIR)

Lead Center: GRC

Participating Center(s): ARC

Scope Title: Neuromorphic Capabilities

Scope Description:

This subtopic specifically focuses on advances in signal and data processing. Neuromorphic processing will enable NASA to meet growing demands for applying artificial intelligence and machine learning algorithms onboard a spacecraft to optimize and automate operations. This includes enabling cognitive systems to improve mission communication and data-processing capabilities, enhance computing performance, and reduce memory requirements. Neuromorphic processors can enable a spacecraft to sense, adapt, act, and learn from its experiences and from the unknown environment without necessitating involvement from a mission operations team. Additionally, this processing architecture shows promise for addressing the power requirements that traditional computing architectures now struggle to meet in space applications.

The goal of this program is to develop neuromorphic processing software, hardware, algorithms, architectures, simulators, and techniques as enabling capability for autonomous space operations. Emerging memristor and other radiation-tolerant devices, which show potential for addressing the need for energy-efficient neuromorphic processors and improved signal processing capability, are of particular interest due to their resistance to the effects of radiation.

Additional areas of interest for research and/or technology development include: (a) spiking algorithms that learn from the environment and improve operations, (b) neuromorphic processing approaches to enhance data processing, computing performance, and memory conservation, and (c) new brain-inspired chips and breakthroughs in machine understanding/intelligence. Novel memristor approaches that show promise for space applications are also sought.

This subtopic seeks innovations focusing on low size, weight, and power (SWaP) applications suitable to lunar orbital or surface operations, thus enabling efficient onboard processing at lunar distances. Focusing on SWaP-constrained platforms opens the potential for applying neuromorphic processors in spacecraft or robotic control situations traditionally reserved for power-hungry general-purpose processors. This technology will allow for increased speed, energy efficiency, and higher performance for computing in unknown and uncharacterized space environments including the Moon and Mars. Proposed innovations should justify their SWaP advantages and target metrics over the comparable relevant state of the art (SOA).

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.1 Situational and Self Awareness

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I will emphasize research aspects for technical feasibility and show a path toward a Phase II proposal. Phase I deliverables include concept of operations of the research topic, simulations, and preliminary results. Early development and delivery of prototype hardware and/or software is encouraged.

Phase II will emphasize hardware and/or software development with delivery of specific hardware and/or software products for NASA, targeting demonstration operations on a low-SWaP platform. Phase II deliverables include a working prototype of the proposed product and/or software, along with documentation and tools necessary for NASA to use the product and/or modify and use the software. In order to enable mission deployment, proposed prototypes should include a path, preferably demonstrated, for fault and mission tolerances. Phase II deliverables should include hardware and/or software necessary to show how the advances made in the development can be applied to a CubeSat, SmallSat, and rover flight demonstration.

State of the Art and Critical Gaps:
The current SOA for in-space processing is the High Performance Spaceflight Computing (HPSC) processor being developed by Boeing for NASA Goddard Space Flight Center (GSFC). The HPSC, called the Chiplet, contains 8 general-purpose processing cores in a dual quad-core configuration. Delivery is expected by December 2022. In a submission to the Space Technology Mission Directorate (STMD) Game Changing Development (GCD) program, the highest computational capability required by a typical space mission is 35 to 70 GFLOPS (billion fast logical operations per second).

The current SOA does not address the capabilities required for artificial intelligence and machine learning applications in the space environment. These applications require significant amounts of multiply and accumulate operations, in addition to a substantial amount of memory to store data and retain intermediate states in a neural network computation. Terrestrially, these operations require general-purpose graphics processing units (GP-GPUs), which are capable of teraflops (TFLOPS) each—approximately 3 orders of magnitude above the anticipated capabilities of the HPSC.

Neuromorphic processing offers the potential to bridge this gap through a novel hardware approach. Existing research in the area shows neuromorphic processors to be up to 1,000 times more energy efficient than GP-GPUs in artificial intelligence applications. Obviously, the true performance depends on the application, but nevertheless the architecture has demonstrated characteristics that make it well-adapted to the space environment.

Relevance / Science Traceability:
The Cognitive Communications Project, through the Human Exploration and Operations Mission Directorate (HEOMD) Space Communications and Navigation (SCaN) Program, is one potential customer of work from this subtopic area. Neuromorphic processors are a key enabler to the cognitive radio and system architecture envisioned by this project. As communications become more complex, cognition and automation will play a larger role to mitigate complexity and reduce operations costs. Machine learning will choose radio configurations and adjust for impairments and failures. Neuromorphic processors will address the power requirements that traditional computing architectures now struggle to meet and are of relevance to lunar return and Mars for autonomous operations, as well as of interest to HEOMD and Science Mission Directorate (SMD) for in situ avionics capabilities.

References:
Several reference papers that have been published at the Cognitive Communications for Aerospace Applications (CCAA) workshop are available at: http://ieee-ccaa.com

H6.23 Spacecraft Autonomous Agent Cognitive Architectures for Human Exploration (SBIR)

Lead Center: ARC
Participating Center(s): JSC

Scope Title: Spacecraft Autonomous Agent Cognitive Architectures for Human Exploration

Scope Description:
Future deep space human missions will place crews at long distances from Earth causing significant communication lag due to the light distance along with occasional complete loss of communication with Earth. In deep space, crews will be required to manage, plan, and execute the mission more autonomously than currently required on the International Space Station (ISS) due to time delays and communication blackouts. NASA must migrate current operations functionality from Mission Control to the spacecraft to be performed by the crew and autonomous agents supervised by the crew so that the crew is not overburdened.

Novel capabilities for crews and ground staff will be required to manage spacecraft operations, including spacecraft and systems health, crew health, maintenance, consumable management, payload management, and activities such as food production and recycling. Autonomous agents with cognitive architectures could interface directly with the crew and with the onboard systems, reducing the cognitive loads on the crew, as well as perform many of the tasks that would otherwise require scheduling crew time. Cognitive agents can provide assistance, operate systems, provide training, perform inspections, and provide crew consulting, among other tasks. In addition, cognitive agents are necessary in many circumstances to respond to off-nominal events that may overload the crew, particularly when the event limits crew activity such as high-radiation events or loss of atmospheric pressure events requiring crew safety or sequestration.

Today, typical computer agents can easily perform super-human memory recall and computation feats, but at the same time are severely cognitively impaired in that they fail to recognize the values, implications, severity, reasonableness, and likelihood of the assertions they hold, and how inferences can be applied. The consequence is that computer agents often fail to recognize what is obvious and important to humans, appear to be easily deceived, and fail to recognize and learn from mistakes. Thus, crew interfaces to such typical computer agents for the current state of the art can be burdensome.

Due to the complexity of such systems and the need for them to be continually updated, the architecture must be modular, such that modules can dynamically be added, removed, and enhanced. Such a cognitive architecture is consistent with that proposed by Prof. Marvin Minsky in "The Society of Mind", 1988. The cognitive architecture is required to be capable of supporting multiple processes executing on multiple processors to be able to meet the expected computational loads as well as be robust to processor failure.

This subtopic solicits intelligent autonomous agent cognitive architectures that are open, modular, make decisions under uncertainty, and learn in a manner that the performance of the system is assured and improves over time. Cognitive agents for space applications need to adapt and learn from observation, instruction, and interaction as missions proceed. The value of preprogrammed agents that do not adapt over time will diminish in extended missions. This subtopic will enable small businesses to develop both the learning technology and the necessary assurance technology within the scope of cognitive agents that forward base mission control to spacecraft and habitats and multiply the cognitive assets available to the crew. It should be feasible for cognitive agents based on these architectures to be certified or licensed for use on deep space missions to act as liaisons that interact with the mission control operators, the crew, and most, if not all, of the spacecraft subsystems. With such a cognitive agent that has access to all onboard data and communications, the agent could continually integrate this dynamic information and advise the crew and mission control accordingly by multiple modes of interaction including text, speech, and animated images. This agent could respond to queries and recommend to the crew courses of action and direct activities that consider all known constraints, the state of the subsystems, available resources, risk analyses, and goal priorities. Cognitive architectures capable of being certified for crew support on spacecraft are required to be open to NASA with interfaces open to NASA partners who develop modules that integrate with the agent, in contrast to proprietary black-box agents. A cognitive agent suitable for providing crew support on spacecraft may be suitable for a wide variety of Earth applications, but the converse is not true, necessitating this NASA investment.

An effective cognitive architecture would be capable of integrating a wide variety of artificial intelligence modules or managers depending on mission requirements. The following (nonexhaustive) list of managers provides capabilities useful for a wide variety of spacecraft cognitive agents:

State estimation manager: This manager’s capabilities include extracting information from sensors, including images, for use by other managers and by crew. State estimation includes separating signal from noise in sensor data, extracting and compressing useful information, along with fault management and prognostics. The state estimation manager must categorize information on both vehicle-wide and subsystem-by-subsystem bases, including crew health and performance, security, and scientific objectives.

Skill/behavior manager: This manager orchestrates execution of individual tasks on short timescales. This involves incorporating specialized knowledge needed for different tasks, e.g., orbit/trajectory planning, robotics operations, and spacecraft subsystem control. The skill/behavior manager includes a "smart executive" that robustly executes high-level plans produced by the planner/scheduler manager, on schedule, by coordinated commanding of multiple subsystems.

Planner/scheduler manager: This manager creates and updates plans and schedules that accomplish goals. This functionality involves maintaining lists of goals, priorities for achieving those goals, and spacecraft and mission-wide constraints.

Knowledge manager: This manager ensures that the system's declarative knowledge is consistent and updated, including the incorporation of learned knowledge. Learning and modeling techniques capture system and operational knowledge from different types of knowledge sources; these must be incorporated into existing knowledge bases.

Human-machine interactions manager - Natural Language Processing (NLP), Extended Reality (XR): This manager enables multimodal interface/communications with the crew about the current and future state of the systems. This manager must communicate information from all other managers.

Cognitive architectures capable of being certified for crew support on spacecraft are required to be open to NASA software, with interfaces open to NASA partners who develop modules that integrate with the agent, in contrast to proprietary black-box agents. A cognitive agent suitable for providing crew support on spacecraft may be suitable for a wide variety of Earth applications, but the converse is not true, necessitating this NASA investment.

Proposals should emphasize analysis and demonstration of the feasibility of various configurations, capabilities, and limitations of a cognitive architecture suitable for crew support on deep space missions and should address learning and adaptation during mission scenarios. The software engineering of a cognitive architecture is to be documented and demonstrated by implementing a prototype goal-directed software agent that interacts as an intermediary/liaison between simulated spacecraft systems and humans.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.3 Collaboration and Interaction

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:
For Phase I, a preliminary cognitive architecture, preliminary feasibility study, and a detailed plan to develop a comprehensive cognitive architecture feasibility study are expected. A preliminary demonstration prototype of the proposed cognitive architecture is highly encouraged.

For Phase II, the Phase I proposed detailed feasibility study plan is executed, generating a comprehensive cognitive architecture, a comprehensive feasibility study report including design artifacts such as Systems Modeling Language/Unified Modeling Language (SysML/UML) diagrams, a demonstration of an extended prototype of an agent that instantiates the architecture interacting with a spacecraft simulator and humans executing a plausible Human Exploration and Operations Mission Directorate (HEOMD) design reference mission beyond cislunar orbit (e.g., Human Exploration of Mars Design Reference Mission: https://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf), associated source code, and a detailed plan to develop a comprehensive cognitive architecture feasibility study suitable for proposing to organizations interested in funding this flight capability. Open-sourcing prototype agent and simulation software on https://github.com/nasa or a similar open-source platform is encouraged. A Phase II prototype suitable for a compelling flight experiment on the ISS is encouraged.

State of the Art and Critical Gaps:
Long-term crewed spacecraft, such as the ISS, are so complex that a significant portion of the crew's time is spent keeping it operational even under nominal conditions in Low Earth Orbit (LEO) and still require significant real-time support from Earth. Autonomous agents performing cognitive computing can provide crew support for future missions beyond cislunar by providing them robust, accurate, and timely information,

and perform tasks enabling the crew more time to perform the mission science. The considerable challenge is to migrate the knowledge and capability embedded in current Earth mission control, with tens to hundreds of human specialists ready to provide instant knowledge, to onboard agents that team with flight crews to autonomously manage a spaceflight mission.

Most Apollo missions required the timely guidance of mission control for success, typically within seconds of an off-nominal situation. Outside of cislunar space, the time delays will become untenable for Earth to manage time-critical decisions as was done for Apollo. The emerging field of cognitive computing is a vast improvement on previous information retrieval and integration technology and is likely capable of providing this essential capability. This subtopic is directly relevant to the HEOMD Advanced Exploration Systems (AES) domain: Foundational Systems - Autonomous Systems and Operations.

Relevance / Science Traceability:
There is growing interest in NASA to support long-term human exploration missions to the Moon and eventually to Mars. Human exploration up to this point has relied on continuous communication with short delays. To enable missions with intermittent communication with long delays while keeping crew sizes small, new artificially intelligent technologies must be developed. Technologies developed under this subtopic are expected to be suitable for testing on Earth analogues of deep space spacecraft, as well as the Deep Space Gateway envisioned by NASA.

References:

1. IBM (Watson), Apple (Siri®), Microsoft (Cortana), Amazon (Alexa), Google (Dialogflow) are just a few of the companies developing intelligent autonomous agents. However, as they generally are proprietary, they do not meet the need of this subtopic. Importantly, these types of systems only contain limited knowledge about specific tasks such as making reservations or ordering takeout from a restaurant, but do not have the depth of knowledge to represent and reason about the spacecraft systems and operations.
2. A survey of cognitive architectures can be found at: https://arxiv.org/pdf/1610.08602.pdf
3. Conferences that include cognitive architecture papers include International Joint Conferences on Artificial Intelligence (IJCAI), Association for the Advancement of Artificial Intelligence (AAAI), Advanced Computer Systems (ACS), Autonomous Agents and Multiagent Systems (AMAAS), as well as the ongoing Cognitive Architectures (CogArch) series of workshops.
4. Human Exploration of Mars Design Reference Mission: https://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf
5. Minsky, Marvin (1988) "The Society of Mind", Simon & Schuster

S17.03 Fault Management Technologies (SBIR)

Lead Center: JPL
Participating Center(s): ARC, MSFC

Scope Title: Development, Design, and Implementation of Fault Management Technologies

Scope Description:
NASA's science program has well over 100 spacecraft in operation, formulation, or development, generating science data accessible to researchers everywhere. As science missions have increasingly complex goals—often on compressed timetables—and have more pressure to reduce operations costs, system autonomy must increase in response.

Fault management (FM) is a key component of system autonomy, serving to detect, interpret, and mitigate failures that threaten mission success. Robust FM must address the full range of hardware failures, and also must consider failure of sensors or the flow of sensor data, harmful or unexpected system interaction with the environment, and problems due to faults in software or incorrect control inputs—including failure of autonomy components themselves.

Despite lessons learned from past missions, spacecraft failures are still not uncommon, and reuse of FM approaches is limited, illustrating deficiencies in our approach to handling faults in all phases of the flight project lifecycle. The need exists at both extremes of space exploration: At one end, well-funded, resource-rich missions continue to experience difficulties due to system complexity, computing capability that fails to keep pace with expanding mission goals, and risk-averse design, ultimately curtailing mission capability and mission objectives when traditional fault management approaches cannot adequately ensure mission success. At the other end, very small and high-risk missions are flourishing because of advances in computing, microdevices, and low-cost access to space, but autonomy and fault management are increasingly seen as essential because of the high probability of faults and extreme resource limitations that make deliberative, ground-directed fault recovery impractical.

Although this subtopic addresses particular interest in onboard FM capabilities (viz. onboard sensing approaches, computing, algorithms, and models to assess and maintain spacecraft health), the goal is to provide a system capability for management of future spacecraft. Offboard components such as modeling techniques and tools, development environments, and verification and validation (V&V) technologies are also relevant, provided they contribute to novel or capable onboard fault management.

Needed innovations in FM can be grouped into the following two categories:

1. Fault management operations approaches: This category encompasses FM "in-the-loop," including algorithms, computing, state estimation/classification, machine learning, and model-based reasoning. Further research into fault detection and diagnosis, prognosis, fault recovery, and mitigation of unrecoverable faults is needed to realize greater system autonomy.
2. Fault management design and implementation tools: Also sought are methods to formalize and optimize onboard FM, such as model-based system engineering (MBSE). New technologies to improve or guarantee fault coverage, manage and streamline complex FM, and improve system modeling and analysis significantly contribute to the quality of FM design and may prove decisive in trades of new versus traditional FM approaches. Automated test case development, false positive/false negative test tools, model V&V tools, and test coverage risk assessments are examples of contributing technologies.

Specific algorithms and sensor technologies are in scope, provided their impact is not limited to a particular subsystem, mission goal, or failure mechanism. Novel artificial-intelligence-inspired algorithms, machine learning, etc., should apply to this and only this subtopic if their design or application is specific to detection, classification, or mitigation of system faults and off-nominal system behavior. Although the core interests of this subtopic are spacecraft resilience and enabling spacecraft autonomy, closed-loop FM for other high-value systems such as launch vehicles and test stands is also in scope, particularly if the techniques can be easily adapted to spacecraft.

Related technologies, but without a primary focus on resolution of system faults, such as machine-learning approaches to spacecraft characterization or science data pre-processing, autonomy architectures, or generalized system modeling and design tools, should be directed to other subtopics such as S134, Accelerating NASA Science and Engineering through the Application of Artificial Intelligence, or S132, Integrated Science Mission Modeling.

Expected outcomes and objectives of this subtopic are to mature the practice of FM, leading to better estimation and control of FM complexity and development costs, more flexible and effective FM designs, and accelerated infusion into future missions through advanced tools and techniques. Specific objectives include the following:

- Increase spacecraft resilience against faults and failures.
- Increase spacecraft autonomy through greater onboard fault estimation and response capability.

- Increase collection and quality of science data through mitigation of interruptions and fault tolerance.
- Enable cost-effective FM design architectures and operations.
- Determine completeness and appropriateness of FM designs and implementations.
- Decrease the labor and time required to develop and test FM models and algorithms.
- Improve visualization of the full FM design across hardware, software, and operations procedures.
- Determine the extent of testing required, completeness of verification planned, and residual risk resulting from incomplete coverage.
- Increase data integrity between multidisciplinary tools.
- Standardize metrics and calculations across FM, systems engineering (SE), safety and mission assurance (S&MA), and operations disciplines.
- Bound and improve costs and implementation risks of FM while improving capability, such that benefits demonstrably outweigh the risks, leading to mission infusion.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.2 Reasoning and Acting

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Software

Desired Deliverables Description:
The aim of the Phase I project should be to demonstrate the technical feasibility of the proposed innovation and thereby bring the innovation closer to commercialization. Note, however, the research and development (R&D) undertaken in Phase I is intended to have high technical risk, and so it is expected that not all projects will achieve the desired technical outcomes.

The required deliverable at the end of an SBIR Phase I contract is a Final Report that summarizes the project’s technical accomplishments. As noted above, it is intended that proposed efforts conduct an initial proof of concept, after which successful efforts would be considered for follow-on funding by Science Mission Directorate (SMD) missions as risk-reduction and infusion activities. Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

The Phase I Final Report should thoroughly document the innovation, its status at the end of the effort, and as much objective evaluation of its strengths and weaknesses as is practical. The report should include a description of the approach along with foundational concepts and operating theory, mathematical basis, and requirements for application. Results should include strengths and weaknesses found and the measured performance in tests where possible.

Additional deliverables may significantly clarify the value and feasibility of the innovation. These deliverables should be planned to demonstrate retirement of development risk, increasing maturity, and targeted applications of particular interest. Although the wide range of innovations precludes a specific list, some possible deliverables are listed below:

- For innovations that are algorithmic in nature, this could include development code or prototype applications, demonstrations of capability, and results of algorithm stress-testing.
- For innovations that are procedural in nature, this may include sample artifacts such as workflows, model prototypes and schema, functional diagrams, examples, or tutorial applications.

- Where a suitable test problem can be found, documentation of the test problem and a report on test results should illustrate the nature of the innovation in a quantifiable and reproducible way. Test reports should discuss maturation of the technology, implementation difficulties encountered and overcome, and results and interpretation.

Phase II proposals require at a minimum a report describing the technical accomplishments of the Phase I award and how these results support the underlying commercial opportunity. Describing the commercial potential is best done through experiment: Ideally the Phase II report should describe results of a prototype implementation to a relevant problem, along with lessons learned and future work expected to adapt the technology to other applications. Further demonstration of commercial value and advantage of the technology can be accomplished through steps such as the following:

- Delivery of the technology in software form, as a reference application, or through providence of trial or evaluation materials to future customers.
- Technical manuals, such as functional descriptions, specifications, and users guides.
- Conference papers or other publications.
- Establishment of a preliminary performance model describing technology metrics and requirements.

Each of these measures represents a step taken to mature the technology and further reduce the difficulty in reducing it to practice. Although it is established that further development and customization will continue beyond Phase II, ideally at the conclusion of Phase II a potential customer should have access to sufficient materials and evidence to make informed project decisions about technology suitability, benefits, and risks.

State of the Art and Critical Gaps:

Many recent SMD missions have encountered major cost overruns and schedule slips due to difficulty in implementing, testing, and verifying FM functions. These overruns are invariably caused by a lack of understanding of FM functions at early stages in mission development and by FM architectures that are not sufficiently transparent, verifiable, or flexible enough to provide needed isolation capability or coverage. In addition, a substantial fraction of SMD missions continue to experience failures with significant mission impact, highlighting the need for better FM understanding early in the design cycle, more comprehensive and more accurate FM techniques, and more operational flexibility in response to failures provided by better visibility into failures and system performance. Furthermore, SMD increasingly selects missions with significant operations challenges, setting expectations for FM to evolve into more capable, faster-reacting, and more reliable onboard systems.

The SBIR program is an appropriate venue because of the following factors:

- Traditional FM design has plateaued, and new technology is needed to address emerging challenges. There is a clear need for collaboration and incorporation of research from outside the spaceflight community, as fielded FM technology is well behind the state of the art and failing to keep pace with desired performance and capability.
- The need for new FM approaches spans a wide range of missions, from improving operations for relatively simple orbiters to enabling entirely new concepts in challenging environments. Development of new FM technologies by SMD missions themselves is likely to produce point solutions with little opportunity for reuse and will be inefficient at best compared to a focused, disciplined research effort external to missions.
- SBIR level of effort is appropriately sized to perform intensive studies of new algorithms, new approaches, and new tools. The approach of this subtopic is to seek the right balance between sufficient reliability and cost appropriate to each mission type and associated risk posture. This is best achieved with small and targeted investigations, enabled by captured data and lessons learned from past or current missions, or through examination of knowledge capture and models of missions in formulation. Following this initial proof of concept, successful technology development efforts under this subtopic would be considered for follow-on funding by SMD missions as risk-reduction and infusion activities. Research should be conducted to demonstrate

technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

Relevance / Science Traceability:

FM technologies are applicable to all SMD missions, albeit with different emphases. Medium-to-large missions have very low tolerance for risk of mission failure, leading to a need for sophisticated and comprehensive FM. Small missions, on the other hand, have a higher tolerance for risks to mission success but must be highly efficient, and are increasingly adopting autonomy and FM as a risk mitigation strategy.

A few examples are provided below, although these may be generalized to a broad class of missions:

- Lunar Flashlight (currently in assembly, test, and launch operations (ATLO), as an example of many similar future missions): Enable very low-cost operations and high science return from a 6U CubeSat through onboard error detection and mitigation, streamlining mission operations. Provide autonomous resilience to onboard errors and disturbances that interrupt or interfere with science observations.
- Europa Lander: Provide onboard capability to detect and correct radiation-induced execution errors. Provide reliable reasoning capability to restart observations after interruptions without requiring ground in-the-loop. Provide MBSE tools to model and analyze FM capabilities in support of design trades, of FM capabilities, and coordinated development with flight software. Maximize science data collection during an expected short mission lifetime due to environmental challenges.
- Rovers and rotorcraft (Mars Sample Return, Dragonfly, future Mars rotorcraft): Provide onboard capability for systems checkout, enabling lengthy drives/flights between Earth contacts and mobility after environmentally induced anomalies (e.g., unexpected terrain interaction). Improve reliability of complex activities (e.g., navigation to features, drilling and sample capture, capsule pickup and remote launch). Ensure safety of open-loop control or enable closed-loop control to prevent or mitigate failures.
- Search for extrasolar planets (observation): Provide sufficient system reliability through onboard detection, reasoning, and response to enable long-period, stable observations. Provide onboard or on-ground analysis capabilities to predict system response and optimize observation schedule. Enable reliable operations while out of direct contact (e.g., deliberately occluded from Earth to reduce photon, thermal, and radio-frequency background).

References:

1. NASA's approach to FM and the various needs are summarized in the NASA FM Handbook: https://www.nasa.gov/pdf/636372main_NASA-HDBK-1002_Draft.pdf
2. Additional information is included in the talks presented at the 2012 FM Workshop:
    - https://www.nasa.gov/offices/oce/documents/2012_fm_workshop.html
    - particularly https://www.nasa.gov/sites/default/files/637595main_day_1-brian_muirhead.pdf
3. Another resource is the NASA Technical Memorandum "Introduction to System Health Engineering and Management for Aerospace (ISHEM),"
    - https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060003929.pdf
    - This is greatly expanded on in the following publication: Johnson, S. (ed): *System Health Management with Aerospace Applications*, Wiley, 2011, https://www.wiley.com/en-us/System+Health+Management+with+Aerospace+Applications-p-9781119998730
4. FM technologies are strongly associated with autonomous systems as a key component of situational awareness and system resilience. A useful overview was presented at the 2018 SMD Autonomy Workshop, archiving a number of talks on mission challenges and design concepts:
    - https://science.nasa.gov/technology/2018-autonomy-workshop

Focus Area 4 Robotic Systems for Space Exploration

This focus area includes development of robotic systems technologies (hardware and software) that will enable and enhance future space exploration missions. In the coming decades, robotic systems will continue to change the way space is explored. Robots will be used in all mission phases: as independent explorers operating in environments too distant or hostile for humans, as precursor systems operating before crewed missions, as crew helpers working alongside and supporting humans, and as caretakers of assets left behind. As humans continue to work and live in space, they will increasingly rely on intelligent and versatile robots to perform mundane activities, freeing human, and ground control teams to tend to more challenging tasks that call for human cognition and judgment. Technologies are needed for robotic systems to improve transport of crew, instruments, and payloads on planetary surfaces, on and around small bodies, and in-space. This includes hazard detection, sensing/perception, active suspension, grappling/anchoring, legged locomotion, robot navigation, end-effectors, propulsion, and user interfaces.

Innovative robot technologies provide a critical capability for space exploration. Multiple forms of mobility, manipulation and human-robot interaction offer great promise in exploring planetary bodies for science investigations and to support human missions. Enhancements and potentially new forms of robotic systems can be realized through advances in component technologies, such as actuation and structures (e.g. 3D printing). Mobility provides a critical capability for space exploration. Multiple forms of mobility offer great promise in exploring planetary bodies for science investigations and to support human missions. Manipulation provides a critical capability for positioning crew members and instruments in space and on planetary bodies. Robotic manipulation allows for the handling of tools, interfaces, and materials not specifically designed for robots, and it provides a capability for drilling, extracting, handling, and processing samples of multiple forms and scales. This increases the range of beneficial tasks robots can perform and allows for improved efficiency of operations across mission scenarios. Furthermore, manipulation is important for human missions, human precursor missions, and unmanned science missions. Moreover, sampling, sample handling, transport, and distribution to instruments, or instrument placement directly on in-place rock or regolith, is important for robotic missions to locales too distant or dangerous for human exploration.

Future space missions may rely on co-located and distributed teams of humans and robots that have complementary capabilities. Tasks that are considered "dull, dirty, or dangerous" can be transferred to robots, thus relieving human crew members to perform more complex tasks or those requiring real-time modifications due to contingencies. Additionally, due to the limited number of astronauts anticipated to crew planetary exploration missions, as well as their constrained schedules, ground control will need to remotely supervise and assist robots using time-delayed and limited bandwidth communications. Advanced methods of human-robot interaction over time delay will enable more productive robotic exploration of the more distant reaches of the solar system. This includes improved visualization of alternative future states of the robot and the terrain, as well as intuitive means of communicating the intent of the human to the robotic system.

S13.01 Robotic Mobility, Manipulation and Sampling (SBIR)

Lead Center: JPL

Participating Center(s): ARC, GRC, GSFC

Scope Title: Robotic Mobility, Manipulation, and Sampling

Scope Description:

Technologies for robotic mobility, manipulation, and sampling are needed to enable access to sites of interest as well as acquisition and handling of samples for in situ analysis or return to Earth from planets and other planetary bodies including the Moon, Mars, Venus, Ceres, Europa, Titan, Enceladus, comets, and asteroids.

Mobility technologies are needed to enable access to steep and rough terrain for planetary bodies where gravity dominates, such as Earth’s Moon and Mars. Wheeled, legged, and aerial solutions are of interest. Wheel concepts with good tractive performance in loose sand while being robust to harsh rocky terrain are of interest. Technologies to enable mobility on small bodies and access to liquid below the surface (e.g., in conduits or deep oceans) are desired, as are the associated sampling technologies.

Manipulation technologies are needed to deploy sampling tools to the surface, transfer samples to in situ instruments and sample storage containers, and hermetically seal sample chambers. Sample acquisition tools are needed to acquire samples on planetary and small bodies through soft and hard materials, including ice. Minimization of mass and ability to work reliably in a harsh mission environment are important characteristics for the tools. Design for planetary protection and contamination control is important for sample acquisition and handling systems.

Component technologies for low-mass and low-power systems tolerant to the in-situ environment (e.g., temperature, radiation, dust) are of particular interest. Technical feasibility and value should be demonstrated during Phase I via analysis or prototype demonstration, and a full capability unit of at least TRL 4 should be delivered in Phase II. Proposals should show an understanding of relevant science needs and engineering constraints and present a feasible plan (to include a discussion of challenges and appropriate testing) to fully develop a technology and infuse it into a NASA program. Specific areas of interest include the following, in rough order of priority:

- Subsurface ocean access such as via a deep drill system.
- Surface and near-subsurface sampling systems for planets, small bodies, and moons.
- Sample handling technologies that minimize cross contamination and preserve mechanical integrity of samples.
- Cryogenic operation actuators.
- Surface mobility systems for planets, small bodies, and moons.
- Pneumatic sample transfer systems and particle flow measurement sensors.
- Low-mass/power vision systems and processing capabilities that enable sampling and fast surface traverse.
- Tethers and tether play-out and retrieval system.
- Miniaturized flight motor controllers.
- Robotic arms for low-gravity environments.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.3 Manipulation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Hardware, software, and designs for component robotic systems:

- Phase I: proof of concept to include research and analysis along with design in a final report.
- Phase II: prototype with test results.

State of the Art and Critical Gaps:
Scoops, powder drills, and rock core drills and their corresponding handling systems have been developed for sample acquisition on Mars and asteroids. Nonflight systems have been developed for sampling on comets, Venus, and Earth's Moon. Some of these environments still present risk and have gaps that need to be addressed. Ocean worlds exploration presents new environments and unique challenges not met by existing

mobility and sampling systems. New mobility, manipulation, and sampling technologies are needed to enable new types of missions and missions to different and challenging environments.

All proposals relevant to the scope described above would be eligible to be considered for award. For proposals featuring technologies intended for use in planetary science applications, this year a preference will be given to those proposals that would benefit in situ studies of icy ocean worlds, especially techniques that would be beneficial to systems that will descend through kilometers of cryogenic ice, acquire and communicate scientific observations during descent, and sample and process meltwater and interior oceans.

Relevance / Science Traceability:
The subtopic supports multiple programs within the Science Mission Directorate (SMD). The Mars program has had infusion of technologies such as a force-torque sensor in the Mars 2020 mission. Recent awards would support the Ocean Worlds program with surface and deep drills for Europa, and future awards could include technologies to support missions to Enceladus, Titan, and other planetary bodies with subsurface oceans. Sample-return missions could be supported such as from Ceres, comets, and asteroids. Products from this subtopic have been proposed for New Frontiers program missions. With renewed interest in return to Earth's Moon, the mobility and sampling technologies could support future robotic missions to the Moon.

References:

1. Mars Exploration—Program & Missions: https://mars.nasa.gov/programmissions/
2. Solar System Exploration: https://solarsystem.nasa.gov/
3. Ocean Worlds website: https://www.nasa.gov/specials/ocean-worlds/
4. Ocean Worlds article: https://science.nasa.gov/news-articles/ocean-worlds

Z5.04 Intravehicular Robot (IVR) Technologies (SBIR)

Lead Center: ARC
Participating Center(s): JSC

Scope Title: Improve the Capability or Performance of Intravehicular Robots

Scope Description:
To support human exploration beyond Earth orbit, NASA is developing Gateway, which will be an orbiting facility near the Moon. This facility will serve as a starting point for missions to cislunar space and beyond. It could enable assembly and servicing of telescopes and deep space exploration vehicles. It could also be used as a platform for astrophysics, Earth observation, heliophysics, and lunar science.

In contrast to the International Space Station (ISS), which is continuously manned, Gateway is expected to be occupied by humans only intermittently—perhaps only 1 month per year. Consequently, there is a significant need for Gateway to have autonomous capabilities for performing payload operations and spacecraft caretaking, particularly when astronauts are not present. Similar capabilities are needed for future lunar or planetary surface habitats. Intravehicular robots (IVR) can potentially perform a wide variety of tasks, including systems inspection, monitoring, diagnostics and repair, logistics and consumables stowage, exploration capability testing, aggregation of robotically returned destination surface samples, and science measurements and operations.

The objective of this subtopic is to develop technologies that can improve the capability or performance of IVR for science utilization and spacecraft caretaking.

Proposals must describe how the technology will make a significant improvement over the current state of the art (SOA), rather than just an incremental enhancement, for a specific IVR application.

Proposals are specifically sought to create IVR-relevant technologies in the following areas:

- Compact, lightweight robotic arms suitable for IVR free-flyers.
- Robotic tools.
- Compact, reliable, modular robotic actuators and controllers for IVR.
- Sensors and perception systems.
- Operational subsystems that enable extended robot operations (power systems, efficient propulsion, etc.).
- Improved robot autonomy (planning, scheduling, and task execution).
- Improved human-robot interaction between IVR and human teams on the ground under communications constraints, including low bandwidth and extended loss-of-signal periods (software architecture, remote operations methods, etc.).
- Improved management of robot operational and hardware faults such that the robot can "fail operational." For example, the software may use algorithms to determine how to automatically respond to a failure in a motion planner for move to a commanded location by taking into account a projected collision and replanning to the next closest point not in collision.

The technologies must be applicable to required IVR capabilities, such as:

- Maintenance and housekeeping (installing and stowing cables or fluid lines, plugging and unplugging MIL-STD-38999 electrical connectors and fluid quick-disconnect connectors, opening panels, swapping out NASA AMPS (Advanced Exploration Systems (AES) Modular Power Systems) avionics cards, opening and closing hatches, cleaning or swapping air filters, cleaning or sterilizing surfaces, etc.).
- Logistics management (inventory tracking, cargo transport, packing and unpacking bags, kitting items, etc.).
- Science utilization (moving samples between cold storage and instruments, swapping out consumables cartridges, moving planetary samples or SmallSat experiments in and out of airlocks, installing items fabricated using in-space manufacturing, etc.).
- Emergency management (detecting and patching leaks, detecting fires, etc.).
- Localization and navigation.
- Environment monitoring, inspection, and modeling.

The technologies must have an infusion path to NASA missions where habitats require IVR support, such as the Gateway habitat, the Artemis lunar surface habitat, or transit vehicles or surface habitats for future Mars missions. To facilitate infusion, proposals are encouraged, but not required, to:

- Target near-term integration and testing with NASA IVR platforms and analogs, such as Astrobee and Valkyrie.
- Limit dependence on third-party proprietary technologies that might complicate NASA adoption of the technology.
- Use industry standard hardware and software interfaces, architectures, and frameworks that align with relevant NASA IVR technology development to reduce future integration technical effort.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.X Other Robotic Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Deliverables should focus on prototype components, subsystems, and the demonstration thereof. Specifically, Phase I awards shall deliver an interim and final report discussing these results. Phase II awards shall deliver demonstration reports along with supporting software, design information, and documentation.

State of the Art and Critical Gaps:
The technology developed by this subtopic would both enable and enhance IVR such as the Astrobee free-flying robot, Robonaut 2, and Valkyrie humanoid mobile manipulators, which are the SOA for IVR. SBIR technology would improve the capability and performance of these robots to routinely and robustly perform IVR tasks, particularly internal spacecraft payload operations and logistics. New technology created by 2022 SBIR awards could potentially be tested with these, or other, robots in ground testbeds at Ames Research Center (ARC) and Johnson Space Center (JSC) in follow-on awards. These platforms make use of the ROS (Robot Operating System) software architecture. Likewise, on-orbit testing on the ISS may be possible during follow-on awards.

The technology developed by this subtopic would also fill technical gaps identified by the Game Changing Development (GCD) Integrated System for Autonomous and Adaptive Caretaking (ISAAC) project, which is maturing autonomy technology to support the caretaking of human exploration spacecraft. In particular, the SBIR technology would help provide autonomy and robotic capabilities that are required for in-flight maintenance (both preventive and corrective) of Gateway during extended periods when crew are not present.

Relevance / Science Traceability:
This subtopic is directly relevant to the following STMD (Space Technology Mission Directorate) investments:

- Astrobee freeflying robot, GCD.
- Integrated System for Autonomous and Adaptive Caretaking (ISAAC), GCD.
- Smart Deep Space Habitats (SmartHabs), Space Technology Research Institutes (STRI).

This subtopic is directly relevant to the following HEOMD (Human Exploration and Operations Mission Directorate) investments:

- Astrobee facility, ISS.
- Gateway program, AES.
- Logistics Reduction project, AES. Autonomous Systems Operations project, AES.

References:

1. What is Astrobee? https://www.nasa.gov/astrobee
2. What is a Robonaut? https://www.nasa.gov/robonaut2
3. The Robot Operating System (ROS) https://www.ros.org
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5. M. Bualat et al. 2018. "Astrobee: A new tool for ISS operations." In Proceedings of AIAA SpaceOps, Marseille, France. https://ntrs.nasa.gov/citations/20180006684
6. T. Fong et al. 2013. "Smart SPHERES: A telerobotic free-flyer for intravehicular activities in space." In Proceedings of AIAA Space 2013, San Diego, CA. https://ntrs.nasa.gov/citations/20160006694
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9. N. Radford et al. 2015. “Valkyrie: NASA's First Bipedal Humanoid Robot.” In Journal of Field Robotics, vol. 32, no. 3, pp. 397-419, 2015.

Z14.01 Lunar Surface Excavation (SBIR)

Lead Center: KSC
Participating Center(s): GRC, JPL, LaRC

Scope Title: Lunar Surface Excavation

Scope Description:
NASA is interested in developing excavation technologies to mine frozen volatiles resources by excavating the icy regolith in permanently shadowed regions (PSRs) and surrounding areas.

Currently, excavation robots that have been prototyped have been designed to excavate in dry regolith [1,2,3,4] to extract the oxygen contained in silicates and other minerals. Frozen volatiles, such as water, may act as a binder in the regolith, therefore possibly creating a very hard consolidated material. Existing excavation robots and implements have not been designed to excavate in this icy regolith mixed material.

In addition to icy regolith excavation capabilities, the excavation systems must be capable of operating in the extremely harsh lunar environment, including inside PSRs expected to be as cold as 40 Kelvin [5].

Excavation of lunar regolith is enabling for in situ resource utilization (ISRU), as the regolith will be the source of many feedstocks that can be used to make needed products in this domain.

This subtopic is focused on the following aspects of lunar regolith excavation:

- Excavation devices and sensors/feedback needed to better understand and eventually automate excavation processes for icy regolith excavation.
- Reliability and durability of regolith excavation hardware during excavation of hard/icy regolith containing frozen volatiles.

Proposals must address strategies and designs for both focus areas, with a strong emphasis on life-cycle reliability and durability.

For ISRU, excavation technologies are required to mine resources that will have been previously located and identified by resource prospecting methods. For oxygen extraction, the surface regolith may be mined, as the oxygen is ubiquitously present in the form of silicates, whereas volatile resources are thought to be beneath an insulating overburden that may be up to 1 m deep and beyond.

Recent missions to the Moon have identified a high potential for the existence of volatiles resources. The suite of Lunar Crater Observation and Sensing Satellite (LCROSS) and Lunar Reconnaissance Orbiter (LRO) instruments determined as much as 20% of the material kicked up by the LCROSS impact was volatiles, including methane, ammonia, hydrogen gas, carbon dioxide, and carbon monoxide. The water signature, considered a highly important and strategic lunar resources ore, was 5.6%. Mars mission data (Phoenix, Mars Reconnaissance Orbiter (MRO), etc.) have also shown that there are vast deposits of water ice in the Martian subsurface, thus providing Mars-forward linkage for subsurface frozen regolith excavation technologies.

This subtopic is seeking proposals for prototype(s) designs, analysis, hardware, test data, and test reports of excavation devices and sensors related to lunar icy regolith excavation technologies capable of excavating icy regolith to depths of greater than 1 m. The required lifetime of the excavation devices shall be 5 years but may include robotic repair and maintenance.

The amount of regolith that is required to be mined corresponds to an ISRU system that can produce at least 15,000 kg of water over the duration of 225 days of actual operation in a calendar year. Assuming an approximately 3% water yield, it can be assumed that the requirement will be to deliver icy regolith to the ISRU water extraction plant at a rate of 100 kg/hr, without including the dry regolith overburden. Excavation system power needs shall be defined by the proposed designs, and it can be assumed that a NASA-provided electrical power plant and distribution system will be provided. It will supply 10-kW electrical power at 120 VDC, and it will provide continuous power regardless of lighting conditions. A relevant, realistic, and effective lunar concept of operations shall be part of the deliverables. Lessons learned, statistical data studies, and strategies from terrestrial excavation, site preparation, and mining operations are welcomed.

While the exact properties of the lunar regolith [6,7] with frozen volatiles are not yet clear, proposers are requested to research the existing literature and use terrestrial analogs to justify their designs and strategies.

Because the excavation systems will be operating in an extreme lunar environment, possibly inside a PSR, the reliability and durability of regolith excavation hardware will be of critical importance to mission success. This subtopic is also seeking studies and technologies that include strategies and designs to allow lunar icy regolith excavation systems to survive 5 years of continuous operation. Robotic maintenance strategies shall be defined and examined, and methods for robotic servicing shall be identified [8].

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.X Other Exploration Destination Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I deliverables may be a conceptual design or development plan with analysis to show feasibility at relevant scales and/or a small demonstration of the concept or of a subsystem.

Phase II deliverables should be hardware demonstrations at a relevant scale. See Scope Description for additional information on Phase I and Phase II deliverables.

State of the Art and Critical Gaps:
The state of the art consists of terrestrial prototypes at Technology Readiness Level (TRL) 3 or 4 that have been previously built and tested for SBIR/STTR, NASA Centennial Challenge, NASA competitions for universities, and in-house NASA technology development, such as the Regolith Advanced Surface Systems Operations Robot (RASSOR) 2.0 and the Advanced Planetary EXcavator (APEX).

Relevance / Science Traceability:
The work desired applies to Technology Taxonomy (TX) Area 7: Exploration Destination Systems. It applies to the 2018 NASA Strategic Plan Strategic Goal 2: Extend Human Presence Deeper into Space and to the Moon for Sustainable Long-Term Exploration and Utilization. It also applies to the Plan's Strategic Objective 3.1: Develop and Transfer Revolutionary Technologies to Enable Exploration Capabilities for NASA and the Nation. It also applies to TX04: Robotic Systems, as the excavation equipment will need to operate without a human crew present during some periods.

References:

1. Mueller, R., & Van Susante, P. (September 2011). A Review of Lunar Regolith Excavation Robotic Device Prototypes. In AIAA SPACE 2011 Conference & Exposition (p. 7234).

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3. Mueller, R. P., van Susante, P., Reiners, E., & Metzger, P. T. (April 2021). NASA Lunabotics Robotic Mining Competition 10th Anniversary (2010–2019): Taxonomy and Technology Review. Earth and Space 2021 (pp. 497-510).
4. Skonieczny, K. (2013). Lightweight Robotic Excavation. (Doctoral dissertation, Carnegie Mellon University).
5. SLS-SPEC-159, Rev. G. Cross-Program Design Specification for Natural Environments (DSNE), Section 3.4. Effective Date: Dec. 11, 2019. https://ntrs.nasa.gov/citations/20200000867
6. Planetary Simulant Database from the Colorado School of Mines. https://simulantdb.com/
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Focus Area 5 Communications and Navigation

NASA seeks proposals to produce innovative technologies in the communications and navigation discipline to support Exploration, Operations, Science, and Space Technology missions, including the eventual return of humans to the Lunar surface. Missions are generating ever-increasing data volumes that require increased performance from communications systems while minimizing spacecraft impact. This requires higher peak throughput from the communications systems with lower flight communication system cost, mass, and power per bit transmitted. Missions to the Moon, Mars, and beyond will require reliable, autonomous, and secure communications systems operating in the radio frequency bands and optical wavelengths to reduce mission operations burden and support data-intensive operations. These missions will rely on enhanced autonomous navigation techniques to support rendezvous and docking; on-orbit servicing, assembly, and manufacturing; and precision landing. This focus area supports the development of novel communications and navigation technologies spanning from radio frequency to optical to quantum communications systems, applications of autonomy and cognition to navigation and networking, data routing and security, and positioning, timing, guidance, navigation, and control techniques that will provide a significant improvement over the current state of the art.

H9.01 Long-Range Optical Telecommunications (SBIR)

Lead Center: JPL
Participating Center(s): GRC, GSFC

Scope Title: Free-Space Optical Communications Technologies

Scope Description:
Summary: This free-space long-range optical communications subtopic seeks innovative technologies for advancing free-space optical communications (FSOC) by pushing future data volume returns to and from space missions in multiple domains with return data rates >100 Gb/s (cislunar, i.e., Earth or lunar orbit to ground), >10 Gb/s (Earth-Sun L1 and L2), >1 Gb/s from 1 astronomical unit (AU) (deep space), and >1 Gb/s (planetary lander to orbiter and/or inter-spacecraft). Ground-to-space forward data rates >25 Mb/s to farthest Mars ranges are targeted. Optical metrology services include high-precision ranging, while Doppler and astrometric measurements derived from the optical communications signal are sought as well.

Innovative technologies offering low size, weight, and power (SWaP) with improved efficiency, reliability, robustness, are sought for novel state-of-the-art (SOA) spaceflight laser communication systems with supporting ground technologies.

Multifunctional photon-counting sensitivity, near infrared (NIR), spaceflight-worthy detectors/detector arrays for supporting acquisition and tracking, uplink communication receiving, and laser ranging for potential navigation and science are of particular interest. High wall-plug efficiency flight-qualified lasers with high peak-to-average power are sought. Ground-based technologies that support operations of large-aperture daytime light collectors are needed to transition deep space optical communications (DSOC) to operational status. High-power, NIR, intensity-modulated lasers with fast rise times and low timing jitter (subnanosecond) are needed to support high forward data rates and laser ranging.

Priorities: This subtopic is broadly divided between Flight and Ground technologies for FSOC. Innovation priorities are listed in order below.

For flight technologies,

1. Lowering SWaP
2. Solutions for pointing narrow laser beams from space platforms
3. Technology choices that ease space qualification for radiation, random vibrations, and thermal-vacuum
4. Photonics solutions for combining with, or replacing, discrete optics

For ground technologies,

1. Innovations leading to large aperture diameters for collecting faint optical signals through atmospheric turbulence while operating under daytime conditions
2. Kilowatt-class ground laser transmitter with narrow pulses and high repetition rates

Proposals are sought in the following specific areas:

FLIGHT LASER TRANSCEIVERS:

Low-mass, high-Effective Isotropic Radiated Power (EIRP) laser transceivers for links over planetary distances with:

- 30- to 50-cm clear aperture diameter telescopes for laser communications.
- Targeted mass of opto-mechanical assembly per aperture area, less than 200 kg/m^2.
- Cumulative wave-front error and transmission loss not to exceed 2 dB.
- Advanced thermal-mechanical designs to withstand planetary launch loads and spaceflight thermal environments by the optics and structure, at least -20 to 70 °C operational range.
- Design to mitigate stray light while pointing transceivers 3° from the edge of Sun.
- Survive direct Sun pointing for extended duration (few hours to days).

Transceivers fitting the above characteristics should support robust link acquisition tracking and pointing characteristics, including point-ahead implementation from space for beacon-assisted and/or "beaconless" architectures. Innovative solutions for mechanically stiff, lightweight thermally stable structural properties are sought.

- Acquisition, tracking, and pointing architectures that can operate with dim laser beacons (irradiance of few picowatts per square meter at entrance of flight aperture) from Mars farthest ranges.
- Pointing loss allocations not to exceed 1 dB (pointing errors associated loss of irradiance at target less than 20%).
- Receiver field-of-view (FOV) of at least 1-mrad angular radius for beacon-assisted acquisition, tracking, and pointing.
- As a goal additional focal plane with wider FOV (>10 mrad) to support onboard astrometry is desired.
- Beaconless pointing subsystems for space-to-ground operations beyond 3 AU.
- Assume integrated spacecraft microvibration angular disturbance of 150 µrad (<0.1 to ~500 Hz).

Low-complexity small-footprint agile laser transceivers for bidirectional optical links (>1 to 10 Gb/s at a nominal link range of 1,000 to 20,000 km) for planetary lander/rover-to-orbiter and/or space-to-space crosslinks.

- Disruptive low-SWaP technologies that can operate reliably in space over extended mission duration.
- Vibration isolation/suppression systems that will integrate to the optical transceiver in order to reject high-frequency base disturbance by at least 50 dB.
- Desire integrated launch locks and latching mechanism.
- Should afford limited ±5 to ±12 mrad actuated field-of-regard for the optical line of sight of the transceiver.

HIGH WALL-PLUG EFFICIENCY FLIGHT LASER TRANSMITTERS:

High-Gb/s laser transmitters:

- 1,550-nm wavelength.
- Lasers, electronics, and optical components ruggedized for extended space operations.
- High rate 10 to 100 Gb/s for cislunar.
- 1 Gb/s for deep space.
- Integrated hardware with embedded software/firmware for innovative coding/modulation/interleaving schemes that are being developed as a part of the emerging Consultative Committee for Space Data Systems (CCSDS) optical communications standards.

High peak-to-average power laser transmitters for regular or augmented M-ary pulse position modulation (PPM) with M = 4, 8, 16, 32, 64, 128, 256 operating at NIR wavelengths, preferably 1,550 nm, with average powers from 5 to 50 W.

- Subnanosecond pulse.
- Low-pulse jitter.
- Long lifetime and reliability operating in space environment (>5 years and as long as 20 years).
- High modulation and polarization extinction ratio with 1- to 10-GHz linewidth.

Space-qualifiable wavelength division multiplexing transmitters and amplifiers with 4 to 20 channels and average output power >20 W per channel; peak-to-average power ratios >200; >10 GHz channel modulation capability.

- >20% wall-plug efficiency, direct current (DC)-to-optical, including support electronics with description of approach for stated efficiency of space-qualifiable lasers. Multiwatt Erbium Doped Fiber Amplifier (EDFA), or alternatives, with high-gain bandwidth (>30 nm, 0.5 dB flatness) concepts will be considered.
- Radiation tolerance greater than 50 krad is required (including resilience to photodarkening).

RECEIVERS/SENSORS:

Space-qualifiable high-speed receivers and low-light-level sensitive acquisition, tracking, and pointing detectors and detector arrays.

- NIR wavelengths: 1,064 and/or 1,550 nm.
- Sensitive to low irradiance incident at flight transceiver aperture (~ femtowatts per square meter to picowatts per square meter) detection.
- Low subnanosecond timing jitter and fast rise time.
- Novel hybridization of optics and electronic readout schemes with built-in preprocessing capability.
- Characteristics compatible with supporting time-of-flight or other means of processing laser communication signals for high-precision range and range-rate measurements.
- Tolerant to space radiation effects, total dose >50 krad, displacement damage and single event effects.

NOVEL TECHNOLOGIES AND ACCESSORIES:

Narrow Bandpass Optical Filters.

- Space-qualifiable, subnanometer to nanometer, noise equivalent bandwidth with ~90% throughput, large spectral range out-of-band blocking (~40 dB).
- NIR wavelengths from 1,064- to 1,550-nm region, with high transmission through Earth’s atmosphere.
- Reliable tuning over limited range.
- Thermally stable with well characterized temperature dependence of passband.

Novel Photonics Integrated Circuit (PIC) devices targeting space applications with the objective of reducing SWaP of modulators without sacrificing performance. Proposed PIC solutions should allow improved integration and efficient coupling to discrete optics, when needed.

Concepts for offering redundancy to laser transmitters in space.

- Optical fiber routing of high average powers (tens of watts) and high peak powers (1 to 10 kW).
- Redundancy in actuators and optical components.
- Reliable optical switching.
- Innovative applications of machine learning to ease flight operations of DSOC transceivers, for example, to achieve improved pointing performance from space.

GROUND ASSETS FOR OPTICAL COMMUNICATIONS:

Low-cost large-aperture receivers for faint optical communication signals from deep space subsystem technologies:

- Demonstrate innovative subsystem technologies for >10-m diameter deep space ground collector.
- Capable of operating to within 3° of solar limb.
- Better than 10-µrad spot size (excluding atmospheric seeing contribution).
- Desire demonstration of low-cost primary mirror segment fabrication to meet a cost goal of less than $35K per square meter.
- Low-cost techniques for segment alignment and control, including daytime operations.
- Partial adaptive correction techniques for reducing the FOV required to collect signal photons under daytime atmospheric "seeing" conditions.
- Adaptive optics for uplink laser transmission in order to be able to transmit low-beam divergence lasers with near diffraction limited performance.
- Innovative adaptive techniques not requiring a wave-front sensor and deformable mirror of particular interest.
- Mirror cleanliness monitor and control systems.
- Active metrology systems for maintaining segment primary figure and its alignment with secondary optics.
- Large core diameter multimode fibers with low temporal dispersion for coupling large optics to detectors remote (30 to 100 m) from the large optics.

1,550-nm sensitive photon counting detector arrays compatible with large-aperture ground collectors with a means of coupling light from large aperture diameters to reasonably sized detectors/detector arrays, including optical fibers with acceptable temporal dispersion.

- Integrated time tagging readout electronics for >5 gigaphotons/sec incident rate.
- Time resolution <50 psec, 1-sigma.
- Highest possible single-photon detection efficiency, at least 50% at highest incident photon-flux rates.
- Total detector active area >0.3 to 1 mm^2.

- Integrated dark rate < 3 megacounts/sec.

Optical filters.

- Subnanometer noise equivalent bandwidths.
- Tunable in a limited range in the 1,550-nm spectral region.
- Transmission losses <0.5 dB.
- Clear aperture >25 mm, and acceptance angle >40 mrad or similar etendue.
- Out-of-band rejection of >50 dB at 0.7 to 1.8 µm.

Multikilowatt laser transmitters for use as ground beacon and uplink laser transmitters.

- NIR wavelengths in 1.0- or 1.55-µm spectral region.
- Narrow linewidths <0.3 nm.
- Capable of modulating with nanosecond and subnanosecond rise times.
- Low timing jitter and stable operation.
- High speed real-time signal processing of serially concatenated PPM operating at a few bits per photon with user interface outputs.
- 15- to 60-MHz repetition rates.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.1 Optical Communications

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:
For all technologies, lowest cost for small volume production (5 to 20 units) is a driver. Research must convincingly prove technical feasibility (proof of concept) during Phase I, ideally with hardware deliverables that can be tested and/or compelling simulations, to validate performance claims, with a clear path to demonstrating and delivering functional hardware meeting all objectives and specifications in Phase II.

State of the Art and Critical Gaps:
The SOA for FSOC can be subdivided into near-Earth (extending to cislunar and translunar distances) and planetary ranges with the Lagrange points falling in between.

Near-Earth FSOC technology has matured through a number of completed and upcoming technology demonstrations from space. Transition from technology demonstration to an operational service demands low-SWaP, novel high-speed (10 to 100 Gbps) space-qualified laser transmitters and receivers. Transmitters and receivers servicing near-Earth applications can possibly be repurposed for deep space proximity links, such as landed assets on planetary surfaces to orbiting assets with distances of 5,000 to 100,000 km or intersatellite links. Innovative lightweight space-qualified modems for handling multiple optical-modulation schemes. Emerging photonics technologies that can benefit space FSOC applications are sought.

Deep space FSOC is motivated by NASA's initiative to send humans to Mars. Critical gaps following a successful technology demonstration will be lightweight 30- to 50-cm optical transceivers with a wide operational temperature range -20 to 50 °C over which wave-front error and focus is stable; high peak-to-average power space-qualified lasers with average powers of 20 to 50 W; and single photon-sensitive radiation-hardened flight detectors with high detection efficiency, fast rise times, and low timing jitter. The detector size should be able to cover 1-mrad FOV with an instantaneous FOV comparable to the transmitted laser beam width. Laser pointing control systems that operate with dim laser beacons transmitted from Earth or use celestial beacon sources. For DSOC, ground laser transmitters with high-average power (kilowatt class) but narrow linewidths (<0.25 nm) and high-variable repetition rates are required. Innovative optical coatings for large-aperture mirrors that are compatible with near-Sun pointing applications for efficiently collecting the signal and lowering background and stray light. Reliability through space-qualified materials and component selection and implementation of redundancy are highly sought after to enable sending humans to planetary destinations, as well as enable higher resolution science instruments. Deriving auxiliary optimetrics from the FSOC signals to support laser ranging and time transfer will also be critical for providing services to future human missions to Mars. High-rate uplink from the ground to Mars with high-modulation-rate high-power lasers are also currently lacking.

Relevance / Science Traceability:
A number of FSOC-related NASA projects are ongoing with launch expected in the 2021 to 2024 time frame. The Laser Communication Relay Demonstration (LCRD) is an Earth-to-geostationary satellite relay demonstration to launch in 2021. The Illuma-T Project will follow to extend the relay demonstration to include a Low Earth Orbit (LEO) node on the International Space Station (ISS). In 2023, the Optical to Orion (O2O), Artemis II, demonstration will transmit data from the Orion crewed capsule as it performs a translunar trajectory and return to Earth.

In 2022, the DSOC Project technology demonstration will be hosted by the Psyche Mission spacecraft extending FSOC links to astronomical unit (AU) distances.

These missions are being funded by NASA's Space Technology Mission Directorate (STMD) Technology Demonstrations Missions (TDM) program and Human Exploration and Operations Mission Directorate (HEOMD) Space Communications and Navigation (SCaN) Program.

Of the 6 technologies recently identified by NASA for sending humans to Mars, laser communications was identified (https://www.nasa.gov/directorates/spacetech/6_Technologies_NASA_is_Advancing_to_Send_Humans_to_Mars)

References:

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H9.03 Flight Dynamics and Navigation Technologies (SBIR)

Lead Center: GSFC
Participating Center(s): JPL, JSC, MSFC

Scope Title: Advanced Techniques for Trajectory Design and Optimization

Scope Description:
NASA seeks innovative advancements in trajectory design and optimization for Earth orbit, cislunar, and interplanetary missions, including:

- Low-thrust spiral trajectories.
- Low-thrust trajectories in a multibody dynamical environment.
- Small-body (moons, asteroids, and comets) exploration.
- Distributed space systems (swarms, constellations, or formations).
- Advanced interactive visualization for spacecraft trajectory design and optimization.

In particular, NASA is seeking innovative techniques for optimization of trajectories that account for:

- System uncertainties (i.e., navigation errors, maneuver execution errors, missed maneuvers, etc.).
- Spacecraft and operational constraints (power, communications, thermal, etc.).
- Trajectory constraints imposed by navigational and/or science observation requirements.

Furthermore, innovative techniques that allow rapid exploration of mission design trade spaces, address high-dimensionality optimization problems (i.e., multimoon/multibody tours; low thrust, multispiral Earth orbits), improved visualization techniques including (but not limited to) 3D graphics, virtual/augmented reality, detailed terrain models, or manipulation of trajectory parameters in a 3D scene are sought.

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can optionally integrate with those packages, such as the General Mission Analysis Tool (GMAT); Collocation Stand Alone Library and Toolkit (CSALT); Copernicus; Evolutionary Mission Trajectory Generator (EMTG); Mission Analysis Low-Thrust Optimization (MALTO); Mission Analysis, Operations, and Navigation (MONTE); and Optimal Trajectories by Implicit Simulation (OTIS), or other available software tools are encouraged. Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

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Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.2 Flight Mechanics

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:
Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature algorithms and software components complete and preliminary integration and testing in an operational environment.

State of the Art and Critical Gaps:
Algorithms and software for optimizing trajectories while considering system uncertainties, spacecraft and operational constraints, and trajectory impacts on making navigational or science observations, do not currently exist. In addition, designing trajectories for complex missions, such as low-thrust cislunar or multibody tour missions that rely heavily on hands-on work by very experienced people. That works reasonably well for designing a single reference trajectory but not as well for exploring trade spaces or when designing thousands of trajectories for a Monte-Carlo or missed-thrust robustness analysis.

Relevance / Science Traceability:
Relevant missions include:

- Artemis - Lunar Gateway.
- Europa Clipper.
- Lucy.
- Psyche.
- Dragonfly.
- Roman Space Telescope.
- Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging, Plus (DAVINCI+).
- SmallSat and CubeSat class missions, such as Lunar IceCube.

Trajectory design for these complex missions can take weeks or months to generate a single reference trajectory. Providing algorithms and software to speed up this process will enable missions to more fully explore trade spaces and more quickly respond to changes in the mission.

References:

1. General Mission Analysis Tool (GMAT): https://software.nasa.gov/software/GSC-18094-1, https://gmat.atlassian.net/wiki/spaces/GW/overview?mode=global
2. Collocation Stand Alone Library and Toolkit (CSALT): https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170003690.pdf
3. Copernicus: https://software.nasa.gov/software/MSC-26673-1, https://www.nasa.gov/centers/johnson/copernicus/index.html
4. Evolutionary Mission Trajectory Generator (EMTG): https://software.nasa.gov/software/GSC-16824-1, https://github.com/nasa/EMTG
5. Mission Analysis Low-Thrust Optimization (MALTO): https://software.nasa.gov/software/NPO-43625-1
6. Mission Analysis, Operations, and Navigation (MONTE): https://montepy.jpl.nasa.gov/

Scope Title: Autonomous Onboard Spacecraft Navigation, Guidance, and Control

Scope Description:
NASA missions require precision landing, rendezvous, formation flying, proximity operations, noncooperative object capture, and coordinated spacecraft operations in Earth orbit, cislunar space, libration orbits, and deep space. These missions require a high degree of autonomy. The subtopic seeks advancements in autonomous, onboard spacecraft navigation and maneuver planning technologies for applications in Earth orbit, lunar, cislunar, libration, and deep space to reduce dependence on ground-based tracking, orbit determination, and maneuver planning, including:

- Onboard relative and proximity navigation (relative position, velocity and attitude, or pose), which support cooperative and collaborative space operations such as On-orbit Servicing, Assembly, and Manufacturing (OSAM).
- Advanced filtering techniques that address rendezvous and proximity operations as a multisensor, multitarget tracking problem; handle nonGaussian uncertainty; or incorporate multiple-model estimation.
- Advanced algorithms for safe, precision landing on small bodies, planets, and moons, including real-time 3D terrain mapping, autonomous hazard detection and avoidance, and terrain relative navigation.
- Machine vision techniques to support optical/terrain relative navigation and/or spacecraft rendezvous/proximity operations in low and variable lighting conditions, including artificial intelligence/machine learning (AI/ML) algorithms.
- Onboard spacecraft trajectory planning and optimization algorithms for real-time mission resequencing, onboard targeting/retargeting, onboard computation of large divert maneuvers, primitive body/lunar proximity operations, and pinpoint landing, including robust onboard

trajectory planning and optimization algorithms that account for system uncertainty (i.e., navigation errors, maneuver execution errors, etc.).
- Software that provides insight into autonomous guidance, navigation, and control system status and its decision-making for ground controllers and crew.

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can optionally integrate with those packages, such as the Goddard Enhanced Onboard Navigation System (GEONS), Navigator NavCube, core Flight System (cFS), or other available NASA hardware and software tools are encouraged. Proposers who contemplate licensing NASA technologies are highly encouraged to coordinate with the appropriate NASA technology transfer offices prior to submission of their proposals.

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Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
Level 2: TX 17.2 Navigation Technologies

Desired Deliverables of Phase I and Phase II:
- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:
Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature algorithms and software components with complete and preliminary integration and testing in an operational environment.

State of the Art and Critical Gaps:
Currently navigation, guidance, and control functions rely heavily on the ground for tracking data, data processing, and decision making. As NASA operates farther from Earth and performs more complex operations requiring coordination between vehicles, round-trip communication time delays make it necessary to reduce reliance on Earth for navigation solutions and maneuver planning. For example, spacecraft that arrive at a planetary surface, may have limited ground inputs and no surface or orbiting navigational aids, and may require rapid navigation updates to feed autonomous trajectory guidance updates and control. NASA currently does not have the navigational, trajectory, and attitude flight control technologies that permit fully autonomous approach, proximity operations, and landing without navigation support from Earth-based resources.

Relevance / Science Traceability:
Relevant missions and projects include:
- Artemis (Lunar Gateway, Orion Multi-Purpose Crew Vehicle, Human Landing Systems).
- OSAM.
- LunaNet.

- Autonomous Navigation, Guidance, and Control (autoNGC).

These complex, deep space missions require a high degree of autonomy. The technology produced in this subtopic enables these kinds of missions by reducing or eliminating reliance on the ground for navigation and maneuver planning. The subtopic aims to reduce the burden of routine navigational support and communications requirements on network services, increase operational agility, and enable near real-time replanning and opportunistic science. It also aims to enable classes of missions that would otherwise not be possible due to round-trip light time constraints.

References:

1. Goddard Enhanced Onboard Navigation System (GEONS): https://software.nasa.gov/software/GSC-14687-1, https://goo.gl/TbVZ7G
2. Navigator: http://itpo.gsfc.nasa.gov/wp-content/uploads/gsc_14793_1_navigator.pdf
3. core Flight System (cFS): https://cfs.gsfc.nasa.gov/
4. NavCube: https://goo.gl/bdobb9
5. On-orbit Servicing, Assembly, and Manufacturing (OSAM): https://nexis.gsfc.nasa.gov/osam/index.html
6. LunaNet: https://esc.gsfc.nasa.gov/news/_LunaNetConcept
7. autonomous Navigation, Guidance and Control (autoNGC): https://techport.nasa.gov/view/94817

Scope Title: Conjunction Assessment Risk Analysis (CARA)

Scope Description:

The U.S. Space Surveillance Network currently tracks more than 22,000 objects larger than 10 cm, and the number of objects in orbit is steadily increasing, which causes an increasing threat to spacecraft in the near-Earth environment. The NASA CARA team is responsible for protecting NASA assets by submitting owner/operator trajectory information on the protected spacecraft, including predicted maneuvers, to the 18th Space Control Squadron (SPCS) at Vandenberg Space Force Base in California. The trajectories are screened against the catalog of space objects, and information about predicted close approaches between NASA satellites and other space objects is sent back to CARA. CARA then determines the risk posed by those events and works with the spacecraft owner/operator to develop an appropriate mitigation strategy. The ability to perform risk assessment more accurately and rapidly will improve space safety for all near-Earth operations and cislunar (Earth + 2 million kilometers) operations.

Because CARA does not produce ephemeris data for the NASA-protected assets or the catalogued objects, the orbit determination aspect of the problem is not of interest in this call. Additionally, CARA does not control the screening process and is therefore not looking for solutions in that area. Only the conjunction assessment (CA) risk assessment aspect is within the scope of this call.

This subtopic seeks innovative technologies to improve the risk assessment process, including the following specific areas (see Reference 1 for the 2020 NASA Technology Taxonomy (TX) areas TX05.6.4, TX10.1.4, TX10.1.5, and TX10.1.6):

1. The Probability of Collision (Pc) is the standard metric for assessing collision likelihood. Its use has substantial advantages over the previous practice of using stand-off distances. The Pc considers the uncertainties in the predicted state estimates at the time of closest approach (TCA) so it provides a probabilistic statement of risk. A number of concerns with the use of the Pc, however, have been identified, including “diluted” probability (see Reference 2) and “false confidence” (see Reference 3). While it is believed that use of the Pc is a responsible approach, there is always interest in alternative risk assessment techniques and parameters that may confer certain advantages. Special consideration will be directed to approaches that explicitly avoid extreme conservatism but instead enable the CARA mission statement of taking “prudent measures, at reasonable cost, to improve safety of flight, without imposing an undue burden on mission

operations" and the balancing required to improve safety while allowing largely unencumbered space mission operations.

2. It is appropriate to take explicit cognizance of all of the uncertainties in the inputs to the Pc calculation in order to emerge with a range or Probability Density Function (PDF) of possible collision probabilities, or some other parameter that takes account of these uncertainties in some way. Approaches to characterizing the uncertainties in the hard-body radius and object covariances are logical (see Reference 4), although NASA is open to entirely different constructs and approaches while keeping in mind that CARA cannot control the orbit determination process and cannot change the state estimation/propagation and uncertainty representation paradigm.
3. The number of conjunction events is expected to continually increase with the increase of resident space objects from large constellations, the ability to track smaller objects, the increasing numbers of CubeSat/SmallSats, and the proliferation of space debris. New or improved techniques are sought to increase the speed of risk analysis of conjunction events that also retain the ability to screen the planned trajectory via the 18 SPCS process. A semiautomatic approach for risk analysis could involve preliminary analysis on the severity levels of a given conjunction as a form of triage. Given the information available in a Conjunction Data Message (CDM) and the historical information of a given space object, new or improved techniques or algorithms using for predicting event severity in either a singular event or an ensemble risk assessment for contiguous close approaches for several events including those using artificial intelligence (AI) or machine learning (ML) are sought.

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Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.6 Networking and Ground Based Orbital Debris Tracking and Management

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:
Phase I research should demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan toward Phase II integration.

Phase II new technology development efforts shall deliver components at the TRL 5 to 6 level with mature algorithms and software components complete and preliminary integration and testing in a quasi-operational environment.

State of the Art and Critical Gaps:
CARA has identified the following challenges to which we are actively looking for solutions: efficient ways to perform conjunction analysis and assessments such as methods for bundling events and performing ensemble risk assessment, middle-duration risk assessment (longer duration than possible for discrete events but shorter than decades-long analyses that use gas dynamics assumptions), improved CA event risk evolution prediction, ML/AI applied to CA risk assessment parameters and/or event evolution. The decision space for collision

avoidance relies on not only the quality of the data (state and covariance) but also the tools and techniques for CA.

Relevance / Science Traceability:
This technology is relevant and needed for all human spaceflight and robotic missions in the near-Earth, cislunar, and lunar environments. The ability to perform CARA more accurately will improve space safety for all near-Earth operations, improve operational support by providing more accurate and longer term predictions, and reduce propellant usage for collision avoidance maneuvers.

References:

1. 2020 NASA Technology Taxonomy: https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy_lowres.pdf
2. Alfano, Salvatore. "A numerical implementation of spherical object collision probability." The Journal of the Astronautical Sciences 53, no. 1 (2005): 103-109.
3. Balch, Michael Scott, Ryan Martin, and Scott Ferson. "Satellite conjunction analysis and the false confidence theorem." Proceedings of the Royal Society A 475, no. 2227 (2019): 20180565.
4. Frigm, Ryan C., Matthew D. Hejduk, Lauren C. Johnson, and Dragan Plakalovic. "Total probability of collision as a metric for finite conjunction assessment and collision risk management." Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, Wailea, Maui, Hawaii. 2015.
5. NASA Conjunction Assessment Risk Analysis (CARA) Office: https://satellitesafety.gsfc.nasa.gov/cara.html
6. NASA Orbital Debris Program Office: https://www.orbitaldebris.jsc.nasa.gov/
7. Newman, Lauri, K., "The NASA robotic conjunction assessment process: Overview and operational experiences," Acta Astronautica, Vol. 66, Issues 7-8, Apr-May 2010, pp. 1253-1261, https://www.sciencedirect.com/science/article/pii/S0094576509004913
8. Newman, Lauri K., et al. "Evolution and Implementation of the NASA Robotic Conjunction Assessment Risk Analysis Concept of Operations." (2014). https://ntrs.nasa.gov/search.jsp?R=20150000159
9. Newman, Lauri K., et al. “NASA Conjunction Assessment Risk Analysis Updated Requirements Architecture”, AIAA/AAS Astrodynamics Specialist Conference, Portland, ME, AAS 19-668, (2019)
10. Office of Safety and Mission Assurance, “NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environments”, NPR 8715.6, https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=8715&s=6B
11. NASA Interim Directive (NID) 7120.132 : Collision Avoidance for Space Environment Protection: https://nodis3.gsfc.nasa.gov/OPD_docs/NID_7120_132_.pdf
12. NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook: https://nodis3.gsfc.nasa.gov/OCE_docs/OCE_50.pdf
13. Consultative Committee for Space Data Systems (CCSDS) Recommended Standard for Conjunction Data Messages: https://public.ccsds.org/Pubs/508x0b1e2c1.pdf

H9.07 Cognitive Communication (SBIR)

Lead Center: GRC
Participating Center(s): GSFC, JPL

Scope Title: Lunar Cognitive Capabilities

Scope Description:
NASA's Space Communication and Navigation (SCaN) program seeks innovative approaches to increase mission science data return, improve resource efficiencies for NASA missions and communication networks, and ensure resilience in the unpredictable space environment. The Cognitive Communication subtopic specifically focuses on advances in space communication driven by onboard data processing and modern space

networking capabilities. A cognitive system is envisioned to sense, detect, adapt, and learn from its experiences and environment to optimize the communications capabilities for the user mission satellite or network infrastructure. The underlying need for these technologies is to reduce both the mission and network operations burden. Examples of these cognitive capabilities include:

- Link technologies—reconfiguration and autonomy, maximizing use of bandwidth while avoiding interference.
- Network technologies—robust intersatellite links, data storage/forwarding, multinode routing in unpredictable environments.
- System technologies—optimal scheduling techniques for satellite and surface relays in distributed and real-time environments.

NASA's Artemis program is committed to landing American astronauts on the Moon in collaboration with our commercial partners. In support of this goal, cognitive communication techniques are needed for lunar communication satellite and surface relays. Cognitive agents operating on lunar elements will manage communication, provide diagnostics, automate resource scheduling, and dynamically update data flow in response to the types of data flowing over the lunar network. Goals of this capability are to improve communications efficiency, mitigate channel impairments, and reduce operations complexity and cost through intelligent and autonomous communications and data handling. Examples of research and/or technology development include:

- Onboard processing technology and techniques to enable data switching, routing, storage, and processing on a relay spacecraft.
- Data-centric, decentralized network data routing and scheduling techniques that are responsive to quality of service metrics.
- Simultaneous wideband sensing and communications for S-, X-, and Ka-bands, coupled with algorithms that learn from the environment.
- Artificial intelligence and machine learning algorithms applied to optimize space communication links, networks, or systems.
- Flexible communication platforms with novel signal processing technology to support cognitive approaches.
- Other innovative, related areas of interest to the field of cognitive communications.

Proposals to this subtopic should consider application to a lunar communications architecture consisting of surface assets (e.g., astronauts, science stations, and surface relays), lunar communication relay satellites, Gateway, and ground stations on Earth. The lunar communication relay satellites require technology with low size, weight, and power (SWaP) suitable for small satellite (e.g., 50 kg) or CubeSat operations. Proposed solutions should highlight advancements to provide the needed communications capability while minimizing use of onboard resources, such as power and propellant. Proposals should consider how the technology can mature into a successful demonstration in the lunar architecture.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.5 Revolutionary Communications Technologies

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I will study technical feasibility, infusion potential for lunar operations, clear/achievable benefits, and show a path towards a Phase II implementation. Phase I deliverables include a feasibility assessment and

concept of operations of the research topic, simulations and/or measurements, validation of the proposed approach to develop a given product (TRL 3 to 4), and a plan for further development of the specific capabilities or products to be performed in Phase II. Early development, integration, test, and delivery prototype hardware/software is encouraged.

Phase II will emphasize hardware/software development with delivery of specific hardware or software product for NASA targeting the Cognitive Communication Project's Cognitive Ground Testbed and/or demonstration operations on a small satellite or CubeSat platform. Phase II deliverables include a working prototype (engineering model) of the proposed product/platform or software, along with documentation of development, capabilities, and measurements, and related documents and tools, as necessary, for NASA to modify and use the cognitive software capability or hardware component(s) and evaluate them in the Cognitive Ground Testbed for greater infusion potential. Hardware prototypes shall show a path towards flight demonstration, such as a flight qualification approach and preliminary estimates of thermal, vibration, and radiation capabilities of the flight hardware. Software prototypes shall be implemented on platforms that have a clear path to a flight qualifiable platform. Algorithms must be implemented in software and should be ready to be run on the testbed's Software Defined Radios and/or appropriate general-purpose processor.

Opportunities and plans should be identified for technology commercialization. Software applications and platform/infrastructure deliverables for software-defined radio platforms shall be compliant with the latest NASA standard for software-defined radios, the Space Telecommunications Radio System (STRS), NASA-STD-4009A, and NASA-HDBK-4009A. The deliverable shall be demonstrated in a relevant emulated environment and have a clear path to Phase III flight implementation on a SWaP-constrained platform.

State of the Art and Critical Gaps:

To summarize NASA Technology Roadmap TA5: "As human and science exploration missions move further from Earth and become increasingly more complex, they present unique challenges to onboard communications systems and networks. Intelligent radio systems will help manage the increased complexity and provide greater capability to the mission to return more science data. Reconfigurable radio systems could autonomously optimize the RF [radio-frequency] links, network protocols, and modes used based on the needs of the various mission phases. A cognitive radio system would sense its RF environment and adapt and learn from its various configuration changes to optimize the communications links throughout the system to maximize science data transfer, enable substantial efficiencies, and reduce latency. The challenges in this area are in the efficient integration of different capabilities and components, unexpected radio or system decisions or behavior, and methods to verify decision-making algorithms as compared to known, planned performance."

The technology need for the lunar communication architecture includes:

- Data routing from surface assets to a lunar communication relay satellite, where data is unscheduled, a-periodic, and ad-hoc.
- Data routing between lunar relay satellites, as necessary, to conserve power, route data to Earth, and meet quality of service requirements.
- Efficient use of lunar communication spectrum while coexisting with future/current interference sources.
- On-demand communication resource scheduling.
- Multihop, delay tolerant routing.

Critical gaps between the state of the art and the technology need include:

- Implementation of artificial intelligence and machine learning techniques on SWaP-constrained platforms.
- Integrated wide-band sensing and narrow-band communication on the same radio terminal.
- Intersatellite networking and routing, especially in unpredictable and unscheduled environments.
- On-demand scheduling technology for communication links.
- Cross-layer optimization approaches for optimum communication efficiency at a system level.

Relevance / Science Traceability:
Cognitive technologies are critical for the lunar communications architecture. The majority of lunar operations will be run remotely from Earth, which could require substantial coordination and planning as NASA, foreign space agencies, and commercial interests all place assets on the Moon. As lunar communications and networks become more complex, cognition and automation are essential to mitigate complexity and reduce operations costs. Machine learning will configure networks, choose radio configurations, adjust for impairments and failures, and monitor short- and long-term performance for improvements.

References:
Several related reference papers and articles include:

1. "Cognitive Communications for NASA Space Systems": https://ntrs.nasa.gov/api/citations/20190032643/downloads/20190032643.pdf
2. "Microservice Architecture for Cognitive Networks": https://ieeexplore.ieee.org/abstract/document/9262617
3. "NASA Explores Artificial Intelligence for Space Communications": https://www.nasa.gov/feature/goddard/2017/nasa-explores-artificial-intelligence-for-space-communications
4. "Implementation of a Space Communications Cognitive Engine": https://ntrs.nasa.gov/search.jsp?R=20180002166
5. "Reinforcement Learning for Satellite Communications: From LEO to Deep Space Operations": https://ieeexplore.ieee.org/document/8713802
6. "Cognitive Communications and Networking Technology Infusion Study Report": https://ntrs.nasa.gov/search.jsp?R=20190011723
7. "Multi-Objective Reinforcement Learning-based Deep Neural Networks for Cognitive Space Communications": https://ntrs.nasa.gov/search.jsp?R=20170009153
8. "Assessment of Cognitive Communications Interest Areas for NASA Needs and Benefits": https://ntrs.nasa.gov/search.jsp?R=20170009386
9. "Architecture for Cognitive Networking within NASA's Future Space Communications Infrastructure": https://ntrs.nasa.gov/citations/20170006033
10. "Modulation Classification of Satellite Communication Signals Using Cumulants and Neural Networks": https://ntrs.nasa.gov/search.jsp?R=20170006541

A related conference, co-sponsored by NASA and the Institute of Electrical and Electronics Engineers (IEEE), the Cognitive Communications for Aerospace Applications Workshop, has additional information available at: https://ieee-ccaa.com/

S16.03 Guidance, Navigation, and Control (SBIR)

Lead Center: GSFC
Participating Center(s): JPL, MSFC

Scope Title: Guidance, Navigation, and Control (GNC) Sensors and Actuators

Scope Description:
NASA seeks innovative, groundbreaking, and high-impact developments in spacecraft guidance, navigation, and control (GNC) technologies in support of future science and exploration mission requirements. This subtopic covers mission-enabling technologies that have significant size, weight and power, cost, and performance (SWaP-CP) improvements over the state-of-the-art commercial off-the-shelf (COTS) capabilities in the areas of (1) spacecraft attitude determination and control systems, (2) absolute and relative navigation systems, (3) pointing control systems, and (4) radiation-hardened GNC hardware.

Component technology developments are sought for the range of flight sensors and actuators required to provide these improved capabilities. Technologies that apply to most spacecraft platform sizes will be considered.

Advances in the following areas are sought:

1. Spacecraft attitude determination and control systems: Sensors and actuators that enable <0.1-arcsecond-level pointing knowledge and arcsecond-level control capabilities for large space telescopes, with improvements in SWaP requirements.
2. Absolute and relative navigation systems: Autonomous onboard flight navigation sensors and algorithms incorporating both spaceborne and ground-based absolute and relative measurements. Special considerations will be given to relative navigation sensors enabling precision formation flying, astrometric alignment of a formation of vehicles, and other GNC techniques for enabling the collection of distributed science measurements. In addition, flight sensors that support onboard terrain relative navigation for landing and sample return capabilities are of interest.
3. Pointing control systems: Mechanisms that enable milliarcsecond-class pointing performance on any spaceborne pointing platforms. Active and passive vibration isolation systems, innovative actuation feedback, or any such technology that can be used to enable other areas within this subtopic applies.
4. Radiation-hardened GNC hardware: GNC sensors that could operate in a high-radiation environment, such as the Jovian environment.
5. Increasing the fundamental precision of gyroscopes and accelerometers that utilize optical cavities could benefit autonomous navigation and open up new science possibilities. Two strategies may be pursued to increase the precision. First, can the scale factor be increased without a concomitant increase in the quantum noise? Possible approaches include but are not limited to: (a) the use of fiber optics to increase cavity length without increasing SWaP, and (b) exploitation of the degeneracies known as exceptional points (EPs) that occur in non-Hermitian systems. Prominent examples of such systems include parity-time symmetric systems and cavities containing a fast-light medium. It remains to be seen, however, whether the boost in scale factor near an EP can result in increased precision or is entirely counteracted by additional quantum noise. Proposals are sought that seek to answer this question through theoretical or experimental means in passive and active systems, including continuous-wave and pulsed lasers. Second, can the quantum noise be reduced without a concomitant reduction in scale factor? The frequency measurement in a laser gyro or accelerometer only involves the uncertainty in phase. Therefore, the relevant quantum noise might be reduced by squeezing. Proposals are sought that investigate and utilize squeezing, for example, via the propagation of quantum solitons, for the improvement of inertial sensors.

Proposals should show an understanding of one or more relevant science or exploration needs and present a feasible plan to fully develop a technology and infuse it into a NASA program.

This subtopic is for all mission-enabling GNC technology in support of Science Mission Directorate (SMD) missions and future mission concepts. Proposals for the development of hardware and supporting software is preferred; however, novel algorithms will also be considered. The specific applications could range from CubeSats/SmallSats, to ISS payloads, to flagship missions. For proposals featuring technologies intended for use in planetary science applications, this year a preference will be given to those proposals that would benefit radiation-hard electronics needed for in situ studies of icy ocean worlds.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
Level 2: TX 17.X Other Guidance, Navigation, and Control

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:
Prototype hardware/software, documented evidence of delivered TRL (test report, data, etc.), summary analysis, supporting documentation:

- Phase I research should be conducted to demonstrate technical feasibility as well as show a plan towards Phase II integration and component/prototype testing in a relevant environment as described in a final report.
- Phase II technology development efforts shall deliver a component/prototype at the NASA SBIR/STTR TRL 5 to 6 level. Delivery of final documentation, test plans, and test results are required. Delivery of a hardware component/prototype under the Phase II contract is preferred.

Phase I research should be conducted to demonstrate technical feasibility as well as show a plan towards Phase II integration and component/prototype testing in a relevant environment. Phase II technology development efforts shall deliver component/prototype at the Technology Readiness Level (TRL) 5 to 6, consistent with NASA SBIR/STTR descriptions. Delivery of final documentation, test plans, and test results are required. Delivery of a hardware component/prototype under the Phase II contract is preferred.

State of the Art and Critical Gaps:
Capability area gaps:

- Spacecraft GNC sensors—highly integrated, low-power, low-weight, and radiation-hard component sensor technologies and multifunctional components.
- Spacecraft GNC estimation and control algorithms—sensor fusion, autonomous proximity operations algorithm, robust distributed vehicle formation sensing, and control algorithms.

Relevance / Science Traceability:
Mission capability requirements in the Science Mission Directorate (SMD) program areas of Heliophysics, Earth Science, Astrophysics, and Planetary Science:

- Spacecraft GNC sensors—optical, radio-frequency (RF), inertial, and advanced concepts for onboard sensing of spacecraft attitude and orbit states.
- Spacecraft GNC estimation and control algorithms—innovative concepts for onboard algorithms for attitude/orbit determination and control for single spacecraft, spacecraft rendezvous and docking, and spacecraft formations.

References:

1. 2020 NASA Technology Taxonomy: https://go.nasa.gov/3hGhFJf
2. 2017 NASA Strategic Technology Investment Plan: https://go.usa.gov/xU7sE

Scope Title: Star-Tracker Technologies for CubeSats

Scope Description:
CubeSats are increasingly being used to perform remote sensing of the Earth's atmosphere and surface. However, their mass, size, and power limitations often prohibit the use of spinning or scanning antennas, especially if such antennas are large relative to the size of the spacecraft (e.g., deployable antennas). A solution is to spin the spacecraft itself; however, spacecraft attitude control and Earth-based geolocation of measurements in this situation requires the use of an onboard star tracker that itself spins or otherwise maintains a consistent frame of reference, or can process star observations quickly enough to update attitude information about the spinning CubeSat. Thus, star trackers capable of providing accurate attitude information to a rapidly spinning CubeSat would significantly benefit future NASA Earth Science CubeSat missions.

The scope of this subtopic is the development of a CubeSat-ready star tracker that can provide accurate attitude information to a rapidly spinning CubeSat hosting an Earth-observing instrument. A CubeSat-ready star tracker that itself spins or maintains a consistent frame of reference while its host CubeSat spins, or one that can process observations significantly faster than the current state of the art (SOA), is a critical enabling technology for CubeSat-based Earth observations that normally would require a spinning antenna (e.g., ocean winds).

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
Level 2: TX 17.4 Attitude Estimation Technologies

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:
Phase I research should be conducted to demonstrate technical feasibility as well as show a plan towards Phase II to include a laboratory-tested to space-qualified hardware prototype of a star tracker capable of providing accurate attitude information to a rapidly spinning CubeSat (~tens of revolutions per minute).

State of the Art and Critical Gaps:
Current CubeSat-ready star trackers can provide ~0.002° pointing information accuracy with low size, weight, and power (SWaP). However, that performance assumes relatively stable attitude control (i.e., a nonrapidly spinning CubeSat). Thus, a CubeSat-ready star tracker that itself spins, or maintains a consistent frame of reference while its host CubeSat spins, or can process observations significantly faster than the current state of the art (SOA), is a critical enabling technology for CubeSat-based Earth observations that normally would require a spinning antenna (e.g., ocean winds).

Relevance / Science Traceability:
Requirement: The star tracker should have the ability to provide 0.05° or better pointing angle accuracy (in roll, pitch, and yaw) while the CubeSat is spinning up to 20 rpm in Low Earth Orbit (300 to 1,000 km altitude).

Relevant CubeSats are anticipated to be oriented such that the Earth-observing antenna is pointing off-nadir by up to 40° to 50°. This provides a sufficient Earth-incidence angle to enable retrieval of ocean surface winds and other horizontally resolved atmospheric measurables (e.g., precipitation). For this science application, the star tracker is providing ~1-km geolocation accuracy for such measurements.

SWaP should be comparable to existing star trackers (~0.2U, ~0.25 kg, ~1 W).

References:

1. Erlank, A.O. and Steyn, W.H.: "Arcminute attitude estimation for CubeSats with a novel nano star tracker," *IFAC Proceedings Volumes*, 47(3), pp. 9679-9684, 2014.
2. C. R. McBryde and E. G. Lightsey: "A star tracker design for CubeSats," 2012 IEEE Aerospace Conference, pp. 1-14, 2012, doi: 10.1109/AERO.2012.6187242.
3. Walton, M.P. and Long, D.G.: "Architectures for Earth-observing CubeSat scatterometers," *CubeSats and NanoSats for Remote Sensing II,* Vol. 10769, 1076904, International Society for Optics and Photonics, 2018.
4. Walton, P. and Long, D.: "Space of solutions to ocean surface wind measurement using scatterometer constellations," *Journal of Applied Remote Sensing*, 13(3), 032506, 2019.

Focus Area 6 Life Support and Habitation Systems

The Life Support and Habitation Systems Focus Area seeks key capabilities and technology needs encompassing a diverse set of engineering and scientific disciplines, all of which provide technology solutions that enable extended human presence in deep space and on planetary surfaces such as Moon and Mars, including Orion, ISS, Gateway, Artemis and Human Landing Systems. The focus is on systems and elements that directly support human missions and astronaut crews, such as Environmental Control and Life Support Systems (ECLSS), Extravehicular Activity (EVA) systems, Human Accommodations, including crew and cabin provisioning, hygiene and clothing systems, and Bioregenerative Life Support, including plant growth for food production.

For future crewed missions beyond low-Earth orbit (LEO) and into the solar system, regular resupply of consumables and emergency or quick-return options will not be feasible. New technologies must be compatible with attributes of the environments expected, including microgravity or partial gravity, varying atmospheric pressure and composition (both internal to the cabin and external to the vehicle), space radiation, and the presence of planetary dust. Technologies of interest are those that enable long-duration, safe, economical, and sustainable deep-space human exploration. Special emphasis is placed on developing technologies that will fill existing gaps as described in this solicitation, that reduce requirements for consumables and other resources, including mass, power, volume and crew time, and which will increase safety and reliability with respect to the state-of-the-art. Spacecraft may be untended by crew for long periods, therefore systems must be operable after these intervals of dormancy.

ECLSS encompass process technologies and monitoring functions necessary to provide and maintain a livable environment within the pressurized cabin of crewed spacecraft, including environmental monitoring, water recycling, waste management and atmosphere revitalization including particulate removal. There are two specific technical areas of interest for ECLSS submissions. Advancements in heaters and thermal swing components are needed for thermally desorbed carbon dioxide removal and compression beds, including considerations for structured monolithic sorbents created by additive manufacturing or slip casting of the sorbent itself. Secondly, proposals are sought to address challenges in carbon dioxide reduction systems, including separation, collection, removal and storage of carbon particulates, methods to recharge or recycle catalysts and solutions to prevent clogging of frits and filters in recycle gas streams. Also, of interest to ECLSS but included elsewhere in this solicitation, is lunar dust filtration and monitoring for spacecraft cabins.

For Human Accommodations, the focus in this solicitation includes advanced heating and refrigeration systems for stored food, personal hygiene including handwash, combination clothes washer and dryer systems and volumetrically efficient concepts for equipment, flexible work surfaces and stowage. In addition, textiles are sought for extreme surface environments and high oxygen atmospheres, applicable to crew clothing. Lastly, of interest to the focus area but included elsewhere, is the subtopic Plant Research Capabilities in Space, which is applicable to Bioregenerative Life Support.

Unique needs also exist for the Exploration Extra-vehicular Mobility Unit (xEMU), commonly called spacesuits. Textiles used for the xEMU Environmental Protection Garment (EPG), the outermost component of the xEMU, must resist extreme surface environments including planetary dust and also be suitable for oxygen-rich atmospheres. Applicable to the xEMU’s Portable Life Support System (PLSS), sorbent technologies are sought for a low volume, low power and low mass carbon dioxide and humidity control system. In addition, miniaturized gas sensor technologies are needed for measurement of oxygen, carbon dioxide and water vapor within the suit.

Please refer to the description and references of each subtopic for further detail to guide development of proposals within this technically diverse focus area.

H3.08 Challenges in Carbon Dioxide Removal and Reduction: Carbon Particulate and Thermal Management (SBIR)

Lead Center: MSFC

Participating Center(s): ARC, GRC, JPL, JSC, KSC

Scope Title: Advancements in Carbon Dioxide Reduction

Scope Description:
Air Revitalization Systems (ARS) are necessary for human survival during space exploration missions. Technologies to efficiently remove carbon dioxide (CO_2) from the cabin atmosphere and to reduce the captured CO_2 to recover oxygen are two systems that face technical challenges. Using adsorption beds to remove CO_2 is a proven technology, but optimization is needed. Please see the second scope "Advanced Heaters for Solid Sorption Systems" for more information. In the area of CO_2 reduction, several technologies produce solid carbon either intentionally or unintentionally. A current challenge to the development of these technologies is carbon management. Technologies and methods that will efficiently separate, remove, and store the carbon are sought. Technical solutions will allow for efficient operation of the carbon reduction process, prevent contamination of downstream hardware receiving effluent gases and avoid contamination of cabin atmosphere during carbon handling and disposal.

Oxygen recovery technology options, including carbon formation reactors and methane pyrolysis reactors, almost universally result in particulates in the form of solid carbon or solid hydrocarbons. Mitigation for these particulates will be essential to the success and maintainability of these systems during long-duration missions. Techniques and methods leading to compact, regenerable devices or components for removing, managing, and disposing of residual particulate matter within Environmental Control and Life Support Systems (ECLSS) process equipment are sought.

NASA has invested in many CO_2 reduction technologies over the years to increase the percentage of oxygen recovery from CO_2 in human spacecraft for long-duration missions. Examples of technologies include, but are not limited to, Series-Bosch, Continuous Bosch, methane pyrolysis, and microfluidic carbon dioxide electrolysis. Significant technical challenges still face these process technologies and are impeding progress in technology maturation. Critical technical elements of these technologies have a high degree of technical difficulty.

Examples where additional component technology development is needed include (this is a partial list):

- Separation of particulate carbon from process gas streams.
- Safe collection, removal, and disposal of solid carbon, including cases when continuously operating reactors are active.
- Subsystems to recharge reactors with new catalyst and to efficiently reuse or recycle consumable catalysts.
- Technology solutions to mitigate solid carbon clogging of frits and filters in recycle gas streams.

Separation performance approaching HEPA rating is desired for ultrafine particulate matter with minimal pressure drop. The separator function should be capable of operating for hours at high particle loading rates. If necessary, periodic operations and methods could be employed to restore capacity/functionality back to nearly 100% of its original clean state through in-place and autonomous regeneration or self-cleaning operations using minimal or no consumables (including media-free hydrodynamic separators). The device must minimize crew exposure to accumulated particulate matter and enable easy particulate matter disposal or chemical repurposing.

This subtopic is open to consider novel ideas that address any of the numerous technical challenges that face development of CO_2 reduction hardware with particular attention to solid carbon management.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Hardware
- Prototype

Desired Deliverables Description:
Phase I deliverables: Reports demonstrating proof of concept and test data from proof-of-concept studies, concepts, and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II. Conceptual solution in Phase I should look ahead to satisfying the requirement of limiting crew exposure to the raw carbon dust as well as carbon exposure to downstream hardware.

Phase II deliverables: Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data and analysis. Prototypes must be full scale unless physical verification in 1g is not possible. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. The system should incorporate safety margins and design features to provide safe operation upon delivery to NASA.

State of the Art and Critical Gaps:
Advanced oxygen recovery systems are necessary for long-duration missions as resupply of consumables will not be available. The state-of-the-art Sabatier system, which has flown on the International Space Station (ISS) as the Carbon Dioxide Reduction Assembly (CRA), only recovers about half of the oxygen from metabolic CO_2. This is because there is insufficient hydrogen to react all available CO_2. The Sabatier reacts hydrogen with CO_2 to produce methane and water. The methane is vented overboard as a waste product causing a net loss of hydrogen. Mars missions target >75% oxygen recovery from CO_2, with a goal to approach 100% recovery. NASA is developing several alternate technologies that have the potential to increase the percentage of oxygen recovery from CO_2, toward fully closing the ARS loop. Methane pyrolysis recovers hydrogen from methane, making additional hydrogen available to react with CO_2. Other technologies under investigation process CO_2, recovering a higher percentage of oxygen than the Sabatier. All these alternative systems, however, need additional technology investment to reach a level of maturity necessary for consideration for use in a flight ECLSS.

Several of these alternative systems produce solid carbon either intentionally or unintentionally and solutions for safely filtering, removing, and storing solid carbon are critical to the maturation of these systems.

Relevance / Science Traceability:
These technologies would be essential and enabling to long-duration human exploration missions, in cases where closure of the atmosphere revitalization loop will trade over alternate ECLSS architectures. The atmosphere revitalization loop on the ISS is only about 50% closed when the Sabatier is operational. These technologies may be applicable to Gateway, lunar surface, and Mars, including surface and transit missions. This technology could be proven on the ISS as a flight demonstration.

This subtopic is directed at needs identified by the Life Support Systems Capability Leadership Team (CLT) in the area of atmosphere revitalization, and specifically, in the areas of CO_2 reduction and oxygen recovery, functional areas of ECLSS.

The Life Support Systems (LSS) Project, under the Advanced Exploration Systems (AES) Program, within the Human Exploration and Operations Mission Directorate (HEOMD), is the expected customer. The LSS Project would be in position to sponsor Phase III and technology infusion.

References:

1. "Hydrogen Recovery by Methane Pyrolysis to Elemental Carbon" (49th International Conference on Environmental Systems, ICES-2019-103)
2. "Evolving Maturation of the Series-Bosch System" (47th International Conference on Environmental Systems, ICES-2017-219)
3. "State of NASA Oxygen Recovery" (48th International Conference on Environmental Systems, ICES-2018-48)
4. "Particulate Filtration from Emissions of a Plasma Pyrolysis Assembly Reactor Using Regenerable Porous Metal Filters" (47th International Conference on Environmental Systems, ICES-2017-174)
5. "Methane Post-Processing and Hydrogen Separation for Spacecraft Oxygen Loop Closure" (47th International Conference on Environmental Systems, ICES-2017-182)
6. “Trading Advanced Oxygen Recovery Architectures and Technologies” (48th International Conference on Environmental Systems, ICES-2018-321)
7. NASA-STD-3001, VOLUME 2, REVISION A, Section 6.4.4.1 “For missions longer than 14 days, the system shall limit the concentration in the cabin atmosphere of particulate matter ranging from 0.5 µm to 10 µm (respirable fraction) in aerodynamic diameter to <1 mg/m3 and 10 µm to 100 µm to <3 mg/m3.” https://www.nasa.gov/sites/default/files/atoms/files/nasa-std-3001-vol-2a.pdf

Scope Title: Advanced Heaters for Sorbent Systems

Scope Description:

Spacecraft carbon dioxide (CO_2), water, and trace contaminant (organics) removal systems must be regenerable and reliable and minimize resupply and equivalent system mass (ESM). In most sorbent systems, heat is used to regenerate the beds by expelling contaminants for disposal or to downstream processes for resource recovery. In future deep space exploration missions, such as those to the Moon and to Mars, sorption systems must drastically reduce power to minimize the dependence on scarce resources. The state-of-the-art (SOA) spacecraft sorption systems utilize commercial off-the-shelf (COTS) resistive heaters coupled with conductive fins. These Joule heating methods lead to inefficiencies such as high thermal contact resistance, high temperature differential within the sorption beds, high component mass and volumes, and long ramp-up times. The SOA cooling options utilize blowers, cooling channels or cold plates in conjunction with spacecraft liquid cooling loops. Since the spacecraft cooling systems are limited in capacity, efficient cooling methods are needed. Although it is recognized that the conductivity of the sorbent material is the limiting factor to the heating of sorption beds, it is also important to design integrated thermal management systems that transfer the heat quickly, uniformly, and efficiently throughout the bed. Some suggested, but not inclusive, areas of heater improvements are listed here:

- Decreasing the contact resistance between the heaters and the sorbent media.
- Increasing temperature uniformity within the sorbent beds.
- Improving tolerance to corrosion.
- Optimizing for various configurations of sorbent media, including granules, beads, porous solids, additively manufactured, and liquid sorbents.

Some thermal management components can function both as heaters and coolers. This will lead to reduced system mass and volume of heaters, fin stock, cooling channels, various supporting hardware, and sorption materials. Proposed concepts may include different heater types as well as heater configurations. Heater configurations could include those that are bound or embedded into the sorbent media.

This subtopic solicits advanced thermal management systems that offer a significant improvement over the SOA. The heaters, coolers, configurations, and all attached hardware must meet the following operational requirements:

- Continuous operation at temperatures as high as 200 ˚C or above.
- Minimize both heating and cooling rates compared to the SOA heaters capability.
- Heaters and cooling options must be able to operate in temperature swing sorption systems continuously 24 hours a day. Some example cycle times are those used in the current spacecraft

system: the Carbon Dioxide Removal Assembly used a 144-minute cycle time; The 4BCO2 beds operate on 80-minute cycle times.
- Compatible with either liquid or solid sorbent systems.
- Capable of operating in microgravity and reduced gravity environment.
- Must be compatible with sorbent regeneration or thermally sorbent systems.
- Must be able to operate continuously for 3 years.
- Offer an improvement in heat conservation, efficiency, power consumption, reliability, resupply, and ESM over the spacecraft SOA systems.
- Heaters and cooling options must utilize the available power and cooling options expected in exploration spacecraft such as avionic air, the low-temperature loops, and the medium-temperature loops.
- Meet the space station safety requirement.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

Desired Deliverables of Phase I and Phase II:
- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Phase I deliverables: Reports demonstrating proof of concept and test data from proof-of-concept studies, concepts, and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II. Phase I analysis should include a trade study between the advanced heaters and the SOA and operation in the spacecraft environments.

Phase II deliverables: Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, test data, and analysis. Prototypes must be for sorption beds sized for 4 crew members. Robustness must be demonstrated with extended operation and with periods of intermittent dormancy. Systems should incorporate safety margins and design features to provide safe operation upon delivery to NASA.

State of the Art and Critical Gaps:
Current and future human exploration missions require regenerable systems that minimize mass, power, volume, and resupply and are highly reliable. Most SOA sorption systems in the Atmosphere Revitalization System (ARS) use COTS heaters that are inefficient, leading to high power requirements. Thermal management in systems such as the Carbon Dioxide Removal Assembly and the Sabatier could be improved by using advanced heating systems. Unfortunately, innovative heaters such as heat pipes and vapor chambers have been used elsewhere in space hardware but have yet to be developed for use in Environmental Control and Life Support Systems (ECLSS).

In addition, a significant amount of the spacecraft power is allocated to a variety of ECLSS. Alternative thermal management approaches that have multiple functions such as heating, cooling, thermal energy storage, and the thermal energy transfer over long distances will drastically reduce the loading on available resources for both in-transit and planetary base missions. These advanced heaters can be used for other NASA mission architectures as well, such as the extravehicular activity (EVA) and the Trash Compaction Processing System.

Relevance / Science Traceability:
This subtopic is relevant to Human Exploration and Operations Mission Directorate (HEOMD), especially ECLSS, by improving thermal management systems to minimize loading on facility resources such as power, heater, and cooling systems. In addition, efficient heaters minimize mass, power, and volume. The following ECLSS systems could benefit from improvements in thermal management technology: the ARSs, the Water Management Systems, and Solid Waste Management Systems including trash compaction. Other technical areas that may have interest are small satellites and EVA.

References:

1. Cmarik, Gregory, James Knox, and Warren Peters. "4-Bed CO2 Scrubber–From Design to Build." 2020 International Conference on Environmental Systems, 2020.
2. Peterson, G. P., and H. B. Ma. "Theoretical analysis of the maximum heat transport in triangular grooves: a study of idealized micro heat pipes." (1996): 731-739.
3. Schunk, Richard, Warren Peters, and John Thomas. "Four Bed Molecular Sieve–Exploration (4BMS-X) Virtual Heater Design and Optimization." 47th International Conference on Environmental Systems, 2017.
4. Wang, G., D. Mishkinis, and D. Nikanpour, "Capillary heat loop technology: space applications and recent Canadian activities." Applied thermal engineering, 2008. 28(4): p. 284-303.
5. Tra-My Justine Richardson and Darrell Jan. "A Trade-off Study of the Spacecraft Carbon Dioxide Management System using the Analytical Hierarchy Process", 48th International Conference on Environmental Systems, ICES-2018-332

H3.09 Human Accommodations (SBIR)

Lead Center: JSC
Participating Center(s): JPL

Scope Title: Human Accommodations for Exploration Missions

Scope Description:
Humans have been living and working in Low Earth Orbit (LEO) for several decades; however, human accommodations such as galley and hygiene facilities are still fairly limited. As mission length and distance increase, these comforts of home will become even more important, and their resource footprint will need to be reduced. Missions to the Moon and Mars will introduce partial gravity where optimal design of human accommodations may be different than in LEO. Additionally, emerging commercial activities in LEO and the lunar vicinity will create a larger demand for human accommodations in space.

Innovative technologies that improve human accommodations over the state of the art are sought in the areas of galley, personal hygiene, laundry, and volumetrically efficient use of space for tasks.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:
Phase I deliverables: Reports demonstrating proof of concept, test data from proof-of-concept studies, and designs leading to Phase II. Phase I tasks should answer critical questions focused on reducing development

risk prior to entering Phase II. Conceptual solutions should clearly describe resource requirements such as hardware mass, volume, and power, as well as water use and crew time to operate.

Phase II deliverables: Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data and analysis. Prototypes should be full scale unless physical verification in 1g is not possible. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to NASA.

State of the Art and Critical Gaps:

State of the art for most human accommodations is defined by International Space Station (ISS) hardware. For sleep and privacy, crew quarters consist of permanent rack-size compartments that accommodate sleeping bag, privacy, personal wall space, ventilation with limited temperature control, lighting, and personal entertainment. The ISS galley consists of a table, food warmer, and potable water dispenser, which can rehydrate food and drinks with hot or ambient temperature water. A small refrigerator has also been added for food and drink storage. Personal hygiene is accomplished with disposable wipes, wetted towels, no-rinse shampoo, Earth-like oral and hair care and normal clothing that is discarded when it gets too dirty. Housekeeping relies mainly on disposable disinfectant wipes and a vacuum cleaner. On ISS, there is no cooking, sink (handwash), shower, dishwasher, washing machine, or dryer.

Critical gaps include:

- Rapid food heating for 4 crewmembers at the same time so that crews can dine together. Ideally, heating of 16 food packages could be accomplished in 30 to 45 minutes with less than 500 W of electricity. Food must be heated in accordance with NASA Standard 3001 and the Human Integration Design Handbook, and all equipment must meet touch temperature limits.
- Food refrigeration for long-term storage on the way to and from Mars. Stored food volumes of 2 to 8 m^3, with average packaged food density of 388 kg/m^3, may be required at temperature ranges of -25 to 5 °C. Concepts must be volumetrically efficient, mass efficient, and highly reliable since loss of food quality can result in loss of crew performance. Secondary mass penalty for cold stowage should be below 0.2 kg per 1 kg of food. The refrigeration and insulation systems should be efficient enough to run (at steady state) on less than 0.15 W/kg of food frozen at -22 °C in a 23 °C ambient.
- Personal hygiene with less consumables is needed. Currently 0.11 kg/person/day of wet wipes are supplied, and the goal is to reduce this below 0.05 kg/person/day.
- Water efficient handwash for use in microgravity environment. Soap, water, and crew interface aspects must all be considered.
- Clothes washer/dryer combination for use on the Moon (1/6g) or Mars (1/3g) that can clean up to 4.5 kg of cotton, polyester, and wool clothing at a time in less than 7 hours using <50 kg machine mass, <0.3 m^3 external machine volume and <300 W electrical power (Note: 101.3 kPa habitat pressure may be assumed for prototype development).
- Devices and systems for volumetrically efficient use of habitable volume in spacecraft. This may include random access stowage concepts where equipment and stowage could be packed together densely and slid open for random access when needed. Such a concept could optimize volumes according to real-time crew needs, while maximizing volume for stowage and equipment. Flexible work surfaces will also be considered. For example, systems that allow the crew to maximize "wall" and "ceiling" as work surfaces in a microgravity environment but allow reconfiguration if the habitat transitions into a gravity environment (i.e., walls and ceilings are less useful, but fold-out table tops or overhead features may deploy on demand). Logistics-2-Living concepts are also of interest, such as secondary stowage structure repurposing for the real-time creation of partitions, furniture, glove-boxes, etc.

Out of Scope:
Proposals are not solicited for toilets nor hardware considered life support systems, including air revitalization, water processing, or waste processing. Lunar dust mitigation technologies are covered elsewhere, but innovative interior surface cleaning including dust removal may be submitted to this subtopic. Crew quarters, exercise devices, and electronic devices for entertainment are not in scope here.

Relevance / Science Traceability:
The Logistics Reduction (LR) Project, under the Advanced Exploration Systems (AES) Program, within the Human Exploration and Operations Mission Directorate (HEOMD), is the expected initial customer. The LR Project will consider sponsoring Phase III Small Business Innovation Research (SBIR) activities and assist with technology infusion into NASA Moon-to-Mars missions.

References:

1. "Life Support Baseline Values and Assumptions Document", NASA/TP-2015–218570/Rev. 1
2. " NASA Spaceflight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health", NASA-STD-3001 Vol. 2, https://www.nasa.gov/hhp/standards
3. "Human Integration Design Handbook, Revision 1", https://www.nasa.gov/feature/human-integration-design/
4. "Dual Use of Packaging on the Moon: Logistics-2-Living", AIAA-2010-6049
5. "Lessons Learned for the International Space Station Potable Water Dispenser", ICES-2018-114
6. "Will Astronauts Wash Clothes on the Way to Mars?", ICES-2015-53

H4.06 Low-Power Multi-Gas Sensor for Spacesuits (SBIR)

Lead Center: JSC
Participating Center(s): N/A

Scope Title: Spacesuit Gas Sensors

Scope Description:
As the design for the new Exploration Extravehicular Mobility Unit (xEMU) is developed, technology gaps have been identified for the gas sensors employed in the portable life support system (PLSS). These gaps need to be fulfilled to meet the new exploration requirements.

In order to ensure the safe operation of the spacesuit there is a need to measure the following major constituents in the gas stream across a total pressure range of 3.5 to 23.5 psia and temperature range of 35 to 125 °F: O_2 = 20 to 100%; CO_2 = 0 to 30 torr over 3.5 to 23.5 psia; H_2O = 5 to 90% relative humidity (RH). During ground testing these measurements can be made by ancillary equipment, however, the current design of the PLSS only includes nondispersive infrared (NDIR) sensors for CO_2. For reference, the outer mold line for these sensors is approximately 2.3 by 2.2 by 6.1 inches.

Since these sensors are continuously powered during an extravehicular activity (EVA) their power consumption is a direct driver of spacesuit battery capacity and, in consequence, spacesuit mass. It is, therefore, desirable to have a sensor power consumption below 2.5 W. The current CO_2 sensors consume 2 W during operation.

The intended use case for these sensors in the PLSS is to provide general situational awareness of the major constituents, in contrast to highly accurate measurements. The required accuracy of the sensors is therefore 1% or better for O_2 concentration and RH and 0.3 torr for CO_2 partial pressure.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems

Level 2: TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Prototype

Desired Deliverables Description:
Phase I products: By the end of Phase I, it would be beneficial to have a concept design for infusion into the xEMU. Testing of the concept is desired at this Phase.

Phase II products: By the end of Phase II, a prototype ready for system-level testing in the xEMU or in a representative loop of the PLSS is desired.

State of the Art and Critical Gaps:
As the design for the new xEMU is developed, there are obvious gaps in technologies that need to be fulfilled to meet the new exploration requirements. The currently employed gas sensors are functionally limited, draw significant power, and require new, innovative ideas. This solicitation is an attempt to seek new technologies for low-power multi-gas sensors. NASA has plans to go to the Moon and as the mission extends further out of low Earth orbit, the additional information provided by such sensors will be indispensable for the situational awareness of astronauts in space, as well as flight controllers on the ground.

Relevance / Science Traceability:
It is relevant to the new xEMU, International Space Station (ISS), as well as commercial space companies. As the xEMU is being designed, built, integrated, and tested at Johnson Space Center, solutions will have a direct infusion path as the xEMU is matured to meet the design and performance goals.

References:

1. https://www.nasa.gov/image-feature/exploration-extravehicular-mobility-unit-xemu

H4.07 Low Volume, Power and Mass CO2 and Humidity Control for xEMU (SBIR)

Lead Center: JSC
Participating Center(s): N/A

Scope Title: Spacesuit CO2 and Humidity Control Technology

Scope Description:
This solicitation is seeking to identify sorbent candidates that will compete with or outperform the current baseline sorbent technology used within the Exploration Extravehicular Mobility Unit (xEMU) for carbon dioxide (CO_2) and humidity control. It is desired that sorbent candidates meet or exceed the characteristics and goals listed below.

Key goals for sorbent characteristics and performance:

- 600- to 1,000-µm-sized beads.
- Vacuum desorb technology (desorb at a pressure of 140 Pa).
- CO_2 loading uptake (noncyclic) 25 °C, 8 mmHg CO_2, 10 °C dewpoint, 6.0 g CO_2/100 g sorbent.
- H_2O loading uptake (noncyclic) 25 °C, 15 °C dewpoint, 7.0 g H_2O/100 g sorbent.
- Uptake (cyclic) 25 °C, 8 mmHg CO_2, 10 °C dewpoint, 2.0 g CO_2/100 g sorbent at 2 to 3 minute half-cycle timing (e.g., adsorb for 2 minutes/desorb for 2 minutes).

In order to ensure the safe operation of the xEMU, CO_2 and humidity levels need to be controlled to levels in accordance with requirements established by the NASA medical community. The technology currently baselined for the xEMU is the Rapid Cycle Amine (RCA) technology and information on the RCA is also available in the reference section below. New technology alternatives to the RCA are desired in order to have a robust suit program that is able to fall back on alternate technologies if the need arises.

For the majority of an extravehicular activity (EVA), the CO_2 partial pressure required at the breathing gas inlet to the helmet of the spacesuit needs to be maintained at or below 2.2 mmHg when the astronaut is generating 2.44 g/min of CO_2. The flow rate of the oxygen ventilation loop that circulates the breathing gas from the suit, through the CO_2 and humidity removal unit and back to the helmet of the suit is maintained at 6 ft^3/min.

The driving humidity requirement is to maintain the relative humidity of the breathing gas flowing into the helmet between 5 and 45% with the water vapor production level of 0.2 lb/hr and 6 ft^3/min ventilation flow rate through the suit. The CO_2 and humidity control unit should also be able to handle situations where the generation rates are higher during shorter periods as described in the detailed requirements listed in the references section.

The goals for the mass of alternate technology units to be less than 14 lb, the volume to be less than 0.4 ft^3, and the power consumption to be less than 1.4 W on average.

This subtopic is relevant to the xEMU, International Space Station (ISS), Gateway, and human landing system (HLS), as well as other endeavors currently in development by commercial space companies. The goal is to have proposed solutions to be designed, built, integrated and tested at Johnson Space Center and integrated into the xEMU. These solutions have the potential for a direct infusion path as the xEMU is matured to meet the design and performance goals.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Prototype

Desired Deliverables Description:
Phase I products: By the end of Phase I, it would be beneficial to have candidate sorbent(s) identified that meet the goals listed for this solicitation. Testing of sorbent candidate is required at this Phase.

Phase II products: By the end of Phase II, testing of sorbent in the xEMU equivalent application and conditions is desired. Vendors may collaborate with research institutes if desired.

State of the Art and Critical Gaps:
The current state-of-the-art utilized on the ISS EMU is a metal oxide technology that requires astronauts to remove the unit from the PLSS, regenerate it in an oven, and reinstall it into the PLSS prior to the subsequent EVA.

The baseline xEMU technology provides regenerative CO_2 and humidity removal via a pressure swing adsorption system with a high-capacity sorbent that desorbs upon exposure to vacuum and requires little to no maintenance by the astronaut. This technology is well developed, but unparalleled. Ultimately, this solicitation is an attempt to lead to an alternate CO_2 and humidity removal system with regenerable capabilities requiring minimal astronaut maintenance to provide options for the new xEMU should unforeseen issues arise with the current technology. Additionally, xEMU has goals of reducing power draw, volume envelope, and mass while maintaining the current CO_2 and humidity removal capacity at the conditions described previously.

Relevance / Science Traceability:
It is relevant to the new xEMU, ISS, as well as commercial space companies. As the xEMU is being designed, built, integrated, and tested at Johnson Space Center, solutions will have a direct infusion path as the xEMU is matured to meet the design and performance goals.

References:

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2. ICES-2019-400 RCA Testing History (Rapid Cycle Amine Testing History (tdl.org))
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Focus Area 7 Human Research and Health Maintenance

NASA's Human Research Program (HRP) investigates and mitigates the highest risks to astronaut health and performance for exploration missions. HRP achieves this through a focused program of basic, applied and operational research leading to the development and delivery of:

- Human health, performance, and habitability standards.
- Countermeasures and other risk mitigation solutions.
- Advanced habitability and medical support technologies.

HRP has developed an Integrated Research Plan (IRP) to describe the requirements and notional approach to understanding and reducing the human health and performance risks. The IRP describes the Program's research activities that are intended to address the needs of human space exploration and serve HRP customers. The Human Research Roadmap (http://humanresearchroadmap.nasa.gov) is a web-based version of the IRP that allows users to search HRP risks, gaps, and tasks.

The HRP is organized into several research Elements:

- Human Health Countermeasures.
- Human Factors and Behavioral Performance.
- Exploration Medical Capability.
- Space Radiation.

Each of the HRP Elements address a subset of the risks. A fifth Element, Research Operations and Integration (ROI), is responsible for the implementation of the research on various space and ground analog platforms. HRP subtopics are aligned with the Elements and solicit technologies identified in their respective research plans.

H12.07 Protective Pharmaceutical Packaging (SBIR)

Lead Center: JSC
Participating Center(s): ARC, GRC

Scope Title: Protective Medication Packaging Technologies Supporting Exploration Spaceflight Operations

Scope Description:
Successful long-duration space exploration missions will require robust crew support systems. These systems will rely on exponentially increasing crew autonomy, operate in low-to-no logistical resupply settings, and facilitate independent decision making within the context of challenging communication scenarios due to limited to no terrestrial-based support asset reach back. In addition, the long-duration spaceflight environment will require medically trained crew members who can assess, diagnose, and treat each other for a variety of illnesses and injuries. These medical events will require the preselection and long-term storage of various medications onboard human crewed spacecraft or pre-deployed in advance of human missions. Although currently there is no available method to sufficiently characterize or quantify the pharmaceutical stability,

quality, or potency of repackaged medications (stored and eventually utilized for human consumption during long-duration space flight missions), available data shows that the median risk of drug failure (based on U.S. Pharmacopeia (USP) acceptance thresholds) for a 2-year exploration mission is approximately 59%. This risk increases to about 82% for a 3-year mission. These factors expose the distinct possibility that the provision of safe and effective drug treatment of long-duration crew may be at significant risk due to the current operationally derived need to repack crew medications to reduce resource "costs" (i.e., mass, volume, and power) possibly adversely impacting crew wellness, performance, and long-term health.

While baseline instability has not been experimentally investigated, most of the pharmaceuticals tested in spaceflight studies to date have been removed (due to mass, volume, and power considerations) from manufacturer's containers and repackaged into either polypropylene containers (Du et al. 2011) or lightweight, resealable plastic zipper storage bags. This type of repackaging remains the norm for supplying medications to the International Space Station (ISS). Unfortunately, such containers are not protective, therefore repackaged pharmaceuticals are exposed to ingress of atmospheric factors at concentrations in equilibrium with the ambient atmosphere (Putcha et al. 2016; Waterman et al. 2002). It is well established that such packaging is permeable to atmospheric factors such as moisture and oxygen and that prolonged exposure of susceptible medications is detrimental to shelf life (Roy et al. 2018; Waterman et al. 2002; Waterman et al. 2004).

Whereas exposure to spaceflight conditions (e.g., galactic cosmic radiation (GCR), microgravity or zero-gravity, etc.) is only a minor factor contributing to the cumulative risk of drug failure, with the significant factor being the baseline risk (observed in paired terrestrial controls under similar environmental conditions), repackaging of pharmaceuticals likely reduces medication effectiveness significantly (and increasingly, as "out of package" exposures extend in long-duration spaceflight), diminishes therapeutic effectiveness, thus potentially compromising crew health and performance.

In the past, repackaging methods have not been a significant limitation for missions where flight duration was much shorter than drug expiry (e.g., Apollo and Space Transport System (STS)) or where Low Earth Orbit permits regular replacement of expiring drugs (i.e., ISS). However, long-duration exposure of pharmaceuticals to atmospheric factors during exploration space missions will increase the risk of analytical drug failure over time, increasing the risk of therapeutic failure and potential exposure to toxicologically active impurities. Therefore, proven repackaging countermeasures are required to assure adequate stability of susceptible medications for the entire duration of exploration space missions.

This subtopic solicits proposals that address the critical need for exploring novel protective packaging technologies. Candidate technologies will retain or replicate (a) "initial" pharmaceutical packaging standards (i.e., minimization or elimination of atmospheric conditions), (b) acceptable shelf life (active pharmaceutical ingredient (API) minimums that meet or exceed Food and Drug Administration standards with respect to planned long-duration spaceflight timelines), (c) reduce reliance or need for cold storage/refrigeration of pharmaceuticals while, (d) preserving, optimizing, or reducing resource "costs" in regards to operational mass, volume, and power constraints (e.g., reducing power and mass requirements for an "in-vehicle" cold storage system), and (e) provide the potential for development of cross-cutting storage/repackaging technologies that integrate across, streamline, or expand the capabilities of multiple vehicle human support systems.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.3 Human Health and Performance

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:
Drug packaging that minimizes mass, volume, and material waste and protects contents from ingress of atmospheric factors, including moisture, oxygen, and carbon dioxide.

Drug packaging technologies that help preserve API integrity and efficacy across exploration spaceflight mission durations with minimal (or reduced) mass/volume/power resource cost(s).

Phase I Deliverable – Candidate packaging solutions.

Phase II Deliverable – Experimentally demonstrated effectiveness under long-term (2-year) and accelerated conditions.

State of the Art and Critical Gaps:
The state of the art of medication/pharmaceuticals packing technologies for exploration missions is uncertain. Foil packaging is an industry standard for pharmaceutical products and ensures low moisture transmission. Aclar® films have similar low moisture transmission and can be layered with other materials to increase the barrier to gas permeation. Mylar ® films have been used as a high-barrier packaging to protect foods and bulk pharmaceutical ingredients from the effects of oxygen, moisture, and light. Such materials—possibly combined with purging packaging headspace with inert gas (argon) or nitrogen—may be effective strategies to extend medication shelf life. Enclosing materials that scavenge oxygen, moisture (e.g., silica gels), and CO_2 may offer additional advantages.

Relevance / Science Traceability:
This subtopic seeks technology development that benefits the Exploration Medical Capability Element (ExMC) of the NASA Human Research Program (HRP). Pharmaceutical repackaging technologies are needed to address the following assigned risks:

- Risk of ineffective or toxic medications during long-duration exploration spaceflight.
- Risk of adverse health outcomes and decrements in performance due to inflight medical conditions.

This subtopic seeks technology development that supports the following identified HRP Gaps:

- Pharm-101: "… determine the optimal packaging/storage strategy for medications in space that balances the needs of mitigating toxicity, preserving effectiveness, and minimizing resource "costs" (mass, volume, power, etc.)."
- Pharm-401: "… perform further research to understand and characterize the active pharmaceutical ingredient and degradation profiles of medications for which we have low to moderate confidence in their safety and effectiveness for exploration missions."
- Pharm-601: "… characterize the extent to which spaceflight alters pharmacokinetics and pharmacodynamics."

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6. HRP Human Research Roadmap: Risks: Medication Stability Analysis: Device: https://humanresearchroadmap.nasa.gov/Tasks/task.aspx?i=1565
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Focus Area 8 In-Situ Resource Utilization

In-Situ Resource Utilization (ISRU) involves any hardware or operation that harnesses and utilizes ‘in-situ’ resources (natural and discarded) to create products and services for robotic and human exploration. Local resources include ‘natural’ resources found on extraterrestrial bodies such as water, solar wind implanted volatiles (hydrogen, helium, carbon, nitrogen, etc.), vast quantities of metals in mineral rocks and soils, and atmospheric constituents, as well as human-made resources such as trash and waste from human crew, and discarded hardware that has completed its primary purpose. The most useful products from ISRU are propellants, fuel cell reactants, life support commodities (such as water, oxygen, and buffer gases), and feedstock for manufacturing and construction. ISRU products and services can be used to i) reduce Earth launch mass or lander mass by not bringing everything from Earth, ii) reduce risks to the crew and/or mission by reducing logistics, increasing shielding, and providing increased self-sufficiency, and/or iii) reducing costs by either needing less launch vehicles to complete the mission or through the reuse of hardware and lander/space transportation vehicles. Since ISRU systems must operate wherever the resource of interest exists, technologies and hardware will need to be designed to operate in harsh environments, reduced gravity, and potential non-homogeneous resource physical, mineral, and ice/volatile characteristics. This year’s solicitation will focus on critical technologies needed in the areas of Resource Acquisition and Consumable Production for the Moon and Mars. The ISRU focus area is seeking innovative technology for:

- Novel Silicate Reduction Methods
- Noncontact High Temperature Measurement
- Regolith Feed/Removal Systems and Mineral Measurement for Oxygen Removal
- Non-Water Volatile Capture
- Regolith/Ice Crushing
- Size-Sorting
- Beneficiation of Water Ice
- Mineral Beneficiation
- Metal Production

As appropriate, the specific needs and metrics of each of these specific technologies are described in the subtopic descriptions.

Z12.01 Extraction of Oxygen, Metal, and Water from Lunar Regolith (SBIR)

Lead Center: JSC

Participating Center(s): GRC, JPL, KSC, MSFC

Scope Title: Oxygen from Regolith

Scope Description:

Lunar regolith is approximately 45% oxygen by mass. The majority of the oxygen is bound in silicate minerals. Previous efforts have shown that it is possible to extract oxygen from regolith using various techniques. NASA is interested in developing novel oxygen extraction systems that can be proven to handle large amounts of lunar regolith throughput while minimizing consumables, mass, and energy. NASA is also interested in developing the supporting technologies that may enable or enhance the ability to extract oxygen from lunar regolith. Each of the following specific areas of technology interest may be proposed as individual efforts or combined.

- Novel Silicate Reduction Methods: Proposed concepts should describe a reduction method for highland anorthosite that avoids reduction of the regolith in the molten liquid state (i.e., gas/granular, liquid/granular, or vacuum/granular material processing). If reactants are utilized in the reduction process, and multiple reaction products are generated, all steps in regenerating the reactants and separating the products need to be considered. Proposed concepts must include a method to move regolith through the reaction zone (e.g., regolith inlet/outlet valves capable of passing abrasive granular material through the valve for hundreds of cycles). The target production rate for a pilot plant system is 1,000 kg of oxygen per year. The target production rate for a full-scale system is 10,000 kg of oxygen per year. Since access to continuous power is not initially planned, proposers will need to consider how to stop and restart their reduction method periodically throughout the year.
- Noncontact High-Temperature Measurement: Proposed concepts should be capable of determining temperatures up to 2,000 ºC without contacting the material being measured (e.g., pyrometer). Compatibility with multiple oxygen extraction methods is desired. Instruments must be capable of operating inside of a vacuum chamber.
- Regolith Feed/Removal Systems and Mineral Measurement for Oxygen Removal: For oxygen extraction from regolith systems, it is anticipated that hardware will be required to transfer regolith from excavators to the reduction reactor and to transfer processed regolith from the reduction reactor to a holding hopper or the lunar surface. To better understand and control oxygen/metal extraction processes, NASA would like to examine the regolith material before and after the reduction process. Proposed concepts should describe a regolith feed/removal system that includes instrumentation to determine the amount of oxygen in the regolith upstream and downstream of an oxygen extraction zone. Measurements should be taken at a frequency that accounts for the regolith feed rate. The target regolith feed rate for a pilot plant system is 2.5 kg/hr. The target regolith feed rate for a full-scale system is 25 kg/hr. Compatibility with multiple oxygen extraction methods is desired. Instruments must be capable of operating inside of a vacuum chamber.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:
Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.1 In-Situ Resource Utilization

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Phase I efforts should provide a feasibility study and/or proof of concept. Phase II efforts should demonstrate the technology using lunar regolith simulant where applicable. Phase II efforts should be demonstrated no less than 1/10 of the pilot plant production rate where applicable and should describe how the process can be applied at the full-scale production rate.

State of the Art and Critical Gaps:
Some oxygen-from-regolith methods have been demonstrated at relevant scales and are progressing toward TRL 6. Many other methods have been demonstrated at the bench scale, but current designs lack a means to

move regolith in and out of the oxygen extraction zone. Many of these processes are used terrestrially, but industrial designs do not provide a means to keep gases from escaping to the vacuum of space.

Relevance / Science Traceability:
STMD (Space Technology Mission Directorate) has identified the need for oxygen extraction from regolith. The alternative path, oxygen from lunar water, currently has much more visibility. However, we currently do not know enough about the concentration and accessibility of lunar water to begin mining it at a useful scale. Lunar water prospecting missions are required to properly assess the utilization potential of water on the lunar surface. Until more water prospecting data becomes available, NASA recognizes the need to make progress on the technology required to extract oxygen from dry lunar regolith.

References:

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Scope Title: Lunar Ice Mining

Scope Description:
We now know that water ice exists on the poles of the Moon from data obtained from missions like the Lunar Prospector, Chandrayaan-1, Lunar Reconnaissance Orbiter (LRO), and the Lunar Crater Observation and Sensing Satellite (LCROSS). We know that water is present in permanently shadowed regions (PSRs), where temperatures are low enough to keep water in a solid form despite the lack of atmospheric pressure. Many efforts are now underway to develop technologies needed to extract and capture lunar water ice. However, many other volatiles may be co-located with the water ice that may have additional in situ resource utilization (ISRU) applications. NASA is interested in developing technologies to capture and utilize other volatiles that may be located in PSRs. NASA is also interested in developing the supporting technologies that may enhance efforts to excavate water ice. Each of the following specific areas of technology interest may be proposed as individual efforts or combined.

- Nonwater Volatile Capture: Proposed concepts should define a target volatile (e.g., H_2S, NH_3, SO_2, C_2H_4, CO_2, CH_3OH, CH_4) to be captured from lunar regolith and describe how it may be utilized in a way that reduces the cost of landing consumables on the lunar surface. Concepts need to operate in PSRs of the lunar poles (<100K) and collected products will be removed from the PSR and processed in a near-permanently lit location nearby. Concepts to minimize electrical power usage are highly encouraged.

- Regolith/Ice Crushing: Proposed concepts should be able to crush frozen regolith simulant with a water ice content of 90% by mass while minimizing temperature increase in the material. The target production rate for a pilot-plant-scale ice-crushing system is 10 kg of regolith per hour. The target production rate for a full-scale system is 100 kg of regolith per hour. Concepts should consider how volatiles released during crushing may be minimized or captured if a significant fraction are lost.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:
Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.1 In-Situ Resource Utilization

Desired Deliverables of Phase I and Phase II:

- Prototype
- Analysis
- Hardware

Desired Deliverables Description:
Phase I efforts should provide a feasibility study and/or proof of concept. Phase II efforts should demonstrate the technology using lunar regolith simulant where applicable. Phase II efforts should be demonstrated no less than 1/10 of the pilot plant production rate where applicable and should describe how the process can be applied at the full-scale production rate.

State of the Art and Critical Gaps:
Multiple efforts are now underway to extract, purify, and capture lunar water ice. However, little work has been performed on developing technologies to capture and utilize other useful volatiles that may be co-located within a PSR. Ice-crushing technology was developed at a small scale to support the Regolith and Environment Science and Oxygen and Lunar Volatiles Extraction (RESOLVE) project, but little work has been performed for larger scale applications.

Relevance / Science Traceability:
NASA has referenced water ice as one of the reasons we have chosen the lunar poles as the location to establish a sustained human presence. The Space Technology Mission Directorate (STMD) has identified the need for water extraction technologies. The Science Mission Directorate (SMD) is currently funding the Volatiles Investigating Polar Exploration Rover (VIPER) mission to investigate lunar water ice.

References:

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vacuum with application to lunar observations. *Journal of Geophysical Research: Planets*, *118*(1), 105-115.

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Scope Title: Size Sorting, Beneficiation, and Metal Production

Scope Description:

Size sorting and beneficiation can be applied to ice mining and to oxygen extraction from regolith. Size sorting is a necessary step in any in situ resource utilization (ISRU) process involving regolith to ensure that the regolith delivered to an ISRU plant does not include objects large enough to cause mechanical failures within the system. Beneficiation allows for improved efficiency of ISRU processes that involve heating regolith to acquire a specific resource. NASA is also interested in processes where the primary product is metal—specifically metals other than iron, since iron extraction from regolith is a fairly advanced technology. Each of the following specific areas of technology interest may be proposed as individual efforts or combined.

- Size Sorting: Proposed concepts should demonstrate a means to remove particles larger than 1 mm from a feedstock of lunar regolith simulant. The target production rate for a pilot-plant-scale system is 10 kg of regolith per hour. The target production rate for a full-scale system is 100 kg of regolith per hour.
- Beneficiation of Water Ice: Proposed concepts should describe a method for separating water ice from bulk regolith without causing the water ice to change phase. The described method should address how sublimation losses can be minimized. The target production rate for a pilot-plant-scale system is 10 kg of regolith per hour. The target production rate for a full-scale system is 100 kg of regolith per hour.
- Mineral Beneficiation: Proposed concepts should define a target mineral to be concentrated from lunar regolith feedstock and describe how it will be utilized in a way that reduces the cost of landing consumables on the lunar surface.
- Metal Production: Proposed concepts should define a target metal (e.g., aluminum) to be extracted from lunar regolith and describe how it will be utilized in a way that reduces the cost of landing consumables on the lunar surface. Proposed concepts must include a method to move regolith through the reaction zone (e.g., regolith inlet/outlet valves capable of passing abrasive granular material through the valve for hundreds of cycles.) Near-pure metals or metal alloys are acceptable. Properties of metals extracted for manufacturing should be considered and provided.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.1 In-Situ Resource Utilization

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I efforts should provide a feasibility study and/or proof of concept. Phase II efforts should demonstrate the technology using lunar regolith simulant where applicable. Phase II efforts should be demonstrated at no less than 1/10 of the pilot plant production rate where applicable and should describe how the process can be applied at the full-scale production rate.

State of the Art and Critical Gaps:
The Moon to Mars Oxygen and Steel Technology (MMOST) SBIR Phase II sequential project is currently implementing size sorting and beneficiation of minerals containing iron at a relevant scale and is also producing iron as the main product. There has been little advancement toward the production of other metals such as aluminum. The Aqua Factorem project funded through the NASA Innovative Advanced Concepts (NIAC) program represents the state of the art for ice beneficiation.

Relevance / Science Traceability:
NASA has referenced water ice as one of the reasons we have chosen the lunar poles as the location to establish a sustained human presence. The Space Technology Mission Directorate (STMD) has identified the need for water extraction technologies. The Science Mission Directorate (SMD) is currently funding the Volatiles Investigating Polar Exploration Rover (VIPER) mission to investigate lunar water ice.

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Focus Area 9 Sensors, Detectors, and Instruments

NASA's Science Mission Directorate (SMD), https://science.nasa.gov/ encompasses research in the areas of Astrophysics, Earth Science, Heliophysics and Planetary Science. The National Academies of Science have provided NASA with recently updated Decadal surveys that are useful to identify technologies that are of interest to the above science divisions. Those documents are available at https://www.nationalacademies.org/

A major objective of SMD instrument development programs is to implement science measurement capabilities with smaller or more affordable aerospace platforms so development programs can meet multiple mission needs and therefore make the best use of limited resources. The rapid development of small, low-cost remote sensing and in-situ instruments capable of making measurements across the electromagnetic spectrum is essential to achieving this objective. For Earth Science needs, in particular, the subtopics reflect a focus on remote sensing (active and passive) and in situ instrument development for space-based, airborne, and uninhabited aerial vehicle (UAV) platforms. A strong focus is placed on reducing the size, weight, power, and cost of remote and in situ instruments to allow for deployment on more affordable and wider range of platforms. Astrophysics has a critical need for sensitive detector arrays with imaging, spectroscopy, and polarimetric capabilities, which can be demonstrated on ground, airborne, balloon, or suborbital rocket instruments. Heliophysics, which focuses on measurements of the sun and its interaction with the Earth and the other planets in the solar system, needs a significant reduction in the size, mass, power, and cost for instruments to fly on smaller spacecraft. Planetary Science has a critical need for miniaturized instruments with in-situ sensors that can be deployed on surface landers, rovers, and airborne platforms. For the 2022 program year, we are continuing to update the included subtopics. Please read each subtopic of interest carefully. We continue to emphasize Ocean Worlds and solicit development of in-situ instrument technologies and components to advance the maturity of science instruments focused on the detection of evidence of life, especially extant of life, in the Ocean Worlds. The microwave technologies continue as two subtopics, one focused on active microwave remote sensing and the second on passive systems such as radiometers and microwave spectrometers. NASA has additional interest in advancing quantum sensing technologies to enable wholly new quantum sensing and measurement techniques focused on the development and maturation towards space application and qualification of atomic systems that leverage their quantum properties. Furthermore, photonic integrated circuit technology is sought to enable size, weight, power, and cost reductions, as well as improved performance of science instruments, subsystems, and components which is particularly critical for enabling use of affordable small spacecraft platforms.

A key objective of this SBIR Focus Area is to develop and demonstrate instrument component and subsystem technologies that reduce the risk, cost, size, and development time of SMD observing instruments and to enable new measurements. Proposals are sought for development of components, subsystems and systems that can be used in planned missions or a current technology program. Research should be conducted to demonstrate feasibility during Phase I and show a path towards a Phase II prototype demonstration. The following subtopics are concomitant with these objectives and are organized by technology.

S11.01 Lidar Remote-Sensing Technologies (SBIR)

Lead Center: **LaRC**
Participating Center(s): **GSFC**

Scope Title: Lidar Remote-Sensing Technologies

Scope Description:
NASA recognizes the potential of lidar technology to meet many of its science objectives by providing new capabilities or offering enhancements over current measurements of atmospheric, geophysical, and topographic parameters from ground, airborne, and space-based platforms. To meet NASA's requirements for remote sensing from space, advances are needed in state-of-the-art lidar technology with an emphasis on compactness, efficiency, reliability, lifetime, and high performance. Innovative lidar subsystem and component technologies that directly address the measurement of atmospheric constituents and surface features of the Earth, Mars, the Moon, and other planetary bodies will be considered under this subtopic. Compact, high-efficiency lidar instruments for deployment on unconventional platforms, such as unmanned aerial vehicles, SmallSats, and CubeSats are also considered and encouraged. Proposals must show relevance to the development of lidar instruments that can be used for NASA science-focused measurements or to support current technology programs. Meeting science needs leads to four primary instrument types:

- Backscatter: Measures beam reflection from aerosols and clouds to retrieve the optical and microphysical properties of suspended particulates.
- Laser spectral absorption: Measures laser absorption by trace gases from atmospheric or surface backscatter and volatiles on surfaces of airless planetary bodies at multiple laser wavelengths to retrieve concentration of gas within measurement volume.
- Ranging: Measures the return beam's time of flight to retrieve distance.
- Doppler: Measures wavelength changes in the return beam to retrieve relative velocity.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I research should demonstrate technical feasibility and show a path toward a Phase II prototype unit. A typical Phase I deliverable could be a technical report demonstrating the feasibility of the technology and a

design that is to be built under a Phase II program. In some instances where a small subsystem is under investigation, a prototype deliverable under the Phase I is acceptable.

Phase II prototypes should be capable of laboratory demonstration and preferably suitable for operation in the field from a ground-based station, an aircraft platform, or any science platform amply defended by the proposer. Higher fidelity Phase II prototypes that are fielded in harsh environments such as aircraft often require follow-on programs such as Phase III SBIR to evaluate and optimize performance in relevant environment.

As seen in the section below on “State of the Art and Critical Gaps,” desired deliverables are oriented toward subsystem or system-level lidar technology solutions, as opposed to a stand-alone component. That is, desired technologies should be toward a lidar system, rather than a component such as a laser or photodetector of unspecified applicability to a measurement goal.

State of the Art and Critical Gaps:

- Transformative technologies and architectures are sought to vastly reduce the cost, size, and complexity of lidar instruments from a system perspective. Advances are sought for high-efficiency high-pulse energy (>>1 mJ) and high power (>>1 W) transmitters for operation on a wide range of compact (SmallSat, CubeSat, or Unmanned Aerial Vehicle size) packages. Reduction in the complexity of laser architectures is sought, while still meeting performance metrics for the measured geophysical observable. Hybrid diode/fiber/crystal architectures are sought as affordable sensor solutions to help reduce complexity and sensitivity to environmental effects (vibration, thermal variations, and pressure variations). Laser thermal management often poses an engineering challenge that drives lidar systems to deploy on large and costly platforms. Hence, novel thermal management systems for laser, optical, and electronic subsystems are sought to increase efficiency, decrease physical footprint, and transition laser systems to more compact platforms. New materials concepts could be of interest for the reduction of weight for lidar-specific telescopes, optical benches, and subcomponents. Integrated subsystems combining laser, optical, fiber, and/or photodetector components are of interest for reducing the size, weight, and power of lidar instruments.
- Compact, efficient, and rugged narrow-linewidth pulsed lasers operating between ultraviolet and infrared wavelengths suitable for lidar are sought. Specific wavelengths are of interest to match absorption lines or atmospheric transmission are: 290 to 320 nm (ozone absorption), 450 to 490 nm (ocean sensing), 532 nm (aerosols), 820 nm (water vapor line), 935 nm (water vapor line), 1064 nm (aerosols), 1550 nm (Doppler wind), 1645 to 1650 nm (high pulse energy (>10 mJ) for methane line, Doppler wind, and orbital debris tracking), 2050 nm (Doppler wind), 3000 to 4000 nm (hydrocarbon lines and ice measurement), and 6000 nm (nonterrestrial ice and water measurement). Architectures involving new developments in high-efficiency diode laser, quantum cascade laser, and fiber laser technologies are especially encouraged. For pulsed lasers two different regimes of repetition rate and pulse energies are desired: from 1 to 10 kHz with pulse energy greater than 1 mJ and from 20 to 100 Hz with pulse energy greater than 100 mJ. For laser spectral absorption applications, such as differential absorption lidar, a single frequency (pulse transform limited) and frequency-agile source is required to tune >100 pm on a shot-by-shot basis while maintaining high spectral purity of >1,000:1. Laser sources of wavelength at or around 780 nm are not sought this year. Laser sources for lidar measurements of carbon dioxide are not sought this year.
- Novel approaches and components for lidar receivers are sought, matching one or more of the wavelengths listed in the bullet above. Such receiver technology could include integrated optical/photonic circuitry, freeform telescopes and/or aft optics, frequency-agile ultra-narrow-band solar blocking filters for water vapor differential absorption lidar (DIAL) (<10 pm FWHM (full width at half maximum), >80% transmission and phase locked to the transmit wavelength), and phased-array or electro-optical beam scanners for large (>10 cm) apertures (especially those preserving transmission of circular polarization). Integrated receivers for Doppler wind

measurement at 1550, 1650, or 2050 nm wavelength are sought for coherent heterodyne detection at bandwidths of 1 GHz or higher, combining local oscillator laser, photodetector, and/or fiber mixing. Development of telescopes should be submitted to a different subtopic (S12.03), unless the design is specifically a lidar component, such as a telescope integrated with other optics. Receivers for direct-detection wind lidar are not sought this year.

- New three-dimensional (3D) mapping and hazard detection lidar with compact and high-efficiency diode and fiber lasers to measure range and surface reflectance of planets or asteroids from >100 km altitude during mapping to <1 m during landing or sample collection, within size, weight, and power to fit into a CubeSat or smaller. New lidar technologies are sought that allow system reconfiguration in orbit, single-photon sensitivities and single beam for long-distance measurement, and variable dynamic range and multiple beams for near-range measurements. High-speed 2D scanners are also sought for single-beam lidars that enable wide scan angles with high repeatability and accuracy.

Relevance / Science Traceability:
The proposed subtopic addresses missions, programs, and projects identified by the Science Mission Directorate (SMD), including:

- Atmospheric water vapor: Profiling of tropospheric water vapor supports studies in weather and dynamics, radiation budget, clouds, and aerosol processes.
- Aerosols: Profiling of atmospheric aerosols and how aerosols relate to clouds and precipitation.
- Atmospheric winds: Profiling of wind fields to support studies in weather and atmospheric dynamics on Earth and atmospheric structure of planets.
- Topography: Altimetry to support studies of vegetation and the cryosphere of Earth, as well as the surface of planets and solar system bodies.
- Greenhouse gases: Column measurements of atmospheric gases, such as methane, that affect climate variability.
- Hydrocarbons: Measurements of planetary atmospheres.
- Gases related to air quality: Sensing of tropospheric ozone, nitrogen dioxide, or formaldehyde to support NASA projects in atmospheric chemistry and health effects.
- Automated landing, hazard avoidance, and docking: Technologies to aid spacecraft and lander maneuvering and safe operations.

References:

1. NASA missions are aligned with the National Research Council's decadal surveys, with the latest survey on earth science published in 2018 under the title "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space": http://sites.nationalacademies.org/DEPS/esas2017/index.htm
2. For planetary science, NASA missions are aligned with the National Research Council Decadal Survey titled "Planetary Science and Astrobiology Decadal Survey 2023-2032": https://www.nationalacademies.org/our-work/planetary-science-and-astrobiology-decadal-survey-2023-2032
3. Description of NASA lidar instruments and applications can be found at:
    - https://science.larc.nasa.gov/lidar/
    - https://science.gsfc.nasa.gov/sci/

S11.02 Technologies for Active Microwave Remote Sensing (SBIR)

Lead Center: JPL
Participating Center(s): GSFC

Scope Title: High-Efficiency Solid-State Power Amplifiers

Scope Description:

This subtopic supports technologies to aid NASA in its active microwave sensing missions. Specifically, we are seeking L- and/or S-band solid-state power amplifiers (SSPAs) to achieve a power-added efficiency (PAE) of >50% for 1 kW peak transmit power, through the use of efficient multidevice power combining techniques or other efficiency improvements. There is also a need for high-efficiency ultra-high-frequency (335 to 535 MHz) monolithic microwave integrated circuit (MMIC) power amplifiers, with saturated output power greater than 20 W, high efficiency of >70%, and gain flatness of 1 dB over the band.

Solid-state amplifiers that meet high efficiency (>50% PAE) requirements and have small form factors would be suitable for SmallSats, support single-satellite missions (such as RainCube), and enable future swarm techniques. No such devices at these high frequencies, high powers, and efficiencies are currently available. We expect a power amplifier with TRL 2 to 4 at the completion of the project.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Phase I: Provide research and analysis to advance scope concept as a final report.

Phase II: Design and simulation of 1-kW S-/L-band amplifiers with >50% PAE, with prototype.

State of the Art and Critical Gaps:
Advances in Surface Deformation and Change are strongly desired for Earth remote sensing, for land use, natural hazards, and disaster response. NASA-ISRO Synthetic Aperture Radar (NISAR) is a Flagship-class mission, but only able to revisit locations on ~weekly basis, whereas future constellation concepts, using SmallSats would decrease revisit time to less than 1 day, which is game changing for studying earthquake precursors and post relaxation. For natural hazards and disaster response, faster revisit times are critical. MMIC devices with high saturated output power in the few to several watts range and with high PAE (>50%) are desired.

Relevance / Science Traceability:
Surface Deformation and Change science is a continuing Decadal Survey topic, and follow-ons to the science desired for NISAR mission are already in planning. Cloud, water, and precipitation measurements increase capability of measurements to smaller particles and enable much more compact instruments.

References:

1. NISAR follow-on for Surface Deformation: https://science.nasa.gov/earth-science/decadal-sdc
2. Radar in a CubeSat (RainCube): https://www.jpl.nasa.gov/cubesat/missions/raincube.php
3. Global Atmospheric Composition Mission: https://www.nap.edu/read/11952/chapter/9
4. Global Precipitation Measurement Mission: https://www.nasa.gov/mission_pages/GPM/overview/index.html

Scope Title: Deployable Antenna Technologies

Scope Description:
Low-frequency deployable antennas for Earth and planetary radar sounders: antennas capable of being hosted by SmallSat/CubeSat platforms are required for missions to icy worlds, large/small body interiors (i.e., comets, asteroids), and for Earth at center frequencies from 5 to 100 MHz, with fractional bandwidths >=10%. Dual-frequency solutions or even tri-frequency solutions are desired; for example, an approximately 5- to 6-MHz band, with an approximately 85- to 95-MHz band. Designs need to be temperature tolerant; that is, not changing performance parameters drastically over flight temperature ranges of ~100 °C.

High-frequency (V-band) deployable antennas for SmallSats and CubeSats: Small-format, deployable antennas are desired (for 65 to 70 GHz) with an aperture size of ~1 m^2 that when stowed, fit into form factors suitable for SmallSats—with a desire for similar on the more-challenging CubeSat format. Concepts that remove, reduce, or control creases/seams in the resulting surface, on the order of a fraction of a wavelength at 70 GHz, are highly desired.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:
- Research
- Analysis
- Prototype

Desired Deliverables Description:
For both antenna types (low and high frequency) a paper design is desired for Phase I, and a prototype for Phase II. Concepts and prototypes for targeted advances in deployment technologies are welcome and do not need to address every need for mission-ready hardware.

State of the Art and Critical Gaps:
Low-frequency antennas, per physics, are large, and so are deployable, even for large spacecraft. For Small/CubeSats the challenges are to get enough of an antenna aperture with the proper length to achieve relatively high bandwidths. No such 10% fractional antenna exists for the Small/CubeSat form factors.

High-frequency antennas can often be hosted without deployment, but a ~1-m^2-diameter antenna on a Small/CubeSat is required to be deployable. A specific challenge for high-frequency deployable antennas is to deploy the aperture with enough accuracy such that the imperfections (i.e., residual folds, support ribs, etc.) are flat enough for antenna performance.

Relevance / Science Traceability:
Low-frequency-band antennas are of great interest to subsurface studies, such as those completed by MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) and SHARAD (Shallow Radar) for Mars, and planned for Europa by the REASON (Radar for Europa Assessment and Sounding: Ocean to Near-surface) on the Europa Clipper. Studying the subsurfaces of other icy worlds is of great interest to planetary science, as is tomography of small bodies such as comets and asteroids. Because of the impact of the ionosphere, low-frequency sounding of Earth is very challenging from space, but there is great interest in solutions to make this a reality. Lastly, such low-frequency bands are also of interest to radio astronomy, such as that being done for OLFAR, https://research.utwente.nl/files/5412596/OLFAR.pdf.

V-band deployable antennas are mission enabling for pressure sounding from space.

References:

For low-frequency deployables, see similar missions (on much larger platforms):

1. REASON: https://www.jpl.nasa.gov/missions/europa-clipper/
2. MARSIS: https://mars.nasa.gov/express/mission/sc_science_marsis01.html

For high-frequency deployables, see similar, but lower frequency mission:

1. RainCube: https://www.jpl.nasa.gov/cubesat/missions/raincube.php

Scope Title: Steerable Aperture Technologies

Scope Description:
Technologies enabling low-mass steerable technologies, especially for L- or S-bands—including, but not limited to—antenna or radio-frequency (RF) electronics, enabling steering: cross track +/-7° and along track +/-15°. This would enable a complete antenna system with a mass density of 10 kg/m^2 (or less) with a minimum aperture of 12 m^2.

Examples of different electronics solutions include completely integrated transmit/receive (TR) modules, with all control features for steering included; or alternatively, an ultra-compact TR module controller, which can control N modules, thus allowing reduction in size and complexity of the TR modules themselves.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:
Phase I: A paper study with analysis.

Phase II: Prototype of subcomponent.

State of the Art and Critical Gaps:
No technology currently exists for such low mass density for steerable arrays.

Relevance / Science Traceability:
Surface Deformation and Change science is a key Earth Science Decadal Survey topic.

References:

1. NISAR Mission: https://nisar.jpl.nasa.gov/
2. Surface Deformation and Change: https://science.nasa.gov/earth-science/decadal-sdc

Scope Title: Low-Power W-Band Transceiver

Scope Description:
Require a low-power compact W-band (monolithic integrated circuit or application-specific integrated circuit (ASIC) preferred) transceiver with up/down converters with excellent cancellers to use the same antenna for transmit and receive. Application is in space landing radar altimetry and velocimetry. Wide-temperature-

tolerant technologies are encouraged to reduce thermal control mass, either through designs insensitive to temperature changes or active compensation through feedback. Electronics must be tolerant to a high-radiation environment through design (rather than excessive shielding). In the early phases of this work, radiation tolerance must be considered in the semiconductor/materials choices, but it is not necessary to demonstrate radiation tolerance until later. For ocean worlds around Jupiter, bounding (worst-case) radiation rates are expected to be at less than 50 rad(Si)/sec—with minimal shielding—during the period of performance (landing or altimeter flyby), but overall total dose is expected to be in the hundreds of krad total ionizing dose (TID). Most cases will be less extreme in radiation.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:
Phase I: Paper study/design.

Phase II: Prototype.

State of the Art and Critical Gaps:
Low-power-consumption transceivers for W-band are critical for studies of atmospheric science, pressure sounding, and atmospheric composition for both Earth and planetary science. Such transceivers currently do not exist.

Relevance / Science Traceability:

- ACE ((Advanced Composition Explorer): https://solarsystem.nasa.gov/missions/ace/in-depth/
- Planetary Terminal Descent and Landing Radar Final Report: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19710011019.pdf

References:
Missions for atmospheric science and altimetry applications:

1. ACE: https://solarsystem.nasa.gov/missions/ace/in-depth/
2. Mars Science Laboratory: https://descanso.jpl.nasa.gov/monograph/series13/DeepCommo_Chapter8--141029.pdf

S11.03 Technologies for Passive Microwave Remote Sensing (SBIR)

Lead Center: GSFC
Participating Center(s): JPL

Scope Title: Components or Methods to Improve the Sensitivity, Calibration, or Resolution of Microwave/Millimeter-Wave Radiometers

Scope Description:
NASA requires novel solutions to challenges of developing stable, sensitive, and high-resolution radiometers and spectrometers operating from microwave frequencies to 1 THz. Novel technologies are requested to address challenges in the current state of the art of passive microwave remote sensing. Technologies could

improve the sensitivity, calibration, or resolution of remote-sensing systems or reduce the size, weight, and power (SWaP). Companies are invited to provide unique solutions to problems in this area. Possible technologies could include:

- Low-noise receivers at frequencies up to 1 THz.
- Solutions to reduce system 1/f noise over time periods greater than 1 sec.
- Internal calibration systems or methods to improve calibration repeatability over time periods greater than days or weeks.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Research
- Analysis
- Software

Desired Deliverables Description:
Research, analysis, software, or hardware prototyping of novel components or methods to improve the performance of passive microwave remote sensing.

- Depending on the complexity of the proposed work, Phase I deliverables may include a prototype system or a study.
- Phase II deliverables should include a prototype component or system with test data verifying functionality.

State of the Art and Critical Gaps:
Depending on frequency, current passive microwave remote-sensing instrumentation is limited in sensitivity (as through system noise, 1/f noise, or calibration uncertainty), resolution, or in SWaP. Critical gaps depend on specific frequency and application.

Relevance / Science Traceability:
Critical need: Creative solutions to improve the performance of future Earth-observing, planetary, and astrophysics missions. The wide range of frequencies in this scope are used for numerous science measurements such as Earth science temperature profiling, ice cloud remote sensing, and planetary molecular species detection.

References:

1. Ulaby, Fawwaz; and Long, David: *Microwave radar and radiometric remote sensing*, Artech House, 2015.

Scope Title: Advanced Digital Electronic or Photonic Systems Technology for Microwave Remote Sensing

Scope Description:
Technology critical to increasing the utility of microwave remote sensing based on photonic (or other novel analog) systems, application-specific integrated circuits (ASICs), and field programmable gate arrays (FPGAs) are showing great promise. This topic solicits proposals for such systems or subsystems to process microwave signals for passive remote-sensing applications for spectrometry or total power radiometry. Example applications include:

- Photonic (or other analog) systems for spectrometers, beam-forming arrays, correlation arrays, oscillators, noise sources, and other active or passive microwave instruments having size, weight, and power (SWaP) or performance advantages over digital technology.
- ASIC-based solutions for digital beam forming, creating one or more beams to replace mechanically scanned antennas.
- Digitizers for spectrometry starting at 20 Gsps, 20 GHz bandwidth, 4 or more-bit resolution, and simple interface to a FPGA.
- ASIC implementations of polyphase spectrometer digital signal processing with ~1 W/GHz; 10-GHz-bandwidth polarimetric spectrometer with 1,024 channels; and radiation-hardened and minimized power dissipation.

All systems or subsystems should also focus on low-power, radiation-tolerant broad-band microwave spectrometers for NASA applications. Proposals should compare predicted performance and SWaP to conventional radio-frequency and digital-processing methods.

NOTE: Proposers for specific photonic integrated circuit (PIC) technology should instead see related STTR subtopic T8.07.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Demonstration of novel subsystem or system to enable increased capability in passive microwave remote-sensing instruments. Photonic systems specifically are low-TRL emerging technologies, so offerors are encouraged to identify and propose designs where photonic technology would be most beneficial. For electronic solutions, low-power spectrometer (or other application in the Scope Description) for an ASIC or other component that can be incorporated into multiple NASA microwave remote-sensing instruments.

- Depending on the complexity of the proposed work, Phase I deliverables may include a prototype system or a study.
- Phase II deliverables should include a prototype component or system with test data verifying functionality.

State of the Art and Critical Gaps:

- Photonic systems for microwave remote sensing are an emerging technology not used in current NASA microwave missions, but they may enable significant increases in bandwidth or reduction in SWaP. Again, state-of-the-art digital electronic solutions typically consume many watts of power.
- Digital beamforming: most digital beamforming applications have focused on either specific narrowband approaches for commercial communications or military radars. NASA needs solutions that consume low power and operate over wide bandwidths.
- Digitizers: High-speed digitizers exist but have poorly designed output interfaces. Specifically designed ASICs could reduce this power by a factor of 10, but pose challenges in design and radiation tolerance. A low-power solution could be used in a wide range of NASA remote-sensing applications.

- Spectrometers: The state of the art is currently the use of conventional microwave electronics for frequency conversion and filtering for spectrometers. Wideband spectrometers still generally require over 10 W. Current FPGA-based spectrometers require ~10 W/GHz and are not flight qualifiable.

Relevance / Science Traceability:
Photonic systems may enable significantly increased bandwidth of Earth-viewing, astrophysics, and planetary science missions. In particular, this may allow for increased bandwidth or resolution receivers, with applications such as hyperspectral radiometry.

Broadband spectrometers are required for Earth-observing, planetary, and astrophysics missions. The rapid increase in speed and reduction in power per gigahertz in the digital realm of digital spectrometer capability is directly applicable to planetary science and enables radio-frequency interference (RFI) mitigation for Earth science.

References:

1. Ulaby, Fawwaz; and Long, David: *Microwave radar and radiometric remote sensing*, Artech House, 2015.
2. Chovan, Jozef; and Uherek, Frantisek: "Photonic Integrated Circuits for Communication Systems," *Radioengineering*, vol. 27, issue 2, pp. 357-363, June 2018.
3. S. Pulipati et al.: "Xilinx RF-SoC-based Digital Multi-Beam Array Processors for 28/60 GHz Wireless Testbeds," Moratuwa Engineering Research Conference (MERCon), Moratuwa, Sri Lanka, July 2020.
4. Johnson, Joel T. et al.: "Real-Time Detection and Filtering of Radio Frequency Interference Onboard a Spaceborne Microwave Radiometer: The CubeRRT Mission," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 13, pp. 1610-1624, 2020.
5. Le Vine, David M.: "RFI and Remote Sensing of the Earth from Space," *Journal of Astronomical Instrumentation* 8.01, 2019, https://ntrs.nasa.gov/citations/20170003103

Scope Title: Deployable Antenna Apertures at Frequencies up to Millimeter Wave

Scope Description:
Deployable antenna apertures are required for a wide range of NASA passive remote-sensing applications from SmallSat platforms. Current deployable antenna technology is extremely limited above Ka-band. NASA requires low-loss deployable antenna apertures at frequencies up to 200 GHz or beyond. Deployed aperture diameters of 0.5 m or larger are desired, but proposers are invited to propose concepts for smaller apertures at higher frequencies.

NASA also requires low-loss broad-band deployable or compact antenna feeds with bandwidths of two octaves. Frequencies of interest start at 500 MHz. Loss should be as low as possible (less than 1%). The possibility of thermal control is desired to improve system calibration stability.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Phase I deliverables should consist of analysis and potential prototyping of key enabling technologies.

Phase II deliverables should include a deployable antenna prototype.

State of the Art and Critical Gaps:
Current low-loss deployable antennas are limited to Ka-band. Deployable apertures at higher frequencies are required for a wide range of applications, as aperture size is currently an instrument size, weight, and power (SWaP) driver for many applications up to 200 GHz.

Relevance / Science Traceability:
Antennas at these frequencies are used for a wide range of passive and active microwave remote sensing, including measurements of water vapor and temperature.

References:

1. Passive remote sensing such as performed by the Global Precipitation Mission (GPM) Microwave Imager (GMI): https://gpm.nasa.gov/missions/GPM/GMI
2. Chahat, N. et al.: "Advanced CubeSat Antennas for Deep Space and Earth Science Missions: A review," *IEEE Antennas and Propagation Magazine*, vol. 61, no. 5, pp. 37-46, Oct. 2019, doi: 10.1109/MAP.2019.2932608.

S11.04 Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter (SBIR)

Lead Center: JPL
Participating Center(s): ARC, GSFC, LaRC

Scope Title: Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter

Scope Description:
NASA is seeking new technologies or improvements to existing technologies to meet the detector needs of future missions, as described in the most recent decadal surveys (links are external):

- Earth Science and Applications from Space (2018 Decadal):http://www.nap.edu/catalog/11820.htmlhttps://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth
- Vision and Voyages for Planetary Science in the Decade 2013-2022: https://solarsystem.nasa.gov/resources/598/vision-and-voyages-for-planetary-science-in-the-decade-2013-2022/
- New Worlds, New Horizons in Astronomy and Astrophysics: https://www.nap.edu/catalog/12951/new-worlds-new-horizons-in-astronomy-and-astrophysics

Please note:

1. Technologies for visible detectors are not being solicited this year.
2. Technologies for lidar detectors are not being solicited this year.
3. For FY 2022 emphasis will be placed on Earth-Science-related technologies (infrared (IR) and far-IR detectors and technologies).

Low-power and low-cost readout integrated electronics:

- Photodiode arrays: In-pixel digital readout integrated circuit (DROIC) for high-dynamic-range IR imaging and spectral imaging (10 to 60 Hz operation) focal plane arrays to circumvent the limitations in charge well capacity, by using in-pixel digital counters that can provide orders-of-magnitude larger effective well depth, thereby affording longer integration times.

- Microwave kinetic inductance detector/transition-edge sensor (MKID/TES) detectors: A radiation-tolerant, digital readout system is needed for the readout of low-temperature detectors such as MKIDs or other detector types that use microwave-frequency-domain multiplexing techniques. Each readout channel of the system should be capable of generating a set of at least 1,500 carrier tones in a bandwidth of at least 1 GHz with 14-bit precision and 1-kHz frequency placement resolution. The returning-frequency multiplexed signals from the detector array will be digitized with at least 12-bit resolution. A channelizer will then perform a down-conversion at each carrier frequency with a configurable decimation factor and maximum individual subchannel bandwidth of at least 50 Hz. The power consumption of a system consisting of multiple readout channels should be at most 20 mW per subchannel or 30 W per 1-GHz readout channel. That requirement would most likely indicate the use of a radio-frequency (RF) system on a chip (SoC) or application-specific integrated circuit (ASIC) with combined digitizer and channelizer functionality.
- Bolometric arrays: Low-power, low-noise, cryogenic multiplexed readout for large-format two-dimensional (2D) bolometer arrays with 1,000 or more pixels, operating at 65 to 350 mK. We require a superconducting readout capable of reading 2 TES per pixel within a 1 mm^2 spacing. The wafer-scale readout of interest will be capable of being indium-bump bonded directly to 2D arrays of membrane bolometers. We require row and column readout with very low crosstalk, low read noise, and low detector noise-equivalent power degradation.

Far-IR/submillimeter-wave detectors:

- Novel materials and devices**:** New or improved technologies leading to measurement of trace atmospheric species (e.g., CO, CH_4, N_2O) or broadband energy balance in the IR and far-IR from geostationary and low-Earth orbital platforms. Of particular interest are new direct detector or heterodyne detector technologies made using high-temperature superconducting films (e.g., thin-film YBCO, MgB_2, or multilayered engineered superconductors with tunable critical temperature) or engineered semiconductor materials, especially 2D electron gas (2DEG) and quantum wells (QW).
- Array receivers**:** Development of a robust wafer-level packaging/integration technology that will allow high-frequency-capable interconnects and allow two dissimilar substrates (i.e., silicon and GaAs) to be aligned and mechanically "welded" together. Specially develop ball grid and/or through-silicon via (TSV) technology that can support submillimeter-wave (frequency above 300 GHz) arrays. Compact and efficient systems for array receiver calibration and control are also needed.
- Receiver components: Development of advanced terahertz receiver components is desired. Such components include:
    - Novel concepts for room-temperature-operated receivers for Earth science with competitive noise performance (goal of 5 times the quantum limit in the 500 to1,200 GHz range).
    - Local oscillators capable of spectral coverage 2 to 5 THz, output power up to >2 mW, frequency agility with >1 GHz near chosen terahertz frequency, and continuous phase-locking ability over the terahertz-tunable range with <100-kHz line width. Both solid-state (low-parasitic Schottky diodes) as well as quantum cascade lasers (for f > 2 THz).
    - Components and devices such as mixers, isolators, and orthomode transducers, working in the terahertz range, that enable future heterodyne array receivers.
    - Novel receiver architectures such as single-sideband heterodyne terahertz receivers and high-precision measurement accuracy for multiple lines.
    - ASIC-based SoC solutions are needed for heterodyne receiver backends. ASICs capable of binning >6 GHz intermediate frequency bandwidth into 0.1- to 0.5-MHz channels with low power dissipation (<0.5 W) would be needed for array receivers.
    - Novel quasi-optical devices for terahertz beam multiplexing for a large (16+) number of pixels with >20% bandwidth.
    - Low-power, low-noise intermediate-frequency (IF) amplifiers that can be used for array receivers. Both cryogenic as well as room temperature operated.

  - Novel concepts for terahertz preamplifiers from 300 GHz to 5 THz.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype

Desired Deliverables Description:
For Phase I activities the deliverables are nominally feasibility studies, detailed design, or determination of the trade space and detailed optimization of the design, as described in a final report. In some circumstances simple prototype models for the hardware can be demonstrated and tested.

For Phase II studies a working prototype that can be tested at one of the NASA centers is highly desirable.

State of the Art and Critical Gaps:
Efficient multipixel readout electronics are needed both for room-temperature operation as well as cryogenic temperatures. We can produce millions-of-pixel detector arrays at IR wavelengths up to about 14 µm, only because there are ROICs available on the market. Without these, high-density, large-format IR arrays such as quantum well IR photodetectors, HgCdTe, and strained-layer superlattices would not exist. The Moore's Law corollary for pixel count describes the number of pixels for the digital camera industry as growing in an exponential manner over the past several decades, and the trend is continuing. The future of long-wave detectors is moving toward tens of thousands of pixels and beyond. Readout circuits capable of addressing their needs do not exist, and without them the astronomical community will not be able to keep up with the needs of the future. These technology needs must be addressed now, or we are at risk of being unable to meet the science requirements of the future:

- Commercially available ROICs typically have well depths of less than 10 million electrons.
- 6- to 9-bit, ROACH-2 board solutions with 2,000 bands, <10 kHz bandwidth in each are state of the art (SOA).
- IR detector systems are needed for Earth imaging based on the recently released Earth Decadal Survey.
- Direct detectors with D ~ 10^9 cm-rtHz/W achieved in this range. Technologies with new materials that take advantage of cooling to the 30 to 100 K range are capable of D ~ 10^{12} cm-rtHz/W. Broadband (>15%) heterodyne detectors that can provide sensitivities of 5× to 10× the quantum limit in the submillimeter-wave range while operating at 30 to 77 K are an improvement in the SOA because of the higher operating temperature.
- Detector array detection efficiency <20% at 532 nm (including fill factor and probability of detection) for low-after-pulsing, low-dead-time designs is SOA.
- Far-IR bolometric heterodyne detectors are limited to 3-dB gain bandwidth of around 3 GHz. Novel superconducting material such as MgB_2 can provide significant enhancement of up to 9 GHz IF bandwidth.
- Cryogenic low-noise amplifiers (LNAs) in the 4 to 8 GHz bandwidth with thermal stability are needed for focal plane arrays, Origins Space Telescope (OST) instruments, Origins Survey Spectrometers (OSSs), MKIDs, far-IR imagers and polarimeters (FIPs), Heterodyne Instrument on OST (HERO), and the Lynx Telescope. DC power dissipation should be only a few milliwatts.
- Another frequency range of interest for LNAs is 0.5 to 8.5 GHz. This is useful for HERO. Other NASA systems in the Space Geodesy Project (SGP) would be interested in bandwidths up to 2 to 14 GHz.
- 15 to 20 dB gain and <5 K noise over the 4 to 8 GHz bandwidth has been demonstrated.

- Currently, all space-borne heterodyne receivers are single pixel. Novel architectures are needed for ~100-pixel arrays at 1.9 THz.
- The current SOA readout circuit is capable of reading 1 TES per pixel in a 1-mm^2 area. 2D arrays developed by NIST have been a boon for current NASA programs. However, NIST has declined to continue to produce 2D circuits or to develop one capable of a 2-TES-per-pixel readout. This work is extremely important to NASA's filled, kilopixel bolometer array program.
- 2D cryogenic readout circuits are analogous to semiconductor ROICs operating at much higher temperatures. We can produce detector arrays of millions-of-pixels at IR wavelengths up to about 14 µm, only because there are ROICs available on the market. Without these, high-density, large-format IR arrays such as quantum well infrared photodiode, HgCdTe, and strained-layer superlattices would not exist.

Relevance / Science Traceability:

- Future short-, mid-, and long-wave IR Earth science and planetary science missions all require detectors that are sensitive and broadband with low power requirements.
- Future astrophysics instruments require cryogenic detectors that are supersensitive and broadband and provide imaging capability (multipixel).
- Aerosol spaceborne lidar as identified by the 2017 decadal survey to reduce uncertainty about climate forcing in aerosol-cloud interactions and ocean ecosystem carbon dioxide uptake. Additional applications in planetary surface mapping, vegetation, and trace-gas lidar.
- Earth radiation budget measurement per 2007 decadal survey Clouds and Earth's Radiant Energy System (CERES) Tier-1 designation to maintain the continuous radiation budget measurement for climate modeling and better understand radiative forcings.
- Astrophysical missions such as OST will need IR and far-IR detector and related technologies.
- LANDSAT Thermal InfraRed Sensor (TIRS), Climate Absolute Radiance and Refractivity Observatory (CLARREO), BOReal Ecosystem Atmosphere Study (BOREAS), Methane Trace Gas Sounder, or other IR Earth-observing missions.
- Current science missions utilizing 2D, large-format cryogenic readout circuits:
    - HAWC + (High Resolution Airborne Wideband Camera Upgrade) for SOFIA (Stratospheric Observatory for Infrared Astronomy) future missions
    - PIPER (Primordial Inflation Polarization Experiment), balloon-borne.
    - PICO (Probe of Inflation and Cosmic Origins), a probe-class cosmic microwave background mission concept.

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S11.05 Suborbital Instruments and Sensor Systems for Earth Science Measurements (SBIR)

Lead Center: LaRC
Participating Center(s): ARC, GSFC, JPL

Scope Title: Sensors and Sensor Systems Targeting Trace Gases

Scope Description:
Earth science measurements from space are considerably enhanced by observations from generally much less costly suborbital instruments and sensor systems. These instruments and sensors support NASA's Earth Science Division science, calibration/validation and environmental monitoring activities by providing ancillary data for satellite calibration and validation; algorithm development/refinement; and finer-scale process studies. NASA seeks measurement capabilities that support current satellite and model validation, advancement of surface-based remote-sensing networks, and targeted Airborne Science Program and ship-based field campaign activities as discussed in the ROSES solicitation. Data from such sensors also inform process studies to improve our scientific understanding of the Earth system. In-situ sensor systems (air-, land-, and water-based) can comprise stand-alone instrument and data packages; instrument systems configured for integration on ship-based (or alternate surface-based platform) and in-water deployments, NASA's Airborne Science aircraft fleet or commercial providers, un-crewed aircraft systems (UAS), balloons, and ground networks; or end-to-end solutions providing needed data products from mated sensor and airborne/surface/subsurface platforms. An important goal is to create sustainable measurement capabilities to support NASA's Earth Science objectives, with infusion of new technologies and systems into current/future NASA research programs. Instrument prototypes as a deliverable in Phase II proposals and/or field demonstrations are highly encouraged.

Complete instrument systems are generally desired, including features such as remote/unattended operation and data acquisition, and minimum size, weight, and power consumption. All proposals must summarize the current state of the art and demonstrate how the proposed sensor or sensor system represents a significant improvement over the state of the art.

Specific desired sensors or subsystems include:

- Small, lightweight, turn-key trace in situ gas measurement sensors with 1 to 10 Hz time response that are suitable for small aircraft, UAV, or balloon deployment and capable of detecting:
    - NO_x, NO_y, CH_2O, O_3, benzene, toluene at <5% uncertainty.
    - CO, CH_4, OCS, N_2O at <1% uncertainty.
    - SO_2 at <100 parts per trillion by volume (pptv) uncertainty.

  where these uncertainties apply to measurements made on airborne platforms under flight conditions (variable ambient pressure and temperature).
- Small, turn-key spectrometer-based Sun photometer sensors capable of detecting NO_2, CH_2O, and O_3, at <5% uncertainty. These sensors must be capable of long-term measurements to support NASA ground networks. Improved performance Sun and sky viewing spectrometer subsystems that increase measurement accuracy and stability and simplify instrument calibration of Sun photometers may be considered. Potential improvements are wavelength stability (<100 pm/°C) and reduced stray light ($<10^{-4}$).
- Real-time, 0.1 to 1 Hz gas-phase radioisotopic (especially radiocarbon) measurements suitable for distinguishing emissions sources and for deployment on aircraft or UAVs.
- Airborne-capable bulk or film retroreflector subsystems that advance NASA open-path trace-gas measurements (similar to the widely used NASA LaRC Diode Laser Hygrometer). Operational at wavelengths between 2 and 12 µm, or some subset of wavelengths within that range, with low return light cone divergence (<2°).
- Low-volume (<0.1 L) multi-pass cell spectrometer subsystems that advance NASA extractive trace-gas measurements. Operational at wavelengths 2 to 5 µm or greater with pathlengths of 50+ meters.
- Aircraft static-air-temperature sensor measurements to better than 0.1 °C accuracy under upper troposphere-lower stratosphere conditions.
- In situ spectrometer instruments for measuring atmospheric trace gases (ozone, NO_2, IO) from fixed platforms, ships, and small autonomous surface vessels. The instrument requirements are: Low-power operation modes; portability; autonomous operation: active, fast, and precise pointing for targeting Sun or Moon while gathering data; absolute radiometric calibration conservation, user-friendly field tools for the validation of the optical characterization of the system such as radiometric and spectral calibration and field of view (FOV); very low straylight and low electrical noise with capability to monitor and account for the electrical noise; wide dynamic range with capabilities of measuring low and high light intensities with the same optics (Sun, Moon, sky, and reflective surfaces); broad UV-vis-IR (ultraviolet-visible-infrared) spectral range with 0.6 nm spectral resolution for trace gases; capability of operating on fixed and moving ocean platforms; and auxiliary environmental sensors (site temperature, humidity, and pressure).
- Innovative, high-value sensors directly targeting a stated NASA need (including aerosols, clouds, and ocean) may also be considered. Proposals responding to this specific bullet are strongly encouraged to identify at least one relevant NASA subject matter expert.

Expected TRL or TRL Range at completion of the Project: 4 to 7

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

The ideal Phase I proposal would demonstrate a clear idea of the problem to be solved, potential solutions to this problem, and an appreciation for potential risks or stumbling blocks that might jeopardize the success of the Phase I and II projects. The ideal Phase I effort would then address and hopefully overcome any major challenges to (1) demonstrate feasibility of the proposed solution and (2) clear the way for the Phase II effort. These accomplishments would be detailed in the Phase I final report and serve as the foundation for a Phase II proposal.

The ideal Phase II effort would build, characterize, and deliver a prototype instrument to NASA including necessary hardware and operating software. The prototype would be fully functional, but the packaging may be more utilitarian (i.e., less polished) than a commercial model.

State of the Art and Critical Gaps:
The subtopic is and remains highly relevant to NASA Science Mission Directorate (SMD) and Earth Science research programs, in particular the Earth Science Atmospheric Composition, Climate Variability & Change, and Carbon Cycle and Ecosystems focus areas. Suborbital in situ and remote sensors sensors inform NASA ground, ship, and airborne science campaigns led by these programs and provide important validation of the current and next generation of satellite-based sensors (e.g., PACE, OCO-2, TEMPO, GLIMR, SBG, A-CCP; see links in References). The solicited measurements will be highly relevant to current and future NASA campaigns with objectives and observing strategies similar to past campaigns (e.g., ACTIVATE, NAAMES, EXPORTS, CAMP2EX, FIREX-AQ, KORUS-AQ, and DISCOVER-AQ; see links in References).

Relevance / Science Traceability:
The subtopic is and remains highly relevant to NASA SMD and Earth Science research programs, in particular the Earth Science Atmospheric Composition, Weather and Atmospheric Dynamics, Climate Variability & Change, Carbon Cycle and Ecosystems, and Earth Surface and Interior focus areas. In situ and ground-based sensors inform NASA ship and airborne science campaigns led by these programs and provide important validation of the current and next generation of satellite-based sensors (e.g., PACE, OCO-2, TEMPO, GLIMR, SBG, A-CCP; see links in References). The solicited measurements will be highly relevant future NASA campaigns with objectives and observing strategies similar to past campaigns (e.g., NAAMES, EXPORTS, CAMP2EX, FIREX-AQ, KORUS-AQ, DISCOVER-AQ; see links in References). The need horizon of the subtopic sensors and sensors systems is both near-term (<5 yr) and midterm (5 to 10 yr).

Relevant Programs and Program Officers include:

- NASA ESD Ocean Biology and Biogeochemistry Program (Laura Lorenzoni, HQ Program Manager).
- NASA ESD Tropospheric Composition Program (Barry Lefer, HQ Program Manager).
- NASA ESD Radiation Sciences Program (Hal Maring, HQ Program Manager).
- NASA ESD Weather and Atmospheric Dynamics Program (Amber Emory, HQ Program Manager).
- NASA ESD Earth Surface and Interior Program (Ben Phillips and Kevin Reath, HQ Program Managers).
- NASA ESD Airborne Science Program (Bruce Tagg, HQ Program Manager).

References:
Relevant current and past satellite missions and field campaigns include:

1. ACTIVATE focuses on studying the atmosphere over the western North Atlantic Ocean and sample its broad range of aerosol, cloud, and meteorological conditions using joint flights with two aircraft based at NASA's Langley Research Center: https://activate.larc.nasa.gov/
2. Decadal Survey Recommended ACCP Mission (now named Atmos) focusing on aerosols, clouds, convection, and precipitation: https://science.nasa.gov/earth-science/decadal-surveys
3. TEMPO Satellite Mission focusing on geostationary observations of air quality over North America: http://tempo.si.edu/overview.html
4. CAMP2Ex airborne field campaign focusing on tropical meteorology and aerosol science: https://espo.nasa.gov/camp2ex

5. FIREX-AQ airborne and ground-based field campaign targeting wildfire and agricultural burning emissions in the United States: https://www.esrl.noaa.gov/csd/projects/firex-aq/
6. GLIMR Satellite Mission focusing on geostationary observations of coastal waters and ocean productivity, land-to-sea carbon fluxes, and harmful algal blooms along the U.S. coast and other regions of interest off South America and the Caribbean Sea: https://www.nasa.gov/press-release/nasa-targets-coastal-ecosystems-with-new-space-sensor
7. KORUS-AQ airborne and ground-based field campaign focusing on pollution and air quality in the vicinity of the Korean Peninsula: https://espo.nasa.gov/korus-aq/content/KORUS-AQ
8. DISCOVER-AQ airborne and ground-based campaign targeting pollution and air quality in four areas of the United States: https://discover-aq.larc.nasa.gov/
9. NAAMES Earth Venture Suborbital field campaign targeting the North Atlantic phytoplankton bloom cycle and impacts on atmospheric aerosols, trace gases, and clouds: https://naames.larc.nasa.gov
10. AToM airborne field campaign mapping the global distribution of aerosols and trace gases from pole to pole: https://espo.nasa.gov/atom/content/ATom
11. PACE Satellite Mission, scheduled to launch in 2022, that focuses on observations of ocean biology, aerosols, and clouds: https://pace.gsfc.nasa.gov/
12. EXPORTS field campaign targeting the export and fate of upper ocean net primary production using satellite observations and surface-based measurements: https://oceanexports.org
13. OCO-2 Satellite Mission that targets spaceborne observations of carbon dioxide and the Earth's carbon cycle: https://www.nasa.gov/mission_pages/oco2/index.html.
14. Decadal Survey Planetary Boundary Layer (PBL) Incubation Study: https://science.nasa.gov/earth-science/decadal-pbl
15. Decadal Survey Surface Topography and Vegetation (STV) Incubation Study: https://science.nasa.gov/earth-science/decadal-stv

S12.06 Detector Technologies for Ultraviolet (UV), X-Ray, and Gamma-Ray Instruments (SBIR)

Lead Center: JPL
Participating Center(s): GSFC, MSFC

Scope Title: Detectors

Scope Description:
This subtopic covers detector requirements for a broad range of wavelengths from ultraviolet (UV) through to gamma ray for applications in Astrophysics, Earth Science, Heliophysics, and Planetary Science. Requirements across the board are for greater numbers of readout pixels, lower power, faster readout rates, greater quantum efficiency, single photon counting, and enhanced energy resolution. The proposed efforts must be directly linked to a requirement for a NASA mission. These include Explorers, Discovery, Cosmic Origins, Physics of the Cosmos, Solar-Terrestrial Probes, Vision Missions, and Decadal Survey missions. Proposals should reference current NASA missions and mission concepts where relevant. Specific technology areas are:

- Large-format, solid-state single-photon-counting radiation-tolerant detectors in charge-coupled device (CCD) or complementary metal-oxide-semiconductor (CMOS) architecture—including 3D stacked architecture—for astrophysics, planetary, and UV heliophysics missions. Detectors with fast readout that can support high count rates and large incident flux from the extreme UV (EUV) and x-rays for heliophysics applications, especially solar-flare measurements.
- Solid-state detectors with polarization sensitivity relevant to astrophysics as well as planetary and Earth science applications; for example, in spectropolarimetry as well as air quality and aerosol monitoring.
- Solid-state detector arrays (2x128) with high sensitivity from 120 to 350 nm in one semiconductor chip; in particular, higher quantum efficiency (QE) and lower dark current than currently available

silicon devices for this wavelength range. The active area of the photodiode should not exceed 40 µm in the 128-element direction, but it can be larger in the cross-array direction. To minimize noise from stray capacitance, the first stage of amplification shall be integrated on the same chip directly adjacent to the photodiode area, in an active pixel sensor configuration with at least three transistors to enable multiplexing between individual pixels. The design shall be amenable to scaling to smaller pixel sizes and larger format two-dimensional arrays in the future.

- UV detectors for O_3, NO_2, SO_2, H_2S, and ash detection. Refer to National Research Council's Earth Science Decadal Survey (2018).
- Supporting technologies that would enable the next-generation x-ray Observatory (Flagship- and Probe-class) that may require the development of x-ray microcalorimeter arrays with much larger field of view, ~10^5 to 10^6 pixels, of pitch ~25 to 100 µm, and ways to read out the signals. For example, modular superconducting magnetic shielding is sought that can be extended to enclose a full-scale focal plane array. All joints between segments of the shielding enclosure must also be superconducting. Improved long-wavelength blocking filters are needed for large-area, x-ray microcalorimeters.
- Significant improvement in wide-band-gap semiconductor materials (such as AlGaN, ZnMgO, and SiC), individual detectors, and detector arrays for astrophysics missions and planetary science composition measurements. For example, SiC avalanche photodiodes (APDs) must show:
    - EUV photon counting, a linear mode gain $>10\times10^6$ at a breakdown reverse voltage between 80 and 100 V.
    - Detection capability of better than 6 photons/pixel/sec down to 135 nm wavelength.
- Solar-blind (visible-blind) UV, far-UV (80 to 200 nm), and EUV sensor technology with high pixel resolution, large format, high sensitivity and high dynamic range, and low voltage and power requirements—with or without photon counting.
- UV detectors suitable for upcoming ultra-high-energy cosmic ray (UHECR) mission concepts.
- Solar x-ray detectors with small independent pixels (10,000 count/sec/pixel) over an energy range from <5 to 300 keV.
- Filters with supporting grids are sought that, in addition to increasing filter strength, also enhance electromagnetic interference (EMI) shielding (1 to 10 GHz) and thermal uniformity for decontamination heating. X-ray transmission of greater than 80% at 600 eV per filter is sought, with infrared transmissions less than 0.01% and UV transmission of less than 5% per filter. A means of producing filter diameters as large as 10 cm should be considered.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Phase I deliverables: results of tests and analysis of designs, as described in a final report.

Phase II deliverables: prototype hardware or hardware for further testing and evaluation is desired.

State of the Art and Critical Gaps:
This subtopic aims to develop, and advance detector technologies focused on UV, x-ray, and gamma-ray spectral ranges. The science needs in this range span a number of fields, focusing on astrophysics, planetary

science, and UV heliophysics. A number of solid-state detector technologies promise to surpass the traditional image-tube-based detectors. Silicon-based detectors leverage enormous investments and promise high-performance detectors, and more complex materials such as gallium nitride and silicon carbide offer intrinsic solar blind response. This subtopic supports efforts to advance technologies that significantly improve the efficiency, dynamic range, noise, radiation tolerance, spectral selectivity, reliability, and manufacturability in detectors.

Relevance / Science Traceability:
NASA Science Mission Directorate (SMD) applications:

- NASA Astrophysics: https://science.nasa.gov/astrophysics/
- The Explorers Program: https://explorers.gsfc.nasa.gov/
- Planetary Missions Program Office: https://www.nasa.gov/planetarymissions/index.html
- Heliophysics: https://science.nasa.gov/heliophysics

Missions under study (Large Ultraviolet Optical Infrared Surveyor (LUVOIR), Habitable Exoplanet Observatory (HabEx), Lynx, and New Frontiers-Io Observer):

- LUVOIR—Large UV/Optical/IR Surveyor: https://asd.gsfc.nasa.gov/luvoir/
- Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/
- The LYNX Mission Concept: https://wwwastro.msfc.nasa.gov/lynx/
- Lunar Science/Missions: UV spectroscopy to understand Lunar water cycle and minerology (water detection using edge at 165 nm, H_2 at 121.6 nm, and OH^- at 308 nm); LRO-LAMP (Lyman Alpha Mapping Project).
- Gravitational Wave Science: Swift detection of X-ray and UV counterparts of gravitation wave sources; Dorado mission to detect early UV counterpart.
- Planetary Science: Europa Clipper (water/plume detection); Enceladus; Venus (sulfur lines in the 140 to 300 nm range).
- Earth Science: ozone mapping, pollution studies.

References:

1. About Cosmic Origins (COR): https://cor.gsfc.nasa.gov/
2. Explorers and Heliophysics Projects Division (EHPD): https://ehpd.gsfc.nasa.gov/
3. NASA Astrophysics Roadmap: https://science.nasa.gov/science-committee/subcommittees/nac-astrophysics-subcommittee/astrophysics-roadmap
4. Planetary Science Decadal Survey 2013-2022: "Vision and Voyages for Planetary Science in the Decade 2013-2022," http://solarsystem.nasa.gov/2013decadal
5. Decadal Survey: "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space (2018)," https://science.nasa.gov/earth-science/decadal-surveys

S13.05 In Situ Instruments/Technologies for Lunar and Planetary Science (SBIR)

Lead Center: JPL
Participating Center(s): ARC, GRC, GSFC, MSFC

Scope Title: In Situ Instruments/Technologies for Planetary Science

Scope Description:
This subtopic solicits development of advanced instrument technologies and components suitable for deployment on in situ planetary and lunar missions. These technologies must be capable of withstanding operation in space and planetary environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance—for both conventional missions as well as for small-satellite missions. In addition, technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific

measurements are solicited. For examples of NASA science missions, see https://science.nasa.gov/missions-page. For details of the specific requirements see the National Research Council report "Vision and Voyages for Planetary Science in the Decade 2013-2022" (http://solarsystem.nasa.gov/2013decadal/, hereafter referred to as the Planetary Decadal Survey). Of particular interest are technologies to support future missions under the New Frontiers and Discovery programs.

Specifically, this subtopic solicits instrument development that provides significant advances in the following areas, broken out by planetary body:

- Mars:
    - Subsystems relevant to current in situ instrument needs (e.g., lasers and other light sources from UV to microwave, x-ray and ion sources, detectors, mixers, mass analyzers, and front-end ion/neutrals separation/transport technologies, etc.) or electronics technologies (e.g., field-programmable gate array (FPGA) and application-specific integrated circuit (ASIC) implementations, advanced array readouts, miniature high-voltage power supplies).
    - Technologies that support high-precision in situ measurements of the elemental, mineralogical, and organic composition of planetary materials.
    - Conceptually simple, low-risk technologies for in situ sample extraction and/or manipulation including fluid and gas storage, pumping, and chemical labeling to support analytical instrumentation.
    - Seismometers, mass analyzers, technologies for heat flow probes, and atmospheric trace gas detectors. Improved robustness and g-force survivability for instrument components, especially for geophysical network sensors, seismometers, and advanced detectors (intensified charge-coupled devices (iCCDs), photomultiplier tube (PMT) arrays, etc.).
    - Instruments geared towards rock/sample interrogation prior to sample return. Sensors to measure dimensions of laser ablation pits in natural rock samples with unprepared rough surfaces to support geochronology measurements on rock samples collected by a rover (spatial and depth resolution of 10 µm or better from a working distance of tens of centimeters desired to characterize ~1-mm-deep by ~0.5-mm-wide pits).
    - Technologies, concepts, or components related to active source imaging systems (e.g., light detection and ranging; lidar) for accurate and precise mobile 3D terrain mapping and navigation, with additional sensor capabilities such as velocimetry.
- Venus:
    - Sensors, mechanisms, and environmental chamber technologies for operation in Venus's high-temperature, high-pressure environment with its unique atmospheric composition.
    - Approaches that can enable precision measurements of surface mineralogy and elemental composition and precision measurements of trace species, noble gases, and isotopes in the atmosphere.
- Small bodies:
    - Technologies that can enable sampling from asteroids, and from within comet nuclei to provide improved *in situ* analysis of comets.
    - Imagers and spectrometers that provide high performance in low-light environments.
    - Dust environment measurements and particle analysis, small-body resource identification, and/or quantification of potential small-body resources (e.g., oxygen, water, and other volatiles; hydrated minerals; carbon compounds; fuels; metals; etc.).
    - Advancements geared toward instruments that enable elemental or mineralogy analysis (such as high-sensitivity x-ray and UV-fluorescence spectrometers, UV-fluorescence systems, scanning electron microscopy with chemical analysis capability, mass spectrometry, gas chromatography and tunable diode laser sensors, calorimetry, imaging spectroscopy, and laser-induced breakdown spectroscopy (LIBS)).
- Saturn, Uranus, and Neptune and their moons:
    - Components, sample acquisition, and instrument systems that can enhance mission science return and withstand the low temperatures/high pressures of the atmospheric probes

    - during entry. Note that in situ instruments and components focused on ocean worlds life detection are specifically solicited in S13.06 and are encouraged to be submitted to S13.06.
- The Moon:
    - This topic seeks advancement of concepts and components to develop a Lunar Geophysical Network as envisioned in the Planetary Decadal Survey. Understanding the distribution and origin of both shallow and deep moonquakes will provide insights into the current dynamics of the lunar interior and its interplay with external phenomena (e.g., tidal interactions with Earth). The network is envisioned to comprise multiple free-standing seismic stations that would operate over many years in even the most extreme lunar temperature environments.
    - Technologies to advance all aspects of the network including sensor emplacement, power, and communications in addition to seismic, heat flow, magnetic field and electromagnetic sounding sensors are desired.
    - This topic also seeks technologies for quantifying lunar water and measuring the D/H ratio in lunar water. Much evidence points to the presence of water ice at cold spots in the permanently shadowed regions at the lunar poles, with estimated abundance of ~5 to 10 wt%.
    - Technologies, concepts, or components related to active source (e.g., lidar) imaging systems for accurate and precise mobile 3D terrain mapping and navigation in lunar South Pole regions with extreme solar incidence conditions (e.g., long persistent shadows and direct solar interference), extreme lunar temperature variation, velocimetry, and with low size, weight, and power (SWaP) and solid-state or minimal moving parts.
- General to Mars, Venus, Small bodies, Saturn and Uranus and Neptune and their moons, and the Moon:
    - Development of mass spectrometer front ends utilizing ion and acoustophoretic guides for a wide range of ions and macromolecules; Miniaturization of mass spectrometers by developing low-loss resonant inductive radio-frequency (RF) tanks at minimized volume and utilization of microelectromechanical system (MEMS) processes.

Novel instrument concepts are encouraged particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired. Proposers should show an understanding of relevant space science needs and present a feasible plan to fully develop a technology and infuse it into a NASA mission.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
The Phase I project should focus on feasibility and proof-of-concept demonstration (TRL 2-3). The required Phase I deliverable is a report documenting the proposed innovation, its status at the end of the Phase I effort, and the evaluation of its strengths and weaknesses compared to the state of the art. The report can include a feasibility assessment and concept of operations, simulations and/or measurements, and a plan for further development to be performed in Phase II.

The Phase II project should focus on component and/or breadboard development with the delivery of specific hardware for NASA (TRL 4-5). Phase II deliverables include a working prototype of the proposed hardware, along with documentation of development, capabilities, and measurements.

State of the Art and Critical Gaps:
In situ instruments and technologies are essential bases to achieve Science Mission Directorate's (SMD's) planetary science goals summarized in the Planetary Decadal Survey. In situ instruments and technologies play an indispensable role for NASA's New Frontiers and Discovery missions to various planetary bodies (Mars, Venus, small bodies, Saturn, Uranus, Neptune, Moon, etc.).

There are currently various in situ instruments for diverse planetary bodies. However, there are ever-increasing science and exploration requirements and challenges for diverse planetary bodies. For example, there is urgent need for exploring RSL (recurring slope lineae) on Mars and plumes from planetary bodies, as well as a growing demand for in situ technologies amenable to small spacecraft.

To narrow the critical gaps between the current state of art and the technology needed for the ever-increasing science/exploration requirements, in situ technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities with lower mass, power, and volume.

Relevance / Science Traceability:
In situ instruments and technologies are essential bases to achieve the Science Mission Directorate's (SMD's) planetary science goals summarized in the Planetary Decadal Survey. In situ instruments and technologies play an indispensable role for NASA's New Frontiers and Discovery missions to various planetary bodies.

In addition to Phase III opportunities, SMD offers several instrument development programs as paths to further development and maturity. These include the Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) Program, which invests in low-TRL technologies and funds instrument feasibility studies, concept formation, proof-of-concept instruments, and advanced component technology, as well as the Maturation of Instruments for Solar System Exploration (MatISSE) Program and the Development and Advancement of Lunar Instrumentation (DALI) Program, which invest in mid-TRL technologies and enable timely and efficient infusion of technology into planetary science missions.

References:

1. Li et al.: "Direct evidence of surface exposed water ice in the lunar polar regions," *PNAS*, 115, 2018, pp. 8907-8912, https://www.pnas.org/content/pnas/115/36/8907.full.pdf
2. Colaprete, A.; Schultz, P.; Heldmann, J.; Wooden, D.; Shirley, M.; Ennico, K.; and Goldstein, D.: "Detection of water in the LCROSS ejecta plume," *Science*, 330 2010, pp. 463-468.
3. Schultz, P.H.; Hermalyn, B.; Colaprete, A.; Ennico, K.; Shirley, M.; and Marshall, W.S.: "The LCROSS cratering experiment," *Science*, 330, 2010, pp. 468-472.
4. Paige et al.: "Diviner Lunar Radiometer Observations of Cold Traps in the Moon's South Polar Region," Science, 330, 2010, pp. 479-482.

S13.06 In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection (SBIR)

Lead Center: JPL
Participating Center(s): ARC, GRC, GSFC

Scope Title: In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection

Scope Description:

This subtopic solicits development of in situ instrument technologies and components to advance the maturity of science instruments and plume sample collection systems focused on the detection of evidence of life, especially extant life, in the ocean worlds (e.g., Europa, Enceladus, Titan, Ganymede, Callisto, Ceres, etc.). Technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are of particular interest. Technologies that allow collection during high-speed (>1 km/sec) passes through a plume are solicited as are technologies that can maximize total sample mass collected while passing through tenuous plumes. This fly-through sampling focus is distinct from S13.01, which solicits sample collection technologies from surface platforms.

These technologies must be capable of withstanding operation in space and planetary environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance.

Specifically, this subtopic solicits instrument technologies and components that provide significant advances in the following areas, broken out by planetary body:

- General to Europa, Enceladus, Titan, and other ocean worlds:
    - Technologies and components relevant to life detection instruments (e.g., microfluidic analyzer, microelectromechanical systems (MEMS) chromatography/mass spectrometers, laser-ablation mass spectrometer, fluorescence microscopic imager, Raman spectrometer, tunable laser system, liquid chromatography/mass spectrometer, x-ray fluorescence spectrometer, digital holographic microscope-fluorescence microscope, antibody microarray biosensor, nanocantilever biodetector, etc.). Technologies for high-radiation environments (e.g., radiation mitigation strategies, radiation-tolerant detectors, and readout electronic components), which enable orbiting instruments to be both radiation hard and undergo the planetary protection requirements of sterilization (or equivalent).
    - Collecting samples for a variety of science purposes is also sought. These include samples that allow for determination of the chemical and physical properties of the source ocean, samples for detailed characterization of the organics present in the gas and particle phases, and samples for analysis for biomarkers indicative of life. Front-end system technologies include sample collection systems and subsystems capable of capture, containment, and/or transfer of gas, liquid, ice, and/or mineral phases from plumes to sample processing and/or instrument interfaces. This includes cold double-walled isolators for sample manipulation at –80 ºC and Biohazard Safety Level (BSL)-4 conditions.
    - Technologies for characterization of collected sample parameters including mass, volume, total dissolved solids in liquid samples, and insoluble solids. Sample collection and sample capture for in situ imaging. Sampling mechanisms and/or containers capable of gas-solid separation or venting water to space (concentration, lyophilization) without altering the sample, including weighing ice samples to measure mass loss under vacuum, cold, microgravity conditions. Systems capable of high-velocity sample collection with minimal sample alteration to allow for habitability and life detection analyses. Microfluidic sample collection systems that enable sample concentration and other manipulations. Plume material collection technologies that minimize risk of terrestrial contamination, including organic chemical and microbial contaminates. These technologies would enable high-priority sampling and potential sample return from the plumes of Enceladus with a fly-by mission. This would be a substantial cost savings over a landed mission.
- Europa: Life detection approaches optimized for evaluating and analyzing the composition of ice matrices with unknown pH and salt content. Instruments capable of detecting and identifying organic molecules (in particular biomolecules), salts, and/or minerals important to understanding the present conditions of Europa's ocean are sought (such as high-resolution gas chromatograph or laser desorption mass spectrometers, dust detectors, organic analysis instruments with chiral discrimination, etc.). These developments should be geared towards analyzing and handling very small sample sizes (microgram to milligram) and/or low column densities/abundances. Also of

interest are imagers and spectrometers that provide high performance in low-light environments (visible and near-infrared (NIR) imaging spectrometers, thermal imagers, etc.), as well as instruments capable of improving our understanding of Europa's habitability by characterizing the ice, ocean, and deeper interior and monitoring ongoing geological activity such as plumes, ice fractures, and fluid motion (e.g., seismometers, magnetometers). Improvements to instruments capable of gravity (or other) measurements that might constrain properties such as ocean and ice shell thickness will also be considered.

- Enceladus (including plume material and E-ring particles): Life detection approaches optimized for analyzing plume particles as well as for determining the chemical state of Enceladus icy surface materials (particularly near plume sites). Instruments capable of detecting and identifying organic molecules (in particular biomolecules), salts, and/or minerals important to understand the present conditions of the Enceladus ocean are sought (such as high-resolution gas chromatograph or laser desorption mass spectrometers, dust detectors, organic analysis instruments with chiral discrimination, etc.). These developments should be geared towards analyzing and handling very small sample sizes (microgram to milligram) and/or low column densities/abundances. Also of interest are imagers and spectrometers that provide high performance in low-light environments (visible and NIR imaging spectrometers, thermal imagers, etc.), as well as instruments capable of monitoring the bulk chemical composition and physical characteristics of the plume (density, velocity, variation with time, etc.). Improvements to instruments capable of gravity (or other) measurements that might constrain properties such as ocean and ice shell thickness will also be considered.
- Titan and other ocean worlds targets, which may include Ganymede, Callisto, Ceres, etc. (1) Life detection approaches optimized for searching for biosignatures and biologically relevant compounds in Titan's lakes, including the presence of diagnostic trace organic species, and also for analyzing Titan's complex aerosols and surface materials, are needed. (2) Mechanical and electrical components and subsystems that work in cryogenic (95 K) environments, sample extraction from liquid methane/ethane, sampling from organic "dunes" at 95 K, and robust sample preparation and handling mechanisms that feed into mass analyzers are sought. (3) Balloon instruments such as IR spectrometers, imagers, meteorological instruments, radar sounders, solid, liquid, and air sampling mechanisms for mass analyzers, and aerosol detectors are solicited. (4) Low-mass and low-power sensors, mechanisms, and concepts for adapting terrestrial instruments such as turbidimeters and echo sounders for lake measurements, weather stations, surface (lake and solid) properties packages, etc., to cryogenic environments (95 K) are sought.

Proposers are strongly encouraged to relate their proposed development to:

- NASA's future ocean worlds exploration goals (see references).
- Existing flight instrument capability, to provide a comparison metric for assessing proposed improvements.

Proposed instrument architectures should be as simple, reliable, and as low risk as possible while enabling compelling science. Novel instrument concepts are encouraged, particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired.

Proposers should show an understanding of relevant space science needs, present a feasible plan to fully develop a technology, and infuse it into a NASA program.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
The Phase I project should focus on feasibility and proof-of-concept demonstration (TRL 2-3). The required Phase I deliverable is a report documenting the proposed innovation, its status at the end of the Phase I effort, and the evaluation of its strengths and weaknesses compared to the state of the art. The report can include a feasibility assessment and concept of operations, simulations and/or measurements, and a plan for further development to be performed in Phase II.

The Phase II project should focus on component and/or breadboard development with the delivery of specific hardware for NASA (TRL 4-5). Phase II deliverables include a working prototype of the proposed hardware along with documentation of development, capabilities, and measurements.

State of the Art and Critical Gaps:
In situ instruments and technologies are essential to achieve NASA's ocean worlds exploration goals. There are currently some in situ instruments for diverse ocean worlds bodies. However, there are ever-increasing science and exploration requirements and challenges for diverse ocean worlds bodies. For example, there are urgent needs for the exploration of icy or liquid surfaces on Europa, Enceladus, Titan, Ganymede, Callisto, etc., and plumes from planetary bodies such as Enceladus.

To narrow the critical gaps between the current state of art and the technology needed for the ever-increasing science/exploration requirements, in situ technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities, and at the same time with lower resource (mass, power, and volume) requirements.

Relevance / Science Traceability:
In situ instruments and technologies are essential to achieve Science Mission Directorate's (SMD) planetary science goals summarized in the Decadal Study (National Research Council's Vision and Voyages for Planetary Science in the Decade 2013-2022). In situ instruments and technologies play indispensable roles for NASA's New Frontiers and Discovery missions to various planetary bodies.

NASA SMD has two programs to bring this subtopic technologies to higher level: PICASSO and MatISSE. The Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) Program invests in low-TRL technologies and funds instrument feasibility studies, concept formation, proof-of-concept instruments, and advanced component technology. The Maturation of Instruments for Solar System Exploration (MatISSE) Program invests in mid-TRL technologies and enables timely and efficient infusion of technology into planetary science missions. The PICASSO and MatISSE are in addition to Phase III opportunities.

References:

1. The NASA Roadmap for Ocean World Exploration: http://www.lpi.usra.edu/opag/ROW
2. In situ instruments and technologies for NASA's ocean worlds exploration goals: https://www.nasa.gov/specials/ocean-worlds/
3. NASA technology solicitation (ROSES 2016/C.20 Concepts for Ocean worlds Life Detection Technology (COLDTECH) call): https://nspires.nasaprs.com/external/solicitations/summary.do?method=init&solId={5C43865B-0C93-6ECABCD2-A3783CB1AAC8}&path=init
4. Instrument Concepts for Europa Exploration 2 (final text released May 17, 2018; PDF): https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=628697/solicitatio

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S14.02 Particle and Field Sensors and Instrument-Enabling Technologies (SBIR)

Lead Center: GSFC
Participating Center(s): MSFC

Scope Title: Particles and Fields Sensors and Instrument Enabling Technologies

Scope Description:
The 2013 National Research Council's "Solar and Space Physics: A Science for a Technological Society" motivates this subtopic: "Deliberate investment in new instrument concepts is necessary to acquire the data needed to further solar and space physics science goals, reduce mission risk, and maintain an active and innovative hardware development community." This subtopic solicits development of advanced in situ instrument technologies and components suitable for deployment on heliophysics missions. Advanced sensors for the detection of neutral and ionized gases (atoms, molecules, and ions) and their motions (winds and ion drifts); energetic particles (electrons and ions), including their energy distribution and pitch angles; thermal plasma populations, including their temperature; and direct current (DC) and wave electric and magnetic fields in space along with associated instrument technologies are often critical for enabling transformational science from the study of the Sun's outer corona, to the solar wind, to the trapped radiation in Earth's and other planetary magnetic fields, and to the ionospheric and upper atmospheric composition of the planets and their moons.

These technologies must be capable of withstanding operation in space environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technology developments that result in a reduction of mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance. In addition, technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are solicited.

Improvements in particle and field sensors and associated instrument technologies enable further scientific advancement for upcoming NASA missions such as CubeSats, Explorers, Solar Terrestrial Probe (STP), Living With a Star (LWS), and planetary exploration missions. Specifically, this year the subtopic solicits instrument development that provides significant advances in the following areas:

- Compactly stowed, lightweight, long, straight, and rigid booms, magnetically clean, that can deploy a sensor with embedded electronics to distances of 2 m or longer on CubeSat and SmallSat constellations in order to measure DC magnetic fields.
- Compactly stowed, lightweight, long, straight, and rigid booms that can deploy a sensor with embedded electronics to distances of 6 m or longer on satellites and sounding rockets in order to measure DC electric fields and plasma waves. Mass target: 1 kg or less.
- Solar-blind solid-state detectors (SSDs) for direct solar viewing energetic particle detection. The SSDs should be able to handle the intense ultraviolet (UV) and visible solar radiation without saturation, with low noise while addressing thermal issues. Typically, a metalized foil is used for UV suppression, but this gives an energy threshold of 1 MeV or more. The target energy threshold for the SSD is ~50 keV or lower with the upper energy range in the several to tens of megaelectronvolts. Pushing the threshold down will increase performance and reduce cost over the current instrument designs.
- Rapid electrostatic analyzer production/high-tolerance assembly for plasma instruments. This will be especially useful for multiple instrument production for constellation missions.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:
Phase I deliverables: Concept study report, preliminary design, and test results.

Phase II deliverables: Detailed design, prototype test results, and a prototype deliverable with guidelines for in-house integration and test (I&T).

State of the Art and Critical Gaps:

- Compactly stowed, lightweight, long, straight, and rigid booms, magnetically clean, that can deploy a sensor with embedded electronics to distances of 2 m or longer on CubeSat and SmallSat constellations to measure DC magnetic fields.
- Compactly stowed, lightweight, long, straight, and rigid booms that can deploy a sensor with embedded electronics to distances of 6 m or longer on satellites and sounding rockets to measure DC electric fields and plasma waves. Mass target: 1 kg or less.
- Solar-blind SSDs for direct solar viewing energetic particle detection. The SSDs should be able to handle the intense UV and visible solar radiation without saturation, with low noise while addressing thermal issues. Typically, a metalized foil is used for UV suppression, but this gives an energy threshold of 1 MeV or more. The target energy threshold for the SSD is ~50 KeV or lower with the upper energy range in the several to tens of megaelectronvolts. Pushing the threshold down will increase performance and reduce cost over the current instrument designs.
- Rapid electrostatic analyzer production/high-tolerance assembly for plasma instruments. This will be especially useful for multiple instrument production for constellation missions.

Relevance / Science Traceability:
Particle and field instruments and technologies are essential bases to achieve the Science Mission Directorate's (SMD's) Heliophysics goals summarized in the National Research Council’s, Solar and Space Physics: A Science for a Technological Society. In situ instruments and technologies play indispensable roles for NASA’s LWS and STP mission programs, as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for particle and field technologies amenable to CubeSats and SmallSats. NASA SMD has two excellent programs to bring this subtopic technologies to higher level: Heliophysics Instrument Development for Science (H-TIDeS) and Heliophysics Flight Opportunities for Research and Technology (H-FORT). H-TIDeS seeks to advance the development of technologies and their application to enable investigation of key heliophysics science questions and space weather. This is done through incubating innovative concepts and development of prototype technologies. It is intended that Phase II and III technologies, further developed through H-TIDeS, would then be proposed to H-FORT to mature by demonstration in a relevant environment. The H-TIDeS and H-FORT programs are in addition to Phase III opportunities. Further opportunities through SMD include Explorer Missions, New Frontiers Missions, and the upcoming Geospace Dynamics Constellation.

References:

1. National Research Council: "Solar and Space Physics: A Science for a Technological Society," http://nap.edu/13060
2. Example missions (e.g., NASA Magnetospheric Multiscale (MMS) mission, Fast Plasma Instrument; Solar Probe; STEREO; and Geospace Dynamics Constellation): http://science.nasa.gov/missions

S14.03 Remote Sensing Instrument Technologies for Heliophysics (SBIR)

Lead Center: GSFC

Participating Center(s): N/A

Scope Title: Remote-Sensing Instruments/Technologies for Heliophysics

Scope Description:
The 2013 National Research Council's Solar and Space Physics: A Science for a Technological Society (http://nap.edu/13060) motivates this subtopic: "Deliberate investment in new instrument concepts is necessary to acquire the data needed to further solar and space physics science goals, reduce mission risk, and maintain an active and innovative hardware development community." This subtopic solicits development of advanced remote-sensing instrument technologies and components suitable for heliophysics missions. These technologies must be capable of withstanding operation in space environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures for Low Earth Orbit (LEO) and beyond. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance. In addition, technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are solicited. Space-qualifying new commercial sensor technologies for Heliophysics observations is an approach that can both reduce accommodation needs as well as bring improved measurement capabilities. For a list of currently operating and past missions, see https://science.nasa.gov/missions-page?field_division_tid=5&field_phase_tid=All. Another valuable reference is the 2013 Heliophysics Decadal Survey https://www.nationalacademies.org/our-work/a-decadal-strategy-for-solar-and-space-physics-heliophysics. Technologies that support science aspects of missions in NASA's Living With a Star and Solar-Terrestrial Probe programs are of top priority, including long-term missions like an Interstellar Probe mission (as called out in the Decadal Survey).

Remote-sensing technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities. Remote-sensing technologies amenable to CubeSats and SmallSats are also encouraged. Specifically, this subtopic solicits instrument development that provides significant advances in the following areas:

- Light detection and ranging (lidar) systems for high-power, high-frequency geospace remote sensing, such as sodium and helium lasers.
- Technologies or components enabling auroral, airglow, geospace, and solar imaging at visible, far and extreme ultraviolet (FUV/EUV), and soft x-ray wavelengths (e.g., mirrors and gratings with high-reflectance coatings, multilayer coatings, narrowband filters, blazed gratings with high ruling densities, diffractive and metamaterial optics).
- Electromagnetic sounding of ionospheric or magnetospheric plasma density structure at radio-frequencies from kHz to >10 MHz.
- Passive sensing of ionospheric and magnetospheric plasma density structure using transmitters of opportunity (e.g., global navigation satellite system (GNSS) or ground-based transmissions).
- Technologies that enable observations of bright solar flares without saturation in wavelength range from EUV to x-rays. This includes but is not limited to:
    - Fast-cadence solid-state detectors (e.g., CCD, CMOS) for imaging in the EUV with or without intrinsic ion suppression.
    - Fast-cadence solid-state detectors for imaging soft or hard x-ray (~0.1 to hundreds of kiloelectron volts) imaging preferably with the ability to detect the energy of individual photons.
    - Technologies that attenuate solar x-ray fluences by flattening the observed spectrum by a factor of 100 to 1,000 across the energy range encompassing both low- and high-energy x-rays—preferably flight programmable.
- Technologies to either reduce the size, complexity, or mass or to improve the imaging resolution of solar telescopes used for imaging solar x-rays in the ~1 to 300 keV range.
    - Technologies capable of smoothly laminating silicon micropore optics with materials that enhance the grazing incidence reflectivity of soft x-rays in the energy range from 0.1 to 2 keV.

- Technologies, including metamaterials and micro-electro-mechanical systems (MEMS) that enable polarization, wavelength, or spatial discrimination without macroscale moving parts.
- Technologies for precise radiometry at terahertz bands corresponding to upper atmosphere thermal emissions in the 1 to 5 THz range, particularly at 4.7 THz. This includes, but is not limited to:
  - Technologies that reduce size, mass, and power of terahertz radiometry instrumentation, for example by increasing the operating temperature of terahertz detectors.
  - Technologies that enable terahertz spectroscopy, for example, by use of a terahertz local oscillator for heterodyne mixing.
  - Technologies that improve signal-to-noise ratio of terahertz instrumentation, particularly at 4.7 THz.

Proposers are strongly encouraged to relate their proposed development to NASA's future heliophysics goals as set out in the Heliophysics Decadal Survey (2013-2022) and the NASA Heliophysics Roadmap (2014-2033). Proposed instrument components and/or architectures should be as simple, reliable, and low risk as possible, while enabling compelling science. Novel instrument concepts are encouraged, particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired. Proposers should show an understanding of relevant space science needs and present a feasible plan to fully develop a technology and infuse it into a NASA program. Detector technology proposals should be referred to the S116 subtopic.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I deliverables may include an analysis or test report, a prototype of an instrument subcomponent, or a full working instrument prototype.

Phase II deliverables must include a prototype or demonstration of a working instrument or subcomponent and may also include analysis or test reports.

State of the Art and Critical Gaps:
Remote-sensing instruments and technologies are essential bases to achieve Science Mission Directorate's (SMD) Heliophysics goals summarized in National Research Council’s "Solar and Space Physics: A Science for a Technological Society." These instruments and technologies play indispensable roles for NASA’s Living With a Star (LWS) and Solar Terrestrial Probe (STP) mission programs as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for remote-sensing technologies amenable to CubeSats and SmallSats. To narrow the critical gaps between the current state of art and the technology needed for the ever increasing science/exploration requirements, remote-sensing technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities—and at the same time with lower mass, power, and volume.

Relevance / Science Traceability:

Remote-sensing instruments and technologies are essential bases to achieve SMD's Heliophysics goals summarized in National Research Council's, Solar and Space Physics: A Science for a Technological Society. These instruments and technologies play indispensable roles for NASA's LWS and STP mission programs, as well as for a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for remote-sensing technologies amenable to CubeSats and SmallSats. NASA SMD has two excellent programs to bring this subtopic's technologies to a higher level: Heliophysics Technology and Instrument Development for Science (H-TIDeS) and Heliophysics Flight Opportunities for Research and Technology (H-FORT). H-TIDeS seeks to advance the development of technologies and their application to enable investigation of key heliophysics science questions. This is done through incubating innovative concepts and development of prototype technologies. It is intended that technologies developed through H-TIDeS would then be proposed to H-FORT to mature by demonstration in a relevant environment. The H-TIDeS and H-FORT programs are in addition to Phase III opportunities.

References:

1. For example missions: https://science.nasa.gov/missions-page?field_division_tid=5&field_phase_tid=All
2. For details of the specific requirements, see the National Research Council's, Solar and Space Physics: A Science for a Technological Society: http://nap.edu/13060
3. For details of NASA's Heliophysics roadmap, see the NASA Heliophysics Roadmap: https://explorers.larc.nasa.gov/HPSMEX/MO/pdf_files/2014_HelioRoadmap_Final_Reduced_0.pdf
4. 2013 Heliophysics Decadal Survey: https://www.nationalacademies.org/our-work/a-decadal-strategy-for-solar-and-space-physics-heliophysics

S15.01 Plant Research Capabilities in Space (SBIR)

Lead Center: KSC
Participating Center(s): ARC, JPL, JSC

Scope Title: CO2 Collection and Dosing Technologies for Plant Chambers

Scope Description:
Carbon dioxide is an essential gas to sustain plant photosynthesis. Spacecraft cabins with humans often have very high CO_2 levels (e.g., 2,000 to 7,000 ppm or 0.2 to 0.7 kPa on the International Space Station, ISS), and this has been used for CO_2 supply to open plant chambers like the Russian Lada and NASA's Veggie unit. This does not provide precise control of the CO_2 concentration, however: the levels are always floating with the cabin, which makes it difficult to replicate for ground controls and optimize for plant growth. NASA Advanced Plant Habitat (APH) is a closed chamber capable of tight CO_2 control, but instead of using cabin air, compressed cylinders of CO_2 are shipped to space, adding mass consumables and pressurized containers to operate APH.

NASA needs a system for selectively scrubbing CO_2 from cabin air, which can vary from 2,000 to 7,000 ppm (0.2 to 0.7 kPa), and then dosing or adding the CO_2 in a controlled fashion to closed plant chambers like APH to maintain constant CO_2 concentrations. Such a capability could eliminate the need for shipping compressed CO_2 cylinders continuously to ISS to operate APH and/or stabilize fluctuating CO_2 levels for open chambers like Veggie. A starting example of such an approach might be something like the ISS Carbon Dioxide Removal Assembly (CDRA), which uses zeolite beds to remove and then release CO_2. For closed plant chambers, the technology would need to be miniaturized, require low power, and capable of being attached or connected directly to the chamber or its internal air plenum and then releasing the CO_2 to inside of the chamber to balance CO_2 removal by the plants. Internal plant chamber concentrations are typically optimal between 1,000 and 2,000 ppm (0.1 and 0.2 kPa), but the plants rapidly remove the CO_2 during the light cycle while they are photosynthetically active; hence the need for controlled CO_2 additions.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:
The Phase I project should focus on feasibility and proof-of-concept demonstration. The required Phase I deliverable is a report documenting the proposed innovation, its status at the end of the Phase I effort, and the evaluation of its strengths and weaknesses compared to the state of the art.

Following Phase II, a working prototype that could be attached to a closed chamber similar to the NASA APH would be desirable.

State of the Art and Critical Gaps:
The state of the art is to send compressed CO_2 gas in cylinders into space and use these to add controlled amounts to closed chambers like APH. For open chambers like Veggie, the SOA is using cabin air for CO_2 supply, but this does not provide very precise CO_2 control. The proposed capability could replace the need to deliver compressed CO_2 to APH and help "smooth" or buffer CO_2 changes in Veggie.

Relevance / Science Traceability:
Accurate CO_2 control is essential for careful research and optimal growth of plants in space. This is possible by supplying compressed CO_2 from Earth, but this is costly and is ironic when the closed plant chambers are already surrounded by a cabin atmosphere with very high levels of CO_2.

References:

1. Drake, B.G.; Gonzalez-Meler, M.A.:, and Long, S.P.: "More efficient plants: A consequence of rising atmospheric CO2?," *Annual Review of Plant Physiology and Plant Molecular Biology*, 48, pp. 609-639, 1997.
2. Gurkan, B. and Jan, D: "Improvements in ionic liquid technology for carbon dioxide removal applications," Intl. Conf. Environ. Systems, ICES 2020-107.
3. Peters, W.T.; Cmarik, G.E.; and Knox, J.C.: "4B-CO2 EDU performance," Intl. Conf. Environ. Systems, ICES 2021-313.
4. Massa, G.D.; Wheeler, R.M.; Morrow, R.C.; and Levine, H.G.: "Growth chambers on the International Space Station for large plants," *Acta Horticulturae,* 1134, pp. 215-221, 2016, DOI 10.17660/ActaHortic.2016.1134.29.
5. Wheeler, R.M.; Mackowiak, C.L.; Yorio, N.C.; and Sager, J.C.: "Effects of CO_2 on stomatal conductance: Do stomata open at very high CO_2 concentrations?" *Annals of Botany,* 83, pp. 243-25, 1999.

Scope Title: Miniature Elemental Analyzer for Water Analysis and Support of Plant Research

Scope Description:
As plant-growing systems mature and expand for future exploration missions and enhanced research capabilities, the ability to generate, analyze, and manage nutrient (fertilizer) solutions will increase. As of now, we can only take “grab” samples of water from systems like the Advanced Plant Habitat (APH) or the proposed Passive Orbital Nutrient Delivery System (PONDS) nutrient delivery system for Veggie, return them to Earth, and then analyze them for the elemental composition. An in situ capability is needed to analyze plant nutrient solutions or feed water to better understand and manage plant nutrient delivery on a near-real-time basis. Inductively coupled plasma (ICP) spectroscopy is one proven approach for elemental analysis, but ion

chromatography (IC) or high-performance liquid chromatography (HPLC) might have overlapping capabilities. Regardless, the technology would need to be robust and miniaturized, operate with low power, and have minimal consumables to augment plant growth and research capabilities for the future missions. The system would also need to be safe for operating in spaceflight environments. Ideally, the technology could provide rapid analysis of elemental composition of water samples. Essential elements for plants include (in approximately descending order): N, K, Mg, Ca, P, S (all typically in tens to hundreds parts per million), and Mn, Fe, Cl, B, Zn, Cu, and Mo (all typically in parts per billion). Detection of as many of these elements as possible would be desirable. In addition, it would be desirable to detect other non-essential elements, such as Ni, Cr, Ag, V, and I, that might be contaminants from chamber materials, plumbing, or supply water. Discrimination between ionic species (e.g., NH_4 and NO_3 forms of nitrogen) would be helpful but not required. A miniaturized elemental analyzer/sensing capability could also have applications beyond those just for plants, where knowledge of the elemental composition of fluids, such as urine or tissue samples, could provide valuable data for supporting research or habitat operations.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:
The Phase I project should focus on feasibility and proof-of-concept demonstration. The required Phase I deliverable is a report documenting the proposed innovation, its status at the end of the Phase I effort, and the evaluation of its strengths and weaknesses compared to the state of the art.

A Phase II deliverable may include a working prototype or engineering development unit (EDU) to demonstrate a miniaturized elemental analyzer system as part of a plant-growth system like the APH, the proposed PONDS watering systems for growing plants in the Veggie plant chamber on ISS, or future proposed "hydroponic" systems being considered for growing plants in space.

State of the Art and Critical Gaps:
Laboratory-scale ICP or IC systems that operate with a plasma torch or high pressure to get the needed emission spectra are a standard state-of-the-art approach for elemental analysis.

Relevance / Science Traceability:
As longer duration plant research tests are conducted in space, there will be a need for addition of nutrient or fertilizer solutions to sustain the plants; for example, the current APH test with chili peppers is scheduled to go for >100 days. Although this uses time-release fertilizer, in situ water analysis could provide information on backwash of nutrients into the water delivery system and verification of the water quality of cabin potable water used for the tests. For the proposed PONDS watering system for Veggie, initial nutrients will come from time-release fertilizer as well, but having in situ nutrient/elemental analysis could assess needs for further nutrient additions. For proposed "hydroponic" systems for space, capabilities to analyze nutrient solutions would be needed throughout the experiment or plant production trial.

References:

1. Barker, A.V. and Pilbeam, D.J.: Handbook of Plant Nutrition (2nd ed.), CRC Press, 2015.
2. Harris, D.C.: Quantitative Chemical Analysis, W. H. Freeman and Company, New York, 2010.
3. Jones, J.B.: Plant nutrition and fertility manual. CRC Press, 2012.

4. Wheeler, R.M.; Berry, W.L.; Mackowiak, C.L.; Corey, K.A.; Sager, J.C.; Heeb, M.M.; and Knott, W.M.: "A data base of crop nutrient use, water use, and carbon dioxide exchange in a 20 m^2 growth chamber. 1. Wheat as a case study., *J. Plant Nutrition,* 16, pp. 1881-1915, 1993.
5. Wheeler, R.M.; Mackowiak, C.L.; Berry, W.L.; Stutte, G.W.; Yorio, N.C.; and Sager, J.C.: Nutrient, acid, and water budgets of hydroponically grown crops," *Acta Hort.,* 481, pp. 655-661, 1999.

S16.07 Cryogenic Systems for Sensors and Detectors (SBIR)

Lead Center: GSFC
Participating Center(s): JPL

Scope Title: Low-Temperature/High-Efficiency Cryocoolers

Scope Description:
NASA seeks improvements to multistage low-temperature spaceflight cryocoolers. Coolers are sought with the lowest temperature stage typically in the range of 4 to 10 K, with cooling power at the coldest stage larger than currently available and with high efficiency. The desired cooling power is application specific, but an example is 0.2 W at 4 K. Devices that produce extremely low vibration, particularly at frequencies below a few hundred hertz, are of special interest. System- or component-level improvements that improve efficiency and reduce complexity and cost are desirable. Examples of target missions include Origins, a mid- to far-infrared observatory that includes a large cold (4 K) telescope, and low-temperature ((<0.1 K) detectors; and the Lynx X-ray Observatory, which has a large, very low-temperature (~0.05 K) array of x-ray microcalorimeters. In addition to the large coolers, there has recently been interest in small, low-power (~10-mW) 4 K coolers for quantum communication and sensing instruments.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:
Phase I: Proof-of-concept demonstration.

Phase II: Functioning hardware ready for functional and possibly environmental testing.

State of the Art and Critical Gaps:
Current spaceflight cryocoolers for this temperature range include linear piston-driven Stirling cycle or pulse-tube cryocoolers with Joule-Thompson low-temperature stages. One such state-of-the-art cryocooler provides 0.09 W of cooling at 6 K. For large future space observatories, large cooling power and much greater efficiency will be needed. For cryogenic instruments or detectors on instruments with tight pointing requirements, orders-of-magnitude improvement in the levels of exported vibration will be required. Some of these requirements are laid out in the "Advanced cryocoolers" Technology Gap in the latest (2017) Cosmic Origins Program Annual Technology Report.

Relevance / Science Traceability:
Science traceability (from NASA's Strategic plan):

- Goal 1: Expand the frontiers of knowledge, capability, and opportunity in space.

- Objective 1.6: Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars.

Low-temperature cryocoolers are listed as a "Technology Gap" in the latest (2017) Cosmic Origins Program Annual Technology Report. Future missions that would benefit from this technology include two of the large missions under study for the 2020 Astrophysics Decadal Survey: Origins Space Telescope and Lynx microcalorimeter instrument.

References:

1. For more information on the Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/
2. For more information on LYNX: https://wwwastro.msfc.nasa.gov/lynx/docs/science/observatory.html

Scope Title: Actuators and Other Cryogenic Devices

Scope Description:
NASA seeks devices for cryogenic instruments, including:

- Small, precise motors and actuators, preferably with superconducting windings, that operate with extremely low power dissipation. Devices using standard NbTi conductors, as well as devices using higher temperature superconductors that can operate above 5 K, are of interest.
- Cryogenic heat pipes for heat transport within instruments. Heat pipes using hydrogen, neon, oxygen, argon, and methane are of interest. Length should be at least 0.3 m. Devices that have reduced gravitational dependence and that can be made low profile, or integrated into structures such as radiators, are of particular interest.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:
Phase I: Proof-of-concept test on a breadboard-level device.

Phase II: Working prototypes ready for testing in the relevant environments.

State of the Art and Critical Gaps:
Motors and actuators: Instruments often have motors and actuators, typically for optical elements such as filter wheels and Fabry-Perot interferometers. Current cryogenic actuators are typically motors with resistive (copper) windings. While heat generation is naturally dependent on the application, an example of a recent case is a stepper motor used to scan a Fabry-Perot cavity; its total dissipation (resistive + hysteric) is ~0.5 W at 4 K. A flight instrument would need heat generation at least 20× smaller.

Cryogenic heat pipes: Heat transport in cryogenic instruments is typically handled with solid thermal straps, which do not scale well for larger heat loads. Currently available heat pipes are optimized for temperatures above ~120 K. They have limited capacity to operate against a gravitational potential.

Relevance / Science Traceability:

Science traceability: NASA Strategic plan 2018, Objective 1.1: Understand the Sun, Earth, Solar System, and Universe.

Almost all instruments have motors and actuators for changing filters, adjusting focus, scanning, and other functions. On low-temperature instruments, for example on mid- to far-IR observatories, dissipation in actuators can be a significant design problem.

References:

For more information on earlier low-temperature heat pipes:

1. Brennen, et al.: AIAA paper 93-2735, NTRS Document ID: 19930062491, https://doi.org/10.2514/6.1993-2735
2. Prager, R.C.: AIAA paper 80-1484, https://doi.org/10.2514/6.1980-1484
3. Alario, J. and Kosson, R.: AIAA paper 80-0212, https://doi.org/10.2514/6.1980-212

Scope Title: Miniaturized/Efficient Cryocooler Systems

Scope Description:

NASA seeks miniature, highly efficient cryocoolers for instruments on Earth and planetary missions. A range of cooling capabilities is sought.

Two examples include 0.2 W at 30 K with heat rejection at 300 K and 0.3 W at 35 K with heat rejection at 150 K. For both examples, an input power of ≤5 W and a total mass of ≤400 g is desired. The ability to fit within the volume and power limitations of a SmallSat platform would be highly advantageous. Cryocooler electronics are also sought in two general categories: (1) low-cost devices that are sufficiently radiation hard for lunar or planetary missions, and (2) very low-cost devices for a relatively short term (~1 year) in low Earth orbit. The latter category could include controllers for very small coolers, such as tactical and rotary coolers.

For many infrared (IR) spectrometer instrument systems, the spectrometer can operate at a temperature more than 60 K higher than the focal plane array. A miniature two-stage cryocooler is ideal for this type of application to minimize the cooler input power. Therefore, NASA is seeking an innovative miniature two-stage cryocooler technology with low exported vibrations. The lowest cooling temperature of interest for the lower stage is 80 K, and the maximum cooling power is about 1 W. The cooling temperature of the second stage should be 60 to 80 K higher than the lower stage, and the cooling power should be about 2 W.

For future advanced heterodyne sensors for submillimeter-wave receivers, the mixer in each sensor requires 50 to 100 mW of cooling at 15 to 20 K, and the local oscillator requires 1 to 2 W cooling power at 80 to 120 K. NASA is seeking advanced multistage cryocooler technologies that will enable these sensors to operate in SmallSat platform. The cryocooler input power must be compatible with available power in Smallsat platform, which is typically several tens of watts.

It is desirable that the cooler can efficiently operate over a wide heat sink temperature range, from -50 to 70 ºC.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:

Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/**Sensors**

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:
Phase I: Proof-of-concept demonstration.

Phase II: Desired deliverables include miniature coolers and components, such as electronics, that are ready for functional and environmental testing.

State of the Art and Critical Gaps:
Present state-of-the-art capabilities provide 0.1 W of cooling capacity with heat rejection at 300 K at approximately 5 W input power with a system mass of 400 g.

Cryocoolers enable the use of highly sensitive detectors, but current coolers cannot operate within the tight power constraints of outer planetary missions. There are no lightweight cryocoolers (<3 kg) that can provide cooling below 20 K. Cryocooler power could be greatly reduced by lowering the heat rejection temperature, but presently there are no spaceflight systems that can operate with a heat rejection temperature significantly below ambient.

Relevance / Science Traceability:
Science traceability: NASA Strategic plan 2018, Objective 1.1: Understand the Sun, Earth, Solar System, and Universe.

NASA is moving toward the use of small, low-cost satellites to achieve many of its Earth science—and some of its planetary—science goals. The development of cryocoolers that fit within the size and power constraints of these platforms will greatly expand their capability, for example, by enabling the use of infrared detectors.

In planetary science, progress on cryogenic coolers will enable the use of far- to mid-infrared sensors with orders-of-magnitude improvement in sensitivity for outer planetary missions. These will allow thermal mapping of outer planets and their moons.

References:
An example of CubeSat mission using cryocoolers: https://www.jpl.nasa.gov/cubesat/missions/ciras.php

Scope Title: Sub-Kelvin Cooling Systems

Scope Description:
Future NASA missions will require sub-Kelvin coolers for extremely low-temperature detectors. Systems are sought that will provide continuous cooling with high cooling power (>5 µW at 50 mK), and high heat rejection temperature (10 K), while maintaining high thermodynamic efficiency and low system mass.

Improvements in components for adiabatic demagnetization refrigerators are also sought. Specific components include:

(1) Compact, lightweight, low-current superconducting magnets capable of producing a field of at least 4 tesla (T) while operating at a temperature of at least 10 K, and preferably above 15 K. Desirable properties include:

- A high engineering current density (including insulation and coil packing density), preferably >300 A/mm^2.
- A field/current ratio of >0.5 T/A, and preferably >0.66 T/A.
- Low hysteresis heating.
- Bore diameters ranging between 22 and 40 mm, and lengths ranging between 50 and 100 mm, depending on the application.

(2) Shielding requirements include:

- Lightweight active/passive magnetic shielding (for use with 4-T magnets) with low hysteresis and eddy current losses as well as low remanence. Shields should reduce stray field to <0.1 mT at 100 mm from the outer surface. In addition to simple cylinders, toroidal and other self-shielding geometries will be considered.
- Lightweight, highly effective outer shields that reduce the field outside an entire multistage device to <5 µT. Outer shields must operate at 4 to 10 K and must have penetrations for low-temperature, non-contacting heat straps.

(3) Heat switches with on/off conductance ratio >30,000 and actuation time of <10 s. Switches are sought to cover the temperature range 20 K > T > 0.03 K, though the hot/cold temperature ratio for any one switch is typically <5. They should have an on-state conductance of >(500 mW/K) x (T/4.5 K). Devices with no moving parts are preferred.

(4) High cooling power density magnetocaloric materials. Examples of desired materials include $GdLiF_4$, $Yb_3Ga_5O_{12}$, GdF_3, and Gd elpasolite. High-quality single crystals are preferred because of their high conductivity at low temperature, but high-density polycrystals are acceptable in some forms. Volume must be >40 cm^3.

(5) Suspensions with the strength and stiffness, but lower thermal conductance from 4 to 0.050 K.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:
Phase I: For components, a subscale prototype that proves critical parameters. For systems, a proof-of-concept test.

Phase II: For components, functioning hardware that is directly usable in NASA systems. For systems, a prototype that demonstrates critical performance parameters.

State of the Art and Critical Gaps:
The adiabatic demagnetization refrigerator in the Soft X-ray Spectrometer instrument on the Hitomi mission represents the state of the art in spaceflight sub-Kelvin cooling systems. The system is a 3-stage, dual-mode device. In the more challenging mode, it provides 650 µW of cooling at 1.625 K, while simultaneously absorbing 0.35 µW from a small detector array at 0.050 K. It rejects heat at 4.5 K. In this mode, the detector is held at temperature for 15.1-h periods, with a 95% duty cycle. Future missions with much larger pixel count will require much higher cooling power at 0.050 K or lower, higher cooling power at intermediate stages, and 100% duty cycle. Heat rejection at a higher temperature is also needed to enable the use of a wider range of more efficient cryocoolers.

Relevance / Science Traceability:
Science traceability: NASA Strategic plan 2018, Objective 1.1: Understand The Sun, Earth, Solar System, And Universe.

Sub-Kelvin coolers are listed as a "Technology Gap" in the latest (2017) Cosmic Origins Program Annual Technology Report.

Future missions that would benefit from this technology include:

(1) Two of the large missions under study for the 2020 Astrophysics Decadal Survey:
- Origins Space Telescope (contact: michael.j.dipirro@nasa.gov).
- LYNX (microcalorimeter instrument) (contact: simon.r.bandler@nasa.gov).

(2) Probe of Inflation and Cosmic Origins (POC: Shaul Hanany, University of Minnesota).

References:

For a description of the state-of-the-art sub-Kelvin cooler in the Hitomi mission:

1. Shirron, et al.: "Thermodynamic performance of the 3-stage ADR for the Astro-H Soft-X-ray Spectrometer instrument," *Cryogenics,* 74, pp. 24-30, 2016, and references therein.

For articles describing magnetic sub-Kelvin coolers and their components:

1. *Cryogenics,* 62, pp. 129-220, July 2014 special issue.

S16.08 Atomic Quantum Sensor and Clocks (SBIR)

Lead Center: GSFC
Participating Center(s): JPL

Scope Title: Atomic Quantum Sensor and Clocks

Scope Description:

Space exploration relies on sensors for science measurements as well as spacecraft operation. As sensing precisions push their limits, quantum phenomena inevitably must be exploited. It is expected that sensors utilizing quantum properties will offer new and significantly improved capabilities. NASA is interested in advancing quantum sensing technologies and infusing them into space science missions. In particular, this call seeks the development and maturation towards space application and qualification of atomic systems that leverage their quantum properties (e.g., optical atomic clocks, atom interferometers, Rydberg atom sensors, artificial atom-based sensors such as nitrogen-vacancy (NV) center point-defect sensors, etc.).

Recent developments of laser control and manipulation of atoms have led to new types of quantum sensors and clocks. Atomic particles, being intrinsically quantum mechanical, have demonstrated their unique advantages in metrology and sensing. Perhaps the most celebrated atomic metrology tool is the atomic clock. Atomic clocks in the optical frequency domain (i.e., optical primary frequency standards) have approached, and are expected to exceed, a frequency uncertainty beyond 1 part in $1x10^{18}$. These optical clocks can be used, in turn, as precision sensors, e.g., sensitivity to the fundamental physics constants has been explored for detection of dark matter and time variations in those fundamental constants.

Similarly, Doppler-sensitive quantum measurements of atomic particles led to exquisite inertial sensors, mostly in the form of atom interferometers. Because the center of mass motion is involved, atom interferometers use atomic particles as test masses and quantum matter-wave interferometry for motional measurements. Indeed, clocks and sensors are two sides of the same coin, sharing many common physical processes, technology approaches, and salient performance features. Therefore, this subtopic combines the two subject areas for leveraged and coordinated technology advancement. For many measurements the sensitivity scales as the square of the interaction time with an atom in free space. As this time can be dramatically longer (x100) in microgravity, these technologies are a natural fit for space exploration.

The gaps to be filled and technologies to be matured include, but are not limited to, the following:

(1) Optical atomic clocks

- Subsystem and components for high-performance and high-accuracy optical clocks, mostly notably Sr and Yb lattice clocks as well as Sr+ and Yb+ singly trapped ion clocks. They comprise atomic physics packages, which are necessarily laser systems, and include clock lasers, optical frequency combs, as well as advanced electronics and controllers based on microprocessors or field-programmable gate arrays (FPGAs). They should have a path to a flight system.
- Space-qualifiable small-size low-power clock lasers at, or subsystems that can lead to, better than 3×10^{-15} Hz/$\sqrt{\tau}$ near 0.1 to 10 s (wavelengths for Yb+, Yb, and Sr clock transitions are of special interest).
- Technical approaches and methods for beyond-state-of-the-art compact and miniature clocks for space with emphasis on the performance per size, power, and mass.

(2) Atom interferometers

- Space-qualifiable high-flux ultra-cold atom sources, related components, and methods (e.g., $>1\times10^{6}$ total atoms near the point at <1 nK for Rb, K, Cs, Yb, and Sr).
- Ultra-high vacuum technologies and approaches for atom interferometer applications that allow small-size and low-power, completely sealed, nonmagnetic enclosures with high-quality optical access and are capable of maintaining $<1\times10^{-9}$ Torr residual gas pressure. Consideration should be given to the inclusion of cold atom sources of interest, such as switchable and/or regulated atom vapor pressure or flux.
- Beyond the state-of-the-art photonic components at wavelengths for atomic species of interest, particularly visible and ultraviolet (UV):
  - Efficient acousto-optic modulators: e.g., low radio-frequency (RF) power ~200 mW, low thermal distortion, ~80% or greater diffraction efficiency.
  - Efficient electro-optic modulators: e.g., low bias drift, residual AM, and return loss; fiber-coupled preferred.
  - Miniature optical isolators: e.g., ~30 dB isolation or greater, ~ -2 dB loss or less.
  - Robust high-speed high-extinction shutters: e.g., switching time <1 ms and extinction >60 dB are highly desired.
- Flight qualifiable: i.e., rugged and long-life lasers or laser systems of narrow linewidth, high tunability, and/or higher power for clock and cooling transitions of atomic species of interest. Also, cooling and trapping lasers of 10 kHz linewidth and ~1 W or greater total optical power are generally needed, but offerors may define and justify their own performance specifications.
- Analysis and simulation tool of a cold atom system in trapped and free-fall states relevant to atom interferometer and clock measurements in space.

(3) Other atomic and artificial atomic sensors

- Rydberg sensors or their subsystems/components for electric field or microwave measurements.
- Space-qualifiable NV diamond or chip-scale atomic magnetometers.
- High-performance, miniaturized or chip-scale optical frequency combs.
- Other innovative atomic quantum sensors for high-fidelity field measurements that have space applications and can be developed into a space-quantifiable instrument.

Because of the breath and diversity of the portfolio, performers are expected to be aware of specific gaps for specific application scenarios. All proposed system performances may be defined by offeror with clear justifications. Subsystem technology development proposals should clearly state the relevance to the anticipated system-level implementation and performance; define requirements, relevant atomic species, and working laser wavelengths; and indicate its path to a space-borne instrument. Finally, for proposals interested in quantum sensing methodologies for achieving the optimal collection of light for photon-starved astronomical observations, it is suggested to consider the STTR subtopic T8.06.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research
- Analysis
- Software

Desired Deliverables Description:
Phase I deliverables: results of a feasibility study, analysis, and preliminary laboratory demonstration, as described in a final report.

Phase II deliverables: prototype or demonstration hardware; summary of performance analysis; and applicable supporting documentation, data, and/or test reports.

State of the Art and Critical Gaps:
Many technology gaps exist in the development state of atomic sensors and clocks intended for NASA space applications. These gaps are mainly in the areas of reducing size, mass, and power, while increasing their performance and advancing them towards space qualification. These gaps may pertain to components, subsystems, instruments/devices, novel approaches, and/or theoretical analysis tools. Most of the needed improvements are elements that are beyond the current state of the art. These needed improvements include high-flux ultra-cold atom sources, atomic physics packages and atomic vacuum cell technology specific to clock and atom interferometer applications, miniature optical isolators, efficient modulators, active wave front and polarization devices, fast high-extension-ratio switches, efficient detectors, and novel frequency conversion methods/devices. Also needed are lasers and laser-optics system approaches with a high degree of integration and robustness that are suitable for atomic devices, small ultra-stabilized laser systems, and miniature self-referenced optical frequency combs. These are examples and not an exhaustive list.

Relevance / Science Traceability:
Currently, no technology exists that can compete with the (potential) sensitivity, (potential) compactness, and robustness of atom-optical-based gravity- and time-measurement devices. Earth science, planetary science, and astrophysics all benefit from unprecedented improvements in gravity and time measurement. Specific roadmap items supporting science instrumentation include, but are not limited to:

- TX07.1.1: Destination Reconnaissance, Prospecting, and Mapping (gravimetry)
- TX08.1.2: Electronics (reliable control electronics for laser systems)
- TX08.1.3: Optical Components (reliable laser systems)
- TX08.1.4: Microwave, Millimeter, and Submillimeter-Waves (ultra-low noise microwave output when coupled w/ optical frequency comb)
- TX08.1.5: Lasers (reliable laser system w/ long lifetime)

References:

1. 2020 NASA Technology Taxonomy: https://go.nasa.gov/3hGhFJf
2. 2017 NASA Strategic Technology Investment Plan: https://go.usa.gov/xU7sE

Focus Area 10 Advanced Telescope Technologies

The NASA Science Mission Directorate (SMD) seeks technology for cost-effective high-performance advanced space telescopes for astrophysics and Earth science. Astrophysics applications require large aperture lightweight highly reflecting mirrors, deployable large structures, innovative wavefront and structural metrology, and cryogenic optics to enable far infrared telescopes. A few of the new astrophysics telescopes and their subsystems will require operation at cryogenic temperatures as cold as 4 K. This focus area will consider technologies necessary to enable future telescopes and observatories collecting electromagnetic bands, ranging from X-rays to millimeter waves, and also include gravity waves. New technologies in innovative mirror materials, such as silicon, silicon carbide and nanolaminates, and innovative structures and deployments are needed on scales ranging from cubesats to flagship class missions. Instruments commonly benefit in size and cost from the use of free-form optics and require innovative fabrication and metrology systems. Instrument technologies for high-contrast exoplanet imaging include deformable mirrors and active structures for high-precision wavefront control and stabilization, as well as technologies to accurately deploy and control scattered light with large scale deployable occulters. Wavelength control and stabilization approaches are critical to the success of high-precision radial velocity measurements. Earth science requires modest apertures in the 2 to 4 meter size category that are cost effective. Both nanotechnology and wavefront sensing and control are needed to build telescopes for Earth science.

S12.01 Exoplanet Detection and Characterization Technologies (SBIR)

Lead Center: JPL
Participating Center(s): GSFC

Scope Title: Control of Scattered Starlight with Coronagraphs

Scope Description:
This scope addresses the unique problem of imaging and spectroscopic characterization of faint astrophysical objects that are located within the obscuring glare of much brighter stellar sources. Examples include planetary systems beyond our own, the detailed inner structure of galaxies with very bright nuclei, binary star formation, and stellar evolution. Contrast ratios of one million to ten billion over an angular spatial scale of 0.05 to 1.5 arcsec are typical of these objects. Achieving a very low background requires control of both scattered and diffracted light. The failure to control either amplitude or phase fluctuations in the optical train severely reduces the effectiveness of starlight cancellation schemes.

This innovative research focuses on advances in coronagraphic instruments that operate at visible and near-infrared wavelengths. The ultimate application of these instruments is to operate in space as part of a future observatory mission concept such as the Habitable Exoplanet Observatory (HabEx) and Large Ultraviolet Optical Infrared Surveyor (LUVOIR). Measurement techniques include imaging, photometry, spectroscopy, and polarimetry. There is interest in component development and innovative instrument design, as well as in the fabrication of subsystem devices that include, but are not limited to, the following areas:

Starlight diffraction control and characterization technologies:

- Diffraction control masks for coronagraphs and scaled starshade experiments, which includes transmissive scalar, polarization-dependent, spatial apodizing, and hybrid metal/dielectric masks, including those with extremely low reflectivity regions that allow them to be used in reflection.
- Systems to measure spatial optical density, phase inhomogeneity, scattering, spectral dispersion, thermal variations, and to otherwise estimate the accuracy of high-dynamic range apodizing masks.
- Methods to distinguish the coherent and incoherent scatter in a broadband speckle field.

Wavefront control technologies:

- Small-stroke, high-precision, deformable mirrors scalable to 10,000 or more actuators (both to further the state of the art towards flight-like hardware and to explore novel concepts). Multiple deformable mirror technologies in various phases of development and processes are encouraged to ultimately improve the state of the art in deformable mirror technology. Process improvements are needed to improve repeatability, yield, power consumption, connectivity, stability, and performance precision of current devices.

- High-precision, stable, deformable mirrors whose nominal surface can carry optical prescriptions for dual use as imaging optics such as off-axis parabolas and apodizing elements. Similar to other technologies, scalable actuator arrays between hundreds and thousands of actuators are encouraged.
- Driving electronics, including multiplexers and application-specific integrated circuits (ASICs) with ultra-low power dissipation for electrical connection to deformable mirrors.

Optical coating and measurement technologies:

- Instruments capable of measuring polarization crosstalk and birefringence to parts per million.
- Polarization-insensitive coatings for large optics.
- Methods to measure the spectral reflectivity and polarization uniformity across large optics.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
A concept study provided as a final report in Phase I is acceptable, and a prototype for Phase II is acceptable.

State of the Art and Critical Gaps:
Coronagraphs have been demonstrated to achieve high contrast in moderate bandwidth in laboratory environments. The extent to which the telescope optics will limit coronagraph performance is a function of the quality of the optical coating and the ability to control polarization over the full wavefront. Wavefront control using deformable mirrors is critical. Controllability and stability to picometer levels is required. To date, deformable mirrors have been up to the task of providing contrast approaching 10^{10}, but they require thousands of wires, and overall wavefront quality and stroke remain concerns.

Relevance / Science Traceability:
These technologies are directly applicable to mission concept studies such as HabEx, LUVOIR, starshades, and any space telescopes that could potentially be used for exoplanet imaging and characterization.

References:
See SPIE conference papers and articles published in the Journal of Astronomical Telescopes and Instrumentation on high-contrast coronagraphy, segmented coronagraph design and analysis, and starshades.

1. Exoplanet Exploration - Planets Beyond Our Solar System: https://exoplanets.jpl.nasa.gov
2. Exoplanet Exploration Program: https://exoplanets.nasa.gov/exep/
    - Specifically the technology pages and those addressing coronagraphs: https://exoplanets.nasa.gov/exep/technology/technology-overview/
    - The 5-year technology development plan: https://exoplanets.nasa.gov/internal_resources/446/
3. Goddard Space Flight Center: https://www.nasa.gov/goddard

Scope Title: Control of Scattered Light with Starshades

Scope Description:
As with coronagraphs, this scope addresses the unique problem of imaging and spectroscopic characterization of faint astrophysical objects that are located within the obscuring glare of much brighter stellar sources. Examples include planetary systems beyond our own, the detailed inner structure of galaxies with very bright nuclei, binary star formation, and stellar evolution. Contrast ratios of one million to ten billion over an angular spatial scale of 0.05 to 1.5 arcsec are typical of these objects. Achieving a very low background requires control of both scattered and diffracted light. The starshade's shape is designed to control the diffraction of starlight and form a deep shadow around the distant telescope. In this way, high contrast is achieved with a diffraction-limited telescope that does not require an internal high-precision wavefront control system. Sources of scatter include sunlight glinting on the sharp edges of the starshade, and multiple reflections between petal surfaces and edge assemblies. Earthshine on the telescope-facing surfaces must also be considered.

The research focuses on:

- Low-scatter, low-reflectivity, sharp, flexible razor-sharp edges for control of solar scatter at the perimeter of the starshade.
- Large-area (hundreds of square meters) anti-reflection and thermal-control coatings for flexible optical shield surfaces that are robust to cleaning and handling for starshade optical surfaces.
- Particulate contamination mitigation measures, including (but not limited to) dust-resistant coatings, vacuum-ultraviolet-eroding coatings, and on-orbit cleaning technologies.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
A concept study provided as a final report in Phase I is acceptable, and a prototype for Phase II is acceptable.

State of the Art and Critical Gaps:
The optical design of the starshade has been tested at laboratory scales and shown to achieve 10^{-10} contrast in broadband light in flight-like geometries. Model validation of perturbation sensitivities have also been demonstrated for contrast levels of 10^{-9}. A full-scale 10-m disk including the optical shield has been constructed, deployed, and shown to meet flight deployment requirements. Half-scale petals have been constructed and tested, validating the required thermal stability. Formation flying sensitivity has been demonstrated in the laboratory and through modeling to levels required for flight. Critical gaps relevant to this call include the fabrication of sharp optical edges and optical edge assemblies as well as methods to mitigate both particulate and molecular contamination of the edges and the telescope-facing surfaces.

Relevance / Science Traceability:
These technologies are directly applicable to mission concept studies such as Habitable Exoplanet Observatory (HabEx), Large Ultraviolet Optical Infrared Surveyor (LUVOIR), starshade missions, and any space telescopes that could potentially be used for exoplanet imaging and characterization.

References:

Technology development reports, concept videos, and prototype deployment videos:
https://exoplanets.nasa.gov/exep/technology/starshade/

Scope Title: Technology for Extreme Precision Radial Velocity

Scope Description:
Astronomical spectrographs have proven to be powerful tools for exoplanet searches. When a star experiences periodic motion due to the gravitational pull of an orbiting planet, its spectrum is Doppler modulated in time. This is the basis for the precision radial velocity (PRV) method, one of the first and most efficient techniques for detecting and characterizing exoplanets. Because spectrographs have their own drifts, which must be separated from the periodic Doppler shift, a stable reference is always needed for calibration. Optical frequency combs (OFCs) and line-referenced etalons are capable of providing the spectral rulers needed for PRV detection of exoplanets. Although "stellar jitter" (a star's photospheric velocity contribution to the RV signal) is unavoidable, the contribution to the error budget from Earth's atmosphere would be eliminated in future space missions. Thus, there is a need to develop robust spectral references, especially at visible wavelengths to detect and characterize Earth-like planets in the habitable zone of their Sun-like host stars, with size, weight, and power (SWaP) suitable for space-qualified operation to calibrate the next generation of high-resolution spectrographs with precision corresponding to <~1 cm/sec over multiple years of observations.

This scope solicits proposals to develop cost-effective component and subsystem technology for low-SWaP, long-lived, robust implementation of RV measurement instruments both on the ground and in space. Research areas of interest include but are not limited to:

- Integrated photonic spectrographs.
- Spectrograph gratings.
- PRV spectrograph calibration sources.
- High-efficiency photonic lanterns.
- Advanced optical fiber delivery systems and subsystems with high levels of image scrambling and modal noise reduction.
- Software for advanced statistical techniques to mitigate effects of telluric absorption and stellar jitter on RV precision and accuracy.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Hardware
- Software

Desired Deliverables Description:

- Phase I will emphasize research aspects for technical feasibility, have infusion potential into ground or space operations, provide clear and achievable benefits (e.g., reduction in SWaP and/or cost, improved RV precision), and show a path towards a Phase II proposal. Phase I deliverables include feasibility and concept of operations of the research topic, simulations, and measurements; validation of the proposed approach to develop a given product (TRL 3 to 4); and a plan for further development of the specific capabilities or products to be performed in Phase II. Early development and delivery of prototype hardware/software is encouraged.
- Phase II will emphasize hardware/software development with delivery of specific hardware or software products for NASA, targeting demonstration operations at a ground-based telescope in coordination with the lead NASA center. Phase II deliverables include a working prototype or engineering model of the proposed product/platform or software along with documentation of

development, capabilities, and measurements (showing specific improvement metrics); and tools as necessary. Proposed prototypes shall demonstrate a path towards a flight-capable platform. Opportunities and plans should also be identified and summarized for potential commercialization or NASA infusion.

State of the Art and Critical Gaps:
High-resolving-power spectrographs (R ~ 150,000) with simultaneous ultraviolet (UV), visible, and near-infrared (NIR) coverage and exquisite long-term stability are required for PRV studies. Classical bulk optic spectrographs traditionally used for PRV science impose architectural constraints because of their large mass and limited optical flexibility. Integrated photonic spectrographs are wafer-thin devices that could reduce instrument volume by up to 3 orders of magnitude. Spectrometers that are fiber fed, with high illumination stability, excellent wavelength calibration, and precise temperature and pressure control represent the immediate future of precision RV measurements.

Traditional RV spectrographs would benefit from improvements in grating technology. Diffraction-limited PRV spectrographs require echelle gratings with low wavefront error and high efficiency—both of which are very challenging to achieve. Echelle spectrographs are designed to operate at high angle of incidence and very high diffraction order; thus, the grating must have very accurate groove placement (for low wavefront error) and very flat groove facets (for high efficiency). For decades, echelle gratings have been fabricated by diamond ruling, but it is difficult to achieve the level of performance required for PRV instruments. Newer grating fabrication techniques using lithographic methods to form the grooves may be a promising approach. As spectrograph stability imposes limits on how precisely RV can be measured, spectral references play a critical role in characterizing and ensuring this precision. Only laser frequency combs (LFCs) and line-referenced Fabry-Pérot etalons are capable of providing the broad spectral coverage and long-term stability needed for extreme PRV detection of exoplanets. Although both frequency combs and etalons can deliver high-precision spectrograph calibration, the former requires relatively complex hardware in the visible portion of the spectrum.

Commercial fiber laser astrocombs covering 450 to 1400 nm at 25 GHz line spacing and <3 dB intensity variations over the entire bandwidth are available for ground-based astronomical spectrographs. However, the cost for these systems is often so prohibitive that recent RV spectrograph projects either do not use a LFC or include it only as a future upgrade. Alternatively, astrocombs produced by electro-optic modulation (EOM) of a laser source have been demonstrated in the NIR. EOM combs produce modes spaced at a radio-frequency (RF) modulation frequency, typically 10 to 30, and they avoid the line-filtering step required by commercial mode-locked fiber laser combs. The comb frequency can be stabilized by referencing the laser pump source to a molecular absorption feature or another frequency comb. Where octave spanning EOM combs are available, f-2f self-referencing provides the greatest stability. EOM combs must be spectrally broadened to provide the bandwidth necessary for PRV applications. This is accomplished through pulse amplification followed by injection into highly nonlinear fiber or nonlinear optical waveguides.

Power consumption of the frequency comb calibration system will be a significant driver of mission cost for space-based PRV systems and motivates the development of a comb system that operates with less than 20 W of spacecraft power. Thus, for flight applications, it is highly desirable to develop frequency comb technology with low power consumption; ~10 to 30 GHz mode spacing; compact size; broad (octave spanning) spectral grasp across both the visible and NIR; low phase noise; stability traceable to the International System of Units definition of the second; and importantly, long life.

The intrinsic illumination stability of the spectrometer also sets a fundamental measurement floor. As the image of the star varies at the entrance to the spectrometer because of atmospheric effects and telescope guiding errors, so too does the recorded stellar spectrum, leading to a spurious RV offset. Current seeing-limited PRV instruments use multimode optical fibers, which provide some degree of azimuthal image scrambling, to efficiently deliver stellar light from the telescope focal plane to the spectrometer input. Novel-core-geometry fibers, in concert with dedicated optical double-scramblers, are often used to further homogenize and stabilize the telescope illumination pattern in both the image and pupil planes. However, these systems still demonstrate measurable sensitivity to incident illumination variations from the telescope and atmosphere. Furthermore, as spectral resolution requirements increase, the commensurate increase in instrument size becomes impractical. Thus, the community has turned to implementing image and pupil slicers to reformat the near or far fields of light entering the spectrometer by preferentially redistributing starlight exiting the fiber to maintain high spectral resolution, efficiency, and compact spectrometer size.

Relevance / Science Traceability:
The NASA Strategic Plan (2018) and Space Mission Directorate Science Plan (2014) both call for discovery and characterization of habitable Earth analogs and the search for biosignatures on those worlds. These goals were endorsed and amplified upon in the recent National Academy of Science (NAS) Exoplanet Report, which emphasized that a knowledge of the orbits and masses is essential to the complete and correct characterization of potentially habitable worlds. PRV measurements are needed to follow up on the transiting worlds discovered by Kepler, K2, and Transiting Exoplanet Survey Satellite (TESS). The interpretation of the transit spectra that the James Webb Space Telescope (JWST) will obtain will depend on knowledge of a planet’s surface gravity, which comes from its radius (from the transit data) and its mass (from PRV measurements or, in some cases, transit timing variations). Without knowledge of a planet's mass, the interpretation of its spectrum is subject to many ambiguities.

These ambiguities will only be exacerbated for the direct-imaging missions such as the proposed Habitable Exoplanet Observatory (HabEx) and Large Ultraviolet Optical Infrared Surveyor (LUVOIR) flagships, which will obtain spectra of Earth analogs around a few tens to hundreds of stars. Even if a radius can be inferred from the planet's brightness and an estimate of its albedo, the lack of a dynamical mass precludes any knowledge of the planet's density, bulk composition, and surface gravity, which are needed to determine, for example, absolute gas column densities. Moreover, a fully characterized orbit is challenging to determine from just a few direct images and may even be confused in the presence of multiple planets. Is a planet in a highly eccentric orbit habitable or not? Only dynamic (PRV) measurements can provide such information. Thus, highly precise and highly stable PRV measurements are absolutely critical to the complete characterization of habitable worlds.

The NAS report also noted that measurements from space might be a final option if the problem of telluric contamination cannot be solved. The Earth’s atmosphere will limit precise radial velocity measurements to ~10 cm/sec at wavelengths longer than ~700 nm and greater than 30 cm/sec at wavelengths >900 nm, making it challenging to mitigate the effects of stellar activity without a measurement of the color dependence due to stellar activity in the PRV time series. A space-based PRV mission, such as has been suggested in the NASA EarthFinder mission concept study, may be necessary. If so, the low-SWaP technologies developed under this SBIR program could help enable space-based implementations of the PRV method.

References:

Precision radial velocity:
1. Fischer et al.: "State of the Field: Extreme Precision Radial Velocities," 2016, http://adsabs.harvard.edu/abs/2016PASP..128f6001
2. Plavchan et al.: "Radial Velocity Prospects Current and Future: A White Paper Report prepared by the Study Analysis Group 8 for the Exoplanet Program Analysis Group (ExoPAG)," 2015, http://adsabs.harvard.edu/abs/2015arXiv150301770P
3. Plavchan et al.: "EarthFinder Probe Mission Concept Study (Final Report)," 2019, https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/Earth_Finder_Study_Rpt.pdf
4. EPRV Working Group report. See this website for preliminary information and the final report from this group due in mid-August: https://exoplanets.nasa.gov/exep/NNExplore/EPRV/

Photonic lanterns:
1. Gris-Sanchez et al.: "Multicore fibre photonic lanterns for precision radial velocity Science," 2018, https://academic.oup.com/mnras/article/475/3/3065/4769655

2. Jovanovic, N. et al.: Integrated photonic building blocks for next-generation astronomical instrumentation I: the multimode waveguide. *Optics Express*, 20, 17029, 2012.

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1. Yi, X. et al.: "Demonstration of a near-IR line-referenced electro-optical laser frequency comb for precision radial velocity measurements in astronomy," *Nature Communications*, 7, 10436, 2016.
2. Halverson, S. et al.: "The habitable-zone planet finder calibration system," Proc. *SPIE 9147*, Ground-based and Airborne Instrumentation for Astronomy V, 91477Z, 2014, https://doi.org/10.1117/12.2054967
3. Suh, M.-G., et al.: "Searching for exoplanets using a microresonator astrocomb," *Nature Photonics*, 13(1), pp. 25–30, 2019.
4. Obrzud, E., et al.: "A Microphotonic Astrocomb," *Nature Photonics*, 13 (1), pp. 31–35, 2019.
5. Metcalf, A., et al.: "Stellar Spectroscopy in the Near-infrared with a Laser Frequency Comb," *Optica,* 6(2), 2019.
6. Lee, S.H., Oh, D.Y., Yang, Q. et al.: "Towards visible soliton microcomb generation," *Nat Commun*, 8, 1295, 2017.

Nonlinear waveguides:

1. Chang, L., et al.: "Heterogeneously integrated GaAs waveguides on insulator for efficient frequency conversion," *Laser Photonics Reviews*, 12, 1800149, 2018, https://doi.org/10.1002/lpor.201800149
2. Halir, R., et al.: "Ultrabroadband supercontinuum generation in a CMOS-compatible platform," *Optics letters*, 37, 1685, 2012, https://doi.org/10.1364/OL.37.001685

Spectral flattening:

1. Probst, R.A., et al.: "Spectrally Flattened, Broadband Astronomical Frequency Combs," 2015, https://doi.org/10.1364/CLEO_SI.2015.SW4G.7

S12.02 Precision Deployable Optical Structures and Metrology (SBIR)

Lead Center: JPL
Participating Center(s): GSFC

Scope Title: Precision Optical Metering Structures and Instruments

Scope Description:

Future space astronomy missions from ultraviolet to millimeter wavelengths will push the state of the art in current optomechanical technologies. Size, dimensional stability, temperature, risk, manufacturability, and cost are important factors, separately and in combination. The Large Ultraviolet Optical Infrared Surveyor (LUVOIR) calls for deployed apertures as large as 15 m in diameter; the Origins Space Telescope (OST), for operational temperatures as low as 4 K; and LUVOIR and the Habitable Exoplanet Observatory (HabEx), for exquisite optical quality. Methods to construct large telescopes in space are also under development. Additionally, sunshields for thermal control and starshades for exoplanet imaging require deployment schemes to achieve 30- to 70-m-class space structures.

This subtopic addresses the need to mature technologies that can be used to fabricate 10- to 20-m-class, lightweight, ambient or cryogenic flight-qualified observatory systems and subsystems (telescopes, sunshields, starshades). Proposals to fabricate demonstration components and subsystems with direct scalability to flight systems through validated models will be given preference. The target launch volume and expected disturbances, along with the estimate of system performance, should be included in the discussion. Novel metrology solutions to establish and maintain optical alignment will also be accepted.

Technologies including, but not limited to, the following areas are of particular interest:

Precision structures/materials:

- Low coefficient of thermal expansion/coefficient of moisture expansion (CTE/CME) materials/structures to enable highly dimensionally stable optics, optical benches, and metering structures.
- Materials/structures to enable deep-cryogenic (down to 4 K) operation.
- Novel athermalization methods to join materials/structures with differing mechanical/thermal properties.
- Lightweight materials/structures to enable high-mass-efficiency structures.
- Precision joints/latches to enable submicron-level repeatability.
- Mechanical connections providing microdynamic stability suitable for robotic assembly.

Deployable technologies:

- Precision deployable modules for assembly of optical telescopes (e.g., innovative active or passive deployable primary or secondary support structures).
- Hybrid deployable/assembled architectures, packaging, and deployment designs for large sunshields and external occulters (20- to 50-m class).
- Packaging techniques to enable more efficient deployable structures.

Metrology:

- Techniques to verify dimensional stability requirements at subnanometer-level precision (10 to 100 pm).
- Techniques to monitor and maintain telescope optical alignment for on-ground and in-orbit operation.

A successful proposal shows a path toward a Phase II delivery of demonstration hardware scalable to 5-m diameter for ground test characterization. Proposals should show an understanding of one or more relevant science needs and present a feasible plan to fully develop the relevant subsystem technologies and transition them into a future NASA program(s).

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.2 Structures

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
For Phase I, a successful deliverable would include a demonstration of the functionality and/or performance of a system/subsystem with model predictions to explain observed behavior as well as make predictions on future designs.

For Phase II this should be demonstrated on units that can be scaled to future flight sizes.

State of the Art and Critical Gaps:
The James Webb Space Telescope represents the state of the art in large deployable telescopes. The Roman Space Telescope (RST) coronagraph instrument (CGI) will drive telescope/instrument stability requirements to new levels. The mission concepts in the upcoming Astro2020 decadal survey will push technological requirements even further in the areas of deployment, size, stability, lightweighting, and operational

temperature. Each of these mission studies have identified technology gaps related to their respective mission requirements.

Relevance / Science Traceability:
These technologies are directly applicable to the RST CGI and the HabEx, LUVOIR, and OST mission concepts. Ultra-stable opto-mechanical systems are listed as a "critical" technology gap with an "urgent" priority in the LUVOIR STDT Final Report for the Astro2020 Decadal Survey.

References:

1. Large UV/Optical/IR Surveyor (LUVOIR): https://asd.gsfc.nasa.gov/luvoir/
2. Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/
3. Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/
4. What is an Exoplanet? https://exoplanets.nasa.gov/what-is-an-exoplanet/technology/
5. NASA in-Space Assembled Telescope (iSAT) Study: https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/

S12.03 Advanced Optical Systems and Fabrication/Testing/Control Technologies for Extended-Ultraviolet/Optical and Infrared Telescope (SBIR)

Lead Center: MSFC
Participating Center(s): GRC, GSFC, JPL, LaRC

Introduction:
Accomplishing NASA's high-priority science at all levels (flagship, probe, Medium-Class Explorers (MIDEX), Small Explorers (SMEX), rocket, and balloon) requires low-cost, ultra-stable, normal-incidence mirror systems with low mass-to-collecting-area ratios. Here, a mirror system is defined as the mirror substrate, supporting structure, and associated actuation and thermal management systems. After performance (diffraction limit, stability, collecting area), the most important metric for an advanced optical system is affordability or areal cost (cost per square meter of collecting aperture), followed by mass.

This subtopic has multiple scopes. Each scope has its own sponsoring NASA center and is important to that Center. Centers will review proposals submitted to their Scope and manage any awarded contracts.

Scopes are defined based on specific applications, technology gap needs, or operating wavelength regime. Each scope has its own defined performance metrics.

Proposals must show an understanding of one or more relevant science needs and present a feasible plan to develop the proposed technology for infusion into a NASA program: suborbital rocket or balloon, competed SMEX or MIDEX, or Decadal-class mission. Successful proposals will demonstrate an ability to manufacture, test, and control ultra-low-cost optical systems that can meet science performance requirements and mission requirements (including processing and infrastructure issues). Material behavior, process control, active and/or passive optical performance, and mounting/deploying issues should be resolved and demonstrated.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype

- Hardware

Desired Deliverables Description:

- An ideal Phase I deliverable would be a precision optical system of at least 0.25 m; a relevant subcomponent of a system; a prototype demonstration of a fabrication, test, or control technology leading to a successful Phase II delivery; or a reviewed preliminary design and manufacturing plan that demonstrates feasibility. Although detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.
- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 m or a relevant subcomponent (with a TRL in the 4 to 5 range) or working fabrication, test, or control system. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase II would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly that can be integrated into the potential mission as well as demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analyses).

State of the Art and Critical Gaps:

Current normal-incidence space mirrors cost $4 million to $6 million per square meter of optical surface area. This research effort seeks to improve the performance of advanced precision optical components while reducing their cost by 5× to 50×, to between $\$100\text{K/m}^2$ and $\$1\text{M/m}^2$.

Relevance / Science Traceability:

This subtopic primarily supports potential Astrophysics Division missions. It has made optical systems in the past for potential balloon experiments. Future potential Decadal missions include Laser Interferometer Space Antenna (LISA), Habitable Exoplanet Observatory (HabEx), Large UV/Optical/Near-IR Surveyor (LUVOIR), and the Origins Space Telescope (OST).

References:

1. The best source for Flagship and Probe mission concepts under consideration: https://science.nasa.gov/astrophysics/2020-decadal-survey-planning
2. The best source for technology gaps that need development is documented in the Astrophysics Division Program Annual Technology Report (PATR): https://apd440.gsfc.nasa.gov/tech-documents.html

Scope Title: Telescopes for Balloon Missions

Scope Description:

Astronomy from a stratospheric balloon platform offers numerous advantages. At typical balloon cruise altitudes (100,000 to 130,000 ft.), 99%+ of the atmosphere is below the balloon, and the attenuation due to the remaining atmosphere is small. This is particularly important in the near-ultraviolet (NUV) bands and in the infrared (IR) bands near 2.7 and 4.25 µm. The lack of atmosphere nearly eliminates scintillation and allows the resolution potential of relatively large optics to be realized, and the small amount of atmosphere reduces scattered light and allows observations of brighter objects, even during daylight hours.

Potential balloon science missions are either in the extreme UV (EUV), UV/optical (UVO), or in the infrared/far-infrared (IR/FIR):

- EUV missions require optical components with surface slopes of <0.1 µrad.

- UVO science missions require 1-m-class telescopes diffraction limited at 500 nm .
- IR science missions require 2-m-class telescopes diffraction limited at 5 µm.
- FIR missions require 2-m-class (or larger) telescopes diffraction limited at 50 µm.

In all cases, telescopes must be able to maintain diffraction-limited performance for elevation angles ranging from 10° to 65° over a temperature range of 220 to 280 K.

Also, the telescopes need to have a total mass of less than 300 kg and be able to survive a 10g shock (on landing) without damage.

For packaging reasons, the primary mirror assembly must have a radius of curvature 3 m (nominal) and a mass <150 kg.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

- Phase I will produce a preliminary design and report including initial design requirements such as wavefront error budget, mass allocation budget, structural stiffness requirements, etc., as well as trade studies performed and an analysis that compares the design to the expected performance over the specified operating range. Development challenges shall be identified during Phase I, including trade studies and challenges to be addressed during Phase II with subsystem proof-of-concept demonstration hardware.
- If Phase II can only produce a subscale component, then it should also produce a detailed final design, including final requirements (wavefront error budget, mass allocation, etc.) and a performance assessment over the specified operating range.

State of the Art and Critical Gaps:
Current SOA (state-of-the-art) UVO mirrors made from Zerodur$^{(R)}$ or Ultra-Low Expansion Glass, ULE$^{(R)}$, for example, require lightweighting to meet balloon mass limitations and cannot meet diffraction-limited performance over the wide temperature range because of the coefficient of thermal expansion limitations. Current SOA IR mirrors are typically made from aluminum and the diffraction-limited performance is limited by gravity sag change as a function of elevation angle.

Relevance / Science Traceability:
“Vision and Voyages for Planetary Science in the Decade 2013-2022”:

- Page 22, last paragraph of NASA Telescope Facilities within the Summary Section: "...Balloon- and rocket-borne telescopes offer a cost-effective means of studying planetary bodies at wavelengths inaccessible from the ground. Because of their modest costs and development times, they also provide training opportunities for would-be developers of future spacecraft instruments. Although NASA’s Science Mission Directorate regularly flies balloon missions into the stratosphere, there are few funding opportunities to take advantage of this resource for planetary science because typical planetary grants are too small to support these missions. A funding line to promote further use of these suborbital observing platforms for planetary observations would complement and reduce the load on the already oversubscribed planetary astronomy program..."

- Page 203, 5th paragraph of section titled "Earth and Space-Based Telescopes": "...Significant planetary work can be done from balloon-based missions flying higher than 45,000 ft. This altitude provides access to electromagnetic radiation that would otherwise be absorbed by Earth's atmosphere and permits high-spatial-resolution imaging unaffected by atmospheric turbulence. These facilities offer a combination of cost, flexibility, risk tolerance, and support for innovative solutions that is ideal for the pursuit of certain scientific opportunities, the development of new instrumentation, and infrastructure support. Given the rarity of giant-planet missions, these types of observing platforms (high-altitude telescopes on balloons and sounding rockets) can be used to fill an important data gap..."

Potential advocates include planetary scientists at Goddard Space Flight Center (GSFC), Johns Hopkins Applied Physics Laboratory (APL), Southwest Research Institute (SWRI), and other sites.

References:
For additional discussion of the advantages of observations from stratosphere platforms, refer to:

1. Dankanich et. al.: "Planetary Balloon-Based Science Platform Evaluation and Program Implementation - Final Report," available from: https://ntrs.nasa.gov/ (search for "NASA/TM-2016-218870").

For additional information about scientific balloons, refer to:

1. https://www.csbf.nasa.gov/docs.html

Scope Title: Optical Components and Telescopes for Large Ultraviolet/Optical/Near-IR Telescopes

Scope Description:
Potential ultraviolet/optical (UVO) space missions require telescopes with apertures ranging from 1 to 8 m monolithic or 3 to 16 m segmented with better than 500 nm diffraction-limited performance or 40 nm rms transmitted wavefront (achieved either passively or via active control). Optical components need to have <5 nm rms surface figures. Additionally, a potential exoplanet mission, using an internal coronagraph, requires total telescope wavefront stability on order of 10 pm rms per 10 min. This stability specification places severe constraints on the dynamic mechanical and thermal performance of a 4-m or larger telescope. Potential enabling technologies include active thermal control systems, ultrastable mirror support structures, athermal telescope structures, athermal mirror struts, ultrastable joints with low coefficients of thermal expansion (CTE), and vibration compensation. Analysis indicates that the first mode for structure and optical components needs to be in the range of 60 to 500 Hz. Also, operating temperatures should range from 250 to 300 K.

Mirror areal density depends upon available launch vehicle capacities to Sun-Earth L2 (i.e., 15 kg/m^2 for a 5-m-fairing Evolved Expendable Launch Vehicle (EELV) versus 150 kg/m^2 for a 10-m-fairing Space Launch System (SLS)). Regarding areal cost, a good goal is to keep the total cost of the primary mirror at or below $100M. Thus, an 8-m-class mirror (with 50 m^2 of collecting area) should have an areal cost of less than $2M/m^2. Also, a 16-m-class mirror (with 200 m^2 of collecting area) should have an areal cost of less than $0.5M/m^2.

Key technologies to enable such a mirror include new and improved:

- Mirror substrate materials and/or architectural designs.
- Processes to rapidly fabricate and test UVO-quality mirrors.
- Mirror support structures, joints, and mechanisms that are athermal or have 0 CTE at the desired scale.
- Mirror support structures, joints, and mechanisms that are ultrastable at the desired scale.
- Mirror support structures with low mass that can survive launch at the desired scale.
- Mechanisms and sensors to align segmented mirrors to <1 nm rms precisions.

- Thermal control (<1 mK) to reduce wavefront stability to <10 pm rms per 10 min.
- Dynamic isolation (>140 dB) to reduce wavefront stability to <10 pm rms per 10 min.

Also needed is the ability to fully characterize surface errors and predict optical performance via integrated optomechanical modeling.

Potential solutions for substrate material/architecture include but are not limited to: ultra-uniform low-CTE glasses, silicon carbide, nanolaminates, or carbon-fiber-reinforced polymer. Potential solutions for mirror support structure material/architecture include, but are not limited to additive manufacturing, nature-inspired architectures, nanoparticle composites, carbon fiber, graphite composite, and ceramic or SiC materials. Potential solutions for new fabrication processes include, but are not limited to: additive manufacturing, direct precision machining, rapid optical fabrication, roller embossing at optical tolerances, slumping, or replication technologies to manufacture 1- to 2-m- (or larger) precision quality components. Potential solutions for achieving the 10-pm wavefront stability include, but are not limited to: metrology, passive control, and active control for optical alignment and mirror phasing; active vibration isolation; metrology; and passive and active thermal control.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Hardware
- Software
- Prototype

Desired Deliverables Description:

- An ideal Phase I deliverable would be a precision optical system of at least 0.25 m; a relevant subcomponent of a system; a prototype demonstration of a fabrication, test, or control technology leading to a successful Phase II delivery; or a reviewed preliminary design and manufacturing plan that demonstrates feasibility. While detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.
- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 m or relevant subcomponent (with a TRL in the 4 to 5 range) or a working fabrication, test, or control system. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase II would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly that can be integrated into the potential mission as well as demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analyses).

State of the Art and Critical Gaps:
The precision fabrication of large mirrors is a daunting task. The fabrication process needs to be scaled from the state-of-the-art (SOA) Hubble mirror at 2.4 m both in precision and dimensions of the mirrors.

Relevance / Science Traceability:
This Subtopic Scope supports potential Astrophysics Division missions. Previously, optical systems have been made for balloon experiments. Future potential Decadal missions include Laser Interferometer Space Antenna (LISA), Habitable Exoplanet Observatory (HabEx), Large UV/Optical/Near-IR Surveyor (LUVOIR), and the Origins Space Telescope (OST).

References:
The HabEx and LUVOIR space telescope studies are developing concepts for UVOIR space telescopes for exo-Earth discovery and characterization, exoplanet science, general astrophysics, and solar system astronomy.

1. The HabEx Interim Report: https://www.jpl.nasa.gov/habex/
2. The LUVOIR Interim Report: https://asd.gsfc.nasa.gov/luvoir/

Scope Title: Two Special Topics: LISA Epoxy Study and Ultra-Stable Structures

Scope Description:
Topic #1: LISA Epoxy Study

Many applications for space-based optical metrology systems require structures with low coefficient of thermal expansion (CTE) to maintain precision alignment and extremely stable optical pathlength. Gravitational wave observatories such as LISA (Laser Interferometer Space Antenna) rely on single-material telescopes to maintain alignment and pathlength stability by constructing the telescopes out of glass such as ULE(R) or low CTE materials such as Zerodur(R) or ClearCeram(R). For manufacturability, these telescopes must be made in pieces that are assembled to make a complete telescope.

For many years the bonding technique of choice has been hydroxide catalysis bonding, originally developed for the Gravity Probe B mission, but used more recently for the optical bench in the LISA Pathfinder mission. This bonding technique easily supports the small 20-mm steering mirrors and optics on an optical bench, but it does not so easily support the expected launch loads of a telescope structure.

Proposals are solicited to develop high-strength, high-glass-transition-temperature, low-viscosity adhesives that can be cured near room temperature and maintain full performance with low cure shrinkage. The near-room-temperature cure is necessary to avoid damaging low-CTE ceramics such as Zerodur(R). The adhesive should cure rapidly so that it can be used during alignment of a telescope without requiring extremely stable alignment support equipment over long durations of time. A cure process that involves an initial ultraviolet (UV) exposure to set the adhesive rapidly and then is followed by a thermal cure at only slightly elevated above room temperature might be one way to accomplish this.

Specific metrics:

- Shear strength: >4,000 psi (28 MPa) at 25 °C.
- Tensile strength: >6,300 psi (45 MPa) at 25 °C.
- Glass transition onset temperature: >60 °C with near-room-temperature cure.
- Low viscosity: ~12 Poise (1.2 PaS).
- Pot life: >60 min.
- Low outgassing.

Topic #2: Ultrastable Structures

Telescope stability is enabling for missions at all wavelengths (UV, optical, infrared (IR) and far-IR). It is particularly enabling for coronagraph and interferometric instruments. The stiffer an optical component and structure is, the more stable the resulting telescope will be. Historically, high-stiffness low-mass mirrors and structures have been achieved using low-density materials (such as beryllium or SiC) or extreme lightweighting of glass mirrors. Currently, this subtopic is investing in additively manufactured mirrors. In all previous cases, however, the fabricated mirrors used "classical" geometric architectural forms. Biologically inspired architectures might yield mirrors and telescope structures with lower mass and higher stiffness. Biologically inspired architectures might enable the design of structures that more efficiently distribute load and control modal responses.

Expected TRL or TRL Range at completion of the Project: 2 to 3

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
For Topic #1:

- Phase I deliverable would be a process, tested in a relevant TRL-6 environment, whose performance metrics are better than hydroxide catalysis bonding of Zerodur$^{(R)}$, as demonstrated on test coupons.
- Phase 2 deliverable would be a data package of: (a) additional testing of coupons with sufficient quantity to provide greater than 99% statistical confidence of performance, (b) testing of flight-traceable component bonds in a relevant environment, and (c) characterization of longitudinal performance.

For Topic #2:

- An ideal Phase I deliverable would be a precision optical system of at least 0.15 m or a relevant subcomponent of a system whose stiffness or modal properties can be modeled and verified by test.
- An ideal Phase II project would further advance the technology by producing a flight-qualifiable optical system greater than 0.5 m or a relevant subcomponent (with a TRL in the 4 to 5 range).
- Phase I and Phase II system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials.

State of the Art and Critical Gaps:
Historically, high-stiffness low-mass mirrors and structures have been achieved using low-density materials such as beryllium or extreme lightweighting of glass mirrors. Previously, this subtopic has invested in alternative materials such as SiC and graphite fiber composites. Currently, this subtopic is investing in additive manufacturing technologies. In all previous cases, however, the fabricated mirrors used "classical" geometric architectural forms.

Relevance / Science Traceability:
Mirror technology is enabling for all potential Science Mission Directorate (SMD) science. At this time, this scope does not require traceability to any specific science mission. However, it may demonstrate the feasibility of this technology for IR or far-IR performance.

References:
NASA X-ray and Cryogenic Facility: https://optics.msfc.nasa.gov/tech-2/

Scope Title: Fabrication, Test, and Control of Optical Components and Telescopes

Scope Description:
The ability to fabricate, test, and control optical components is enabling for future missions of all spectral bands (ultraviolet (UV), optical, infrared (IR), and far-IR). This scope solicits technology advances that enable the manufacture of optical components (of all diffraction limits, sizes, and operating temperatures) for a lower cost. Achieving this goal requires technologies that enable/enhance the deterministic manufacture of optical components to their desired optical prescription or technologies that enable/enhance the control of the shape of optical components "in flight."

Given that deterministic optical fabrication is relatively mature, technology advances are solicited that primarily reduce cost—particularly for large mirrors. Technology that increases remove rate (to reduce processing time) while producing smoother surfaces (less mid- and high-spatial frequency error) are potentially enhancing. Potential technologies for improvement include (but are not limited to): computer-controlled grinding/polishing, electrolytic in-process dressing (ELID) processes, electrochemical processes, on-machine in-process metrology feedback, etc.

Regarding precision, this subtopic encourages proposals to develop technology that makes a significant advance in the ability to fabricate and test an optical system.

One area of current emphasis is the ability to nondestructively characterize coefficient of thermal expansion (CTE) homogeneity in 4-m-class Zerodur$^{(R)}$ and 2-m-class ULE$^{(R)}$ mirror substrates to an uncertainty of 1 ppb/K and a spatial sampling of 100×100. This characterization capability is needed to select mirror substrates before undergoing the expense of turning them into a lightweight space mirror.

Regarding stability, to achieve high-contrast imaging for exoplanet science using a coronagraph instrument, systems must maintain wavefront stability to <10 pm rms over intervals of ~10 min during critical observations. The ~10-min time period of this stability is driven by current wavefront sensing and control techniques that rely on stellar photons from the target object to generate estimates of the system wavefront. This subtopic aims to develop new technologies and techniques for wavefront sensing, metrology, and verification and validation of optical system wavefront stability.

Current methods of wavefront sensing include image-based techniques such as phase retrieval, focal-plane contrast techniques such as electric field conjugation and speckle nulling, and low-order and out-of-band wavefront sensing that use nonscience light rejected by the coronagraph to estimate drifts in the system wavefront during observations. These techniques are limited by the low stellar photon rates of the dim objects being observed (~5 to 11 Vmag), leading to tens of minutes between wavefront control updates.

New methods may include: new techniques of using out-of-band light to improve sensing speed and spatial frequency content, new control laws incorporating feedback and feedforward for more optimal control, new algorithms for estimating absolute and relative wavefront changes, and the use of artificial guide stars for improved sensing signal-to-noise ratio and speed.

Current methods of metrology include edge sensors (capacitive, inductive, or optical) for maintaining segment cophasing, and laser distance interferometers for absolute measurement of system rigid-body alignment. Development of these techniques to improve sensitivity, speed, and component reliability is desired. Low-power, high-reliability electronics are also needed. Metrology techniques for system verification and validation at the picometer level during integration and test (I&T) are also needed. High-speed spatial and speckle interferometers are currently capable of measuring single-digit picometer displacements and deformations on small components in controlled environments. Extension of these techniques to large-scale optics and structures in typical I&T environments is needed.

Finally, mirror segment actuators are needed to align and cophase segmented aperture mirrors to diffraction-limited tolerances. Depending upon the mission, these mechanisms may need to operate at temperatures as low as 10 K. Potential technologies include superconducting optomechanisms.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Hardware
- Software
- Prototype

Desired Deliverables Description:

- An ideal Phase I deliverable would be a prototype demonstration of a fabrication, test, or control technology leading to a successful Phase II delivery; or a reviewed preliminary design and manufacturing plan that demonstrates feasibility.
- Although the detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.

State of the Art and Critical Gaps:
Deterministic optical fabrication is relatively mature. There are multiple small and large companies offering commercial products and services. The Webb and Roman telescopes were/are being fabricated by deterministic processes. However, these processes are expensive. Technology advances are required to enhance these processes and reduce their cost—particularly for large mirrors.

Wavefront (WF) sensing using star images, including dispersed-fringe and phase-retrieval methods, is at TRL 6, qualified for space by the James Webb Space Telescope (JWST). WF sensing and control for coronagraphs, including electric field conjugation and low-order WF sensing (LOWFS), is at TRL4 and is being developed and demonstrated by the Wide Field Infrared Survey Telescope Coronagraph Instrument (WFIRST/CGI).

Laser-distance interferometers for point-to-point measurements with accuracies from nanometers to picometers have been demonstrated on the ground by the Space Interferometry Mission and other projects, and in orbit by the LISA Pathfinder and Grace Follow-On missions. Application to telescope alignment metrology has been demonstrated on testbeds to TRL 4 for nanometer accuracy. Picometer accuracy for telescopes awaits demonstration.

Edge sensors are in use on segmented ground telescopes but are not yet on space telescopes. New designs are needed to provide picometer sensitivity and millimeter range in a space-qualified package.

Higher order WF sensing for coronagraphs using out-of-band light is beginning development, with data limited to computer simulations.

Mechanism SOA is defined by the JWST actuators. They provide ample range for far-IR applications, but have more precision than necessary. Thus, they are expensive.

Relevance / Science Traceability:
Fabrication and testing technologies for deterministic optical manufacturing are enabling/enhancing for monolithic aperture missions ranging from UV to optical to far-IR. Control technologies are enabling for coronagraph-equipped space telescopes and segmented space telescopes. The Large UV/Optical/IR Surveyor (LUVOIR), Habitable Exoplanet Observatory (HabEx), and Origins Space Telescope (OST) mission concepts currently provide good examples.

References:

1. HabEx: https://www.jpl.nasa.gov/habex/
2. LUVOIR: https://asd.gsfc.nasa.gov/luvoir/reports/
3. OST: https://asd.gsfc.nasa.gov/firs/docs/

Scope Title: Optical Components and Telescopes for Infrared/Far-Infrared Missions

Scope Description:
Potential far-infrared (IR) space missions require telescopes with apertures ranging from 1 to 4 m monolithic or 3 to 10 m segmented with diffraction-limited performance as good as 5 µm operating at lower than 10 K (survival temperature from 4 to 315 K). Mirror substrate thermal conductivity at 4 K must be greater than 2 W/m·K. Mirror systems (mirror substrate and mount) need to have a cryodeformation of less than 100 nm rms. Mirror areal density goal is 15 kg/m^2 for the primary mirror substrate and 35 kg/m^2 for the primary mirror assembly (including structure). Areal cost goal is total cost of the primary mirror at or below \$100K/m^2.

Key technologies to enable such a mirror include new and improved:

- Mirror substrate materials and/or architectural designs.
- Processes to rapidly fabricate and test far-IR quality mirrors.
- Mirror support structures, joints, and mechanisms that are athermal or have matched coefficients of thermal expansion (CTEs) at the desired scale.
- Mirror support structures with low mass that can survive launch at the desired scale.

Also needed is the ability to fully characterize surface errors and predict optical performance via integrated optomechanical modeling.

Potential solutions for substrate material/architecture include but are not limited to: mirror materials with low CTE, homogenous CTE, and high thermal conductivity. Potential solutions for mirrors and support structure material include, but are not limited to metal alloys, nanoparticle composites, carbon fiber, graphite composites, ceramic or SiC materials, etc. Potential solutions for new fabrication processes include, but are not limited to: additive manufacture, direct precision machining, rapid optical fabrication, roller embossing at optical tolerances, slumping, or replication technologies to manufacture 1- to 2-m- (or larger) precision quality components.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype

- Hardware

Desired Deliverables Description:

- An ideal Phase I deliverable would be a cryogenic optical system of at least 0.25 m and suitable for a far-IR mission or a relevant subcomponent of a system. Although detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.
- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 m; a relevant subcomponent (with a TRL in the 4 to 5 range); or a working fabrication, test, or control system. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase II would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly that can be integrated into the potential mission as well as demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analyses).

State of the Art and Critical Gaps:
Current state of the art (SOA) is represented by the Herschel Space Observatory (3.5-m monolith; SiC) and the James Webb Space Telescope (6.5-m segmented primary mirror; beryllium). Technologies are needed to advance the fabrication precision and the size of the mirrors, both monolithic and segmented, beyond the current SOA.

Relevance / Science Traceability:
NASA needs telescopes and interferometers that reach fundamental sensitivity limits imposed by astrophysical background photon noise. Only telescopes cooled to a cryogenic temperature can provide such sensitivity. Novel approaches to fabrication and test developed for a far-IR astrophysics mission may be applicable to far-IR optical systems employed in other divisions of the NASA Science Mission Directorate (SMD), or to optical systems designed to operate at wavelengths shorter than the far-IR.

References:

1. Program Annual Technology Reports (PATR) can be downloaded from the NASA Physics of the Cosmos and Cosmic Origins (PCOS/COR) Technology Development website: https://apd440.gsfc.nasa.gov/technology/
2. The Origins Space Telescope (OST) final report: https://asd.gsfc.nasa.gov/firs/
3. The Space Infrared Interferometric Telescope (SPIRIT) and its optical system requirements: https://asd.gsfc.nasa.gov/cosmology/spirit/

Scope Title: Telescopes for CubeSAT Missions

Scope Description:
The need exists for a low-cost, compact (e.g., CubeSat-class), scalable, diffraction-limited, and athermalized off-axis reflective and on-axis telescopes. A particular interest of this Scope is off-axis reflective telescopes for near-infrared/short-wave-infrared- (NIR/SWIR-) band optical communication.

Typically, specialty optical aperture systems are designed and built as “one-offs,” which are inherently high in cost and often out of scope for smaller projects. A Phase I effort would investigate current compact off-axis reflective designs and develop a trade space to identify the most effective path forward. The work would include a strategy for aperture diameter scalability, athermalization, and low-cost fabrication. Detailed optical designs would be developed along with detailed structural, thermal, optical performance (STOP) analyses confirming diffraction-limited operation across a wide range of operational disturbances, both structural dynamic and thermal. Phase II may follow up with development of prototypes, built at multiple aperture diameters and fidelities.

NIR/SWIR optical-communication-support hardware should be assumed towards an integrated approach, including fiber optics, fast-steering mirrors, and applicable detectors.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Analysis

Desired Deliverables Description:

- An ideal Phase I deliverable would be a prototype unobscured telescope with the required performance and size or a reviewed preliminary design and manufacturing plan that demonstrates feasibility. Although detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.
- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system with the required performance for a CubeSat mission. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase II would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly that can be integrated into the potential mission as well as demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analyses).

State of the Art and Critical Gaps:
Currently, the state of the art for reflective optical system for communications applications are:

1. On-axis or axisymmetric designs are typically used for (space) optical communications and imaging, which inherently are problematic because of the central obscuration.
2. Off-axis designs provide superior optical performance because of the clear aperture; however, they are rarely considered because of the complex design, manufacturing, and metrology procedures.

Relevance / Science Traceability:
Optical communications enable high-data-rate downlink of science data. The initial motivation for this scalable off-axis optical design approach is for bringing high-performance reflective optics within reach of laser communication projects with limited resources. However, this exact optical hardware is applicable for any diffraction-limited, athermalized, science imaging application. Any science mission could potentially be able to select from a “catalog” of optical aperture systems that would already have (flight) heritage and reduced risks.

References:

1. An example of an on-axis design has been utilized in the Lunar Laser Communications Demonstration (LLCD): https://www.spiedigitallibrary.org/conference-proceedings- of-

spie/10563/105630X/NASAs-current-activities-in-free-space-optical-communications/10.1117/12.2304175.full?SSO=1

2. An example of an off-axis design is being developed by the Jet Propulsion Laboratory (JPL) for Deep Space Optical Communications (DSOC): https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10096/100960V/Discovery-deep-space-optical- communications-DSOC-transceiver/10.1117/12.2256001.full

S12.04 X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics (SBIR)

Lead Center: GSFC
Participating Center(s): JPL, MSFC

Introduction:
The National Academy Astro2010 Decadal Report identifies studies of optical components and ability to manufacture, coat, and perform metrology needed to enable future x-ray observatory missions.

The Astrophysics Decadal Report specifically calls for optical coating technology investment for future ultraviolet (UV), optical, exoplanet, and infrared (IR) missions, and the Heliophysics 2009 Roadmap identifies the coating technology for space missions to enhance rejection of undesirable spectral lines and improve space/solar-flux durability of extreme UV (EUV) optical coatings, as well as coating deposition to increase the maximum spatial resolution.

Future optical systems for NASA's low-cost missions, CubeSat, and other small-scale payloads, are moving away from traditional spherical optics to nonrotationally symmetric surfaces with anticipated benefits of free-form optics such as fast wide-field and distortion-free cameras.

This subtopic solicits proposals in the following three focus areas:

- X-ray manufacturing, coating, testing, and assembling complete mirror systems in addition to maturing the current technology.
- Coating technology including carbon nanotubes (CNTs) for a wide range of wavelengths from x-ray to IR (x-ray, EUV, Lyman UV (LUV), vacuum UV (VUV), visible, and IR).
- Free-form optics design, fabrication, and metrology for CubeSat, SmallSat, and various coronagraph instruments.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Typical deliverables based on sub-elements of this subtopic:

Phase I:

- X-ray optical mirror system: analysis, reports, prototype.

- Coating: analysis, reports, software, demonstration of the concept and prototype.
- Free-form optics: analysis, design, software, and hardware prototype of optical components.

Phase II:

- X-ray optical mirror system: analysis and prototype.
- Coating: analysis, reports, software, demonstration of the concept and prototype.
- Free-form optics: analysis, design, software, and hardware prototype of optical components.

State of the Art and Critical Gaps:
This subtopic focuses on three areas of technology development:

- This work is a very costly and time consuming. Most of the state of the art (SOA) requiring improvement is ~10 arcsec angular resolution. SOA stray light suppression is bulky and ineffective for wide-field-of-view telescopes. We seek significant reduction in both expense and time. Reduce the areal cost of telescope by 2× such that the larger collecting area can be produced for the same cost or half the cost.
- Coating technology for wide range of wavelengths from x-ray to IR (x-ray, EUV, LUV, VUV, visible, and IR). The current x-ray coating is defined by NuSTAR. Current EUV is defined by Heliophysics (80% reflectivity from 60 to 200 nm). Current UVOIR is defined by Hubble. MgF_2-overcoated aluminum on a 2.4-m mirror has birefringence concerns and only marginally acceptable reflectivity between 100 to 200 nm.
- Free-form optics design, fabrication, and metrology for package-constrained imaging systems. This field is in early stages of development. Improving the optical surfaces with large field of view and fast F/#s is highly desirable.

Relevance / Science Traceability:
This subtopic supports a variety of Astrophysics Division missions. The technologies in this subtopic encompasses fields of x-ray, coating technologies ranging from UV to IR, and free-form optics in preparation for Decadal missions such as HabEx, LUVOIR, and OST.

Optical components, systems, and stray-light suppression for x-ray missions: The 2010 National Academy Decadal Report specifically identifies optical components and the ability to manufacture and perform precise metrology on them needed to enable several different future missions (Next Generation x-ray Optics, NGXO). The National Research Council (NRC) NASA Technology Roadmap Assessment ranked advanced mirror technology for new x-ray telescopes as the #1 Object C technology requiring NASA investment.

Free-form optics: NASA missions with alternative low-cost science and small-size payload are increasing. However, the traditional interferometric testing as a means of metrology are unsuited to free-form optical surfaces because of changing curvature and lack of symmetry. Metrology techniques for large fields of view and fast F/#s in small-size instruments is highly desirable, specifically if they could enable cost-effective manufacturing of these surfaces (CubeSat, SmallSat, NanoSat, various coronagraph instruments).

Coating for x-ray, EUV, LUV, UV, visible, and IR telescopes: The Astrophysics Decadal specifically calls for optical coating technology investment for future UV/optical and exoplanet missions (Habitable Exoplanet Observatory (HabEx) or Large Ultraviolet Optical Infrared Surveyor (LUVOIR)).The Heliophysics 2009 Roadmap identifies optical coating technology investments for Origins of Near-Earth Plasma (ONEP); Ion-Neutral Coupling in the Atmosphere (INCA); Dynamic Geospace Coupling (DGC); Fine-scale Advanced Coronal Transition-Region Spectrograph (FACTS); Reconnection and Micro-scale (RAM); and Solar-C Nulling polarimetry/coronagraph for exoplanet imaging and characterization, dust and debris disks, extra-galactic studies, and relativistic and nonrelativistic jet studies.

References:
The study pages are available at:

1. The Habitable Exoplanet Observatory (HabEx) is a concept for a mission to directly image planetary systems around Sun-like stars. HabEx will be sensitive to all types of planets; however, its main goal is, for the first time, to directly image Earth-like exoplanets, and characterize their atmospheric content. By measuring the spectra of these planets, HabEx will search for signatures of habitability such as water and be sensitive to gases in the atmosphere possibility indicative of biological activity, such as oxygen or ozone.
    - Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/
2. The Large UV/Optical/IR Surveyor (LUVOIR) is a concept for a highly capable, multiwavelength space observatory with ambitious science goals. This mission would enable great leaps forward in a broad range of science, from the epoch of re-ionization, through galaxy formation and evolution, star and planet formation, to solar system remote sensing. LUVOIR also has the major goal of characterizing a wide range of exoplanets, including those that might be habitable—or even inhabited.
    - The LUVOIR Interim Report: https://asd.gsfc.nasa.gov/luvoir/
3. The LYNX Mission Concept: https://wwwastro.msfc.nasa.gov/lynx/
4. The Origins Space Telescope (OST) is the mission concept for the Far-IR Surveyor study.
    - The Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/
5. NASA's Astrophysics Roadmap, Enduring Quests, Daring Visions, recognized the need for an OST mission with enhanced measurement capabilities relative to those of the Herschel Space Observatory, such as a 3-order-of-magnitude gain in sensitivity, angular resolution sufficient to overcome spatial confusion in deep cosmic surveys or to resolve protoplanetary disks, and new spectroscopic capability.
    - The NASA Astrophysics Roadmap: https://science.nasa.gov/science-committee/subcommittees/nac-astrophysics-subcommittee/astrophysics-roadmap

Scope Title: X-Ray Mirror Systems Technology

Scope Description:
NASA large x-ray observatory requires low-cost, ultrastable, lightweight mirrors with high-reflectance optical coatings and effective stray-light suppression. The current state of the art of mirror fabrication technology for x-ray missions is very expensive and time consuming. Additionally, a number of improvements such as 10 arcsec angular resolutions and 1 to 5 m^2 collecting area are needed for this technology. Likewise, the stray-light suppression system is bulky and ineffective for wide-field-of-view telescopes.

In this area, we are looking to address the multiple technologies, including: improvements to manufacturing (machining, rapid optical fabrication, slumping, or replication technologies), improved metrology, performance prediction and testing techniques, active control of mirror shapes, new structures for holding and actively aligning of mirrors in a telescope assembly to enable x-ray observatories while lowering the cost per square meter of collecting aperture, and effective design of stray-light suppression in preparation for the Decadal Survey of 2020. Additionally, we need epoxies made of silicon to bond mirrors. The epoxies should absorb infrared (IR) radiation (with wavelengths between 1.5 and 6 µm that traverse silicon with little or no absorption) and therefore be cured quickly with a beam of IR radiation. Currently, x-ray space mirrors cost $4 million to $6 million per square meter of optical surface area. This research effort seeks a cost reduction for precision optical components by 5 to 50 times, to less than $1M to $100K per square meter.

Additionally, proposals are solicited to develop new advanced-technology computer-numerical-control (CNC) machines to polish inside and/or outside full-shell substrate (between 100 and 1,000 mm in height, 100 to 2,800 mm in diameter, varying radial prescription along azimuth, ~2 mm in thickness), grazing-incidence optics to x-ray-quality surface tolerances (with surface figure error <1 arcsec half-power diameter (HPD), radial slope error <1 µrad, out-of-round <2 µm). Current state-of-the-art technology in CNC polishing of full-shell substrate, grazing-incidence optics yields 2.5 arcsec HPD on the outside of a mandrel used for replicating shells. Technology advances beyond current state of the art include application of CNC and deterministic polishing techniques that (1) allow for direct force closed-loop control, (2) reduce alignment precision requirements, and (3) optimize the machine for polishing cylindrical optics through simplifying the axis arrangement and the layout of the cavity of the CNC polishing machine.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Typical deliverable based on subelements of this subtopic:
X-ray optical mirror system – Demonstration, analysis, reports, software, and hardware prototype:

- Phase I deliverables: Reports, analysis, demonstration, and prototype.
- Phase II deliverables: Analysis, demonstration, and prototype.

State of the Art and Critical Gaps:
X-ray optics manufacturing, metrology, coating, testing, and assembling complete mirror systems in addition to maturing the current technology: This work is very costly and time consuming. Most of the SOA (state of the art) requiring improvement is ~10 arcsec angular resolution. SOA stray-light suppression is bulky and ineffective for wide-field-of-view telescopes. We seek a significant reduction in both expense and time. Reduce the areal cost of a telescope by 2× such that the larger collecting area can be produced for the same cost or half the cost.

The gaps to be covered in this track are:

- Lightweight, low-cost, ultrastable mirrors for large x-ray observatory.
- Stray-light suppression systems (baffles) for large advanced x-ray observatories.
- Ultrastable, inexpensive, lightweight x-ray telescope using grazing-incidence optics for high-altitude balloon-borne and rocket-borne missions.

Relevance / Science Traceability:
The 2010 National Academy Decadal Report specifically identifies optical components and the ability to manufacture and perform precise metrology on them needed to enable several different future missions (Lynx and Advanced X-ray Imaging Satellite (AXIS)).

The National Research Council NASA Technology Roadmap Assessment ranked advanced mirror technology for new x-ray telescopes as the #1 Object C technology requiring NASA investment.

References:
NASA High Energy Astrophysics (HEA) mission concepts including x-ray missions and studies are available at:

1. https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/concepts.html

Scope Title: Coating Technology for X-Ray-UV-OIR

Scope Description:

The optical coating technology is a mission-enabling feature that enhances the optical performance and science return of a mission. Lowering the areal cost of coating determines if a proposed mission could be funded in the current cost environment. The most common forms of coating used on precision optics are antireflective (AR) coating and high-reflective (HR) coating.

The current coating technology of optical components is needed to support the 2020 Astrophysics Decadal process. Historically, it takes 10 years to mature mirror technology from TRL 3 to 6.

Achieving these objectives requires sustained systematic investment.

The telescope optical coating needs to meet a low-temperature operation requirement. It is desirable to achieve 35 K in the future.

Many future NASA missions require suppression of scattered light. For instance, the precision optical cube utilized in a beam-splitter application forms a knife-edge that is positioned within the optical system to split a single beam into two halves. The scattered light from the knife-edge could be suppressed by carbon nanotube (CNT) coating. Similarly, scattered light suppression for gravitational-wave observatories and lasercom systems where simultaneous transmit/receive operation is required could be achieved by a highly absorbing coating such as CNT. Ideally, the application of CNT coatings needs to:

- Achieve broadband (visible plus near-infrared (IR)) reflectivity of 0.1% or less.
- Resist bleaching or significant albedo changes over a mission life of at least 10 years.
- Withstand launch conditions such as vibration, acoustics, etc.
- Tolerate both high continuous-wave (CW) and pulsed power and power densities without damage: ~10 W for CW and ~0.1 GW/cm^2 power density, and 1-kW/nsec pulses.
- Adhere to a multilayer dielectric or protected metal coating, including ion beam sputtering (IBS) coating.

NASA's Laser Interferometer Space Antenna (LISA) mission requires a telescope that operates simultaneously in transmission and reception. An off-axis optical design is used to avoid having the secondary mirror send the transmitted beam directly back at the receiver. Very low reflectivity coatings will help further suppress scattered light from the telescope structure and mounts. In addition, the ability to fabricate very low reflectivity apodized petal-shaped masks at the center of a secondary mirror may enable the use of an on-axis optical telescope design, which may have some advantages in stability as well as in fabrication and alignment because of its symmetry. The emerging cryogenic etching of black silicon has demonstrated bidirectional reflectance distribution function (BRDF) ultralow reflectance with specular reflectance of 1×10^{-7} in the range of 500 to 1064 nm. The advancement of this technology is desired to obtain ultralow reflectivity:

- Improve the specular reflectance to 1×10^{-10} and hemispherical reflectance to better than 0.1%.
- Improve the cryogenic etching process to provide a variation of the reflectance (apodization effect) by increasing or decreasing the height of the features.
- Explore etching process and duration.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

- Software

Desired Deliverables Description:
Coating—Analysis, reports, software, demonstration of the concept, and prototype:

- Phase I deliverables: Report, analysis, demonstration, and prototype.
- Phase II deliverables: Analysis, demonstration, and prototype.

State of the Art and Critical Gaps:
Coating technology (for wide range of wavelengths from x-ray to IR: x-ray, extended ultraviolet (EUV), Lyman UV (LUV), vacuum UV (VUV), visible, and IR):

- The current x-ray coating is defined by Nuclear Spectroscopic Telescope Array (NuSTAR).
- Current EUV is defined by Heliophysics (80% reflectivity from 60 to 200 nm).
- Current UV-optical-IR (UVOIR) is defined by Hubble. MgF_2-overcoated aluminum on 2.4-m mirror. This coating has birefringence concerns and marginally acceptable reflectivity between 100 and 200 nm.

Metrics for x-ray:

- Multilayer high-reflectance coatings for hard x-ray mirrors.
- Multilayer depth-gradient coatings for 5 to 80 keV with high broadband reflectivity.
- Zero-net-stress coating of iridium or other high-reflectance elements on thin substrates (<0.5 mm).

Metrics for EUV:

- Reflectivity >90% from 6 to 90 nm onto a <2 m mirror substrate.

Metrics for Large UV/Optical/IR Surveyor (LUVOIR):

- Broadband reflectivity >70% from 90 to 120 nm (LUV) and >90% from 120 nm to 2.5 µm (VUV/visible/IR).
- Reflectivity non-uniformity <1% from 90 nm to 2.5 µm.
- Induced polarization aberration <1% for 400 nm to 2.5 µm spectral range from mirror coating applicable to a 1- to 8-m substrate.

Metrics for LISA:

- HR: Reflectivity >99% at 1064+/-2 nm with very low scattered light and polarization-independent performance over apertures of ~0.5 m.
- AR: Reflectivity <0.005% at 1064+/-2 nm.
    - Low-absorption, low-scatter, laser-line optical coatings at 1064 nm.
    - High reflectivity, R > 0.9995.
    - Performance in a space environment without significant degradation over time due, for example, to radiation exposure or outgassing.
    - High polarization purity, low optical birefringence over a range of incident angles from ~5° to ~20°.
    - Low coating noise (thermal, photothermal, etc.) for high-precision interferometric measurements.
    - Ability to endure applied temperature gradients (without destructive effects, such as delamination from the substrate).
    - Ability to clean and protect the coatings and optical surfaces during mission integration and testing. Cleaning should not degrade the coating performance.

Nonstationary optical coatings:

- Used in reflection and transmission that vary with location on the optical surface.

CNT coatings:

- Broadband visible to near-IR (NIR), total hemispherical reflectivity of 0.01% or less, adhere to the multilayer dielectric or protected metal coating.

Black-silicon cryogenic etching (new):

- Broadband UV+visible+NIR+IR, reflectivity of 0.01% or less, adhere to the multilayer dielectric (silicon) or protected metal.

Software tools to simulate and assist the anisotropic etching by employing a variety of modeling techniques such as rigorous coupled wave analysis (RCWA), method of moments (MOM), finite-difference time domain (FDTD), finite element method (FEM), transfer matrix method (TMM), and effective medium theory (EMT).

Relevance / Science Traceability:

- Coating for x-ray, EUV, LUV, UV, visible, and IR telescopes: Astrophysics Decadal specifically calls for optical coating technology investment for future UV/optical and exoplanet missions.
- Heliophysics 2009 Roadmap identifies optical coating technology investments for Origins of Near-Earth Plasma (ONEP), Ion-Neutral Coupling in the Atmosphere (INCA), Dynamic Geospace Coupling (DGC), Fine-scale Advanced Coronal Transition-Region Spectrograph (FACTS), Reconnection and Micro-scale (RAM), and Solar-C.
- LISA requires low-scatter HR coatings and low reflectivity coatings for scatter suppression near 1064 nm. Polarization-independent performance is important.
- Nulling polarimetry/coronagraphy for exoplanets imaging and characterization, dust and debris disks, extra-galactic studies, and relativistic and nonrelativistic jet studies.

References:

Laser Interferometer Space Antenna (LISA) is a space-based gravitational wave observatory building on the success of LISA Pathfinder and Laser Interferometer Gravitational-Wave Observatory (LIGO). Led by the European Space Agency (ESA), the new LISA mission (based on the 2017 L3 competition) is a collaboration between ESA and NASA.

More information can be found at:

- https://lisa.nasa.gov

Scope Title: Free-Form Optics

Scope Description:

Future NASA science missions demand wider fields of view in a smaller package. These missions could benefit greatly by free-form optics as they provide nonrotationally symmetric optics, which allow for better packaging while maintaining desired image quality. Currently, the design and fabrication of free-form surfaces is costly. Even though various techniques are being investigated to create complex optical surfaces, small-size missions highly desire efficient small packages with lower cost that increase the field of view and expand operational temperature range of unobscured systems. In addition to the free-form fabrication, the metrology of free-form optical components is difficult and challenging because of the large departure from planar or spherical shapes accommodated by conventional interferometric testing. New methods such as multibeam low-coherence optical probe and slope-sensitive optical probe are highly desirable.

Specific metrics are:

- Design: Innovative design methods/tools for free-form systems, including applications to novel reflective optical designs with large fields of view (>30°) and fast F/#s (<2.0).
- Fabrication: 10-cm-diameter optical surfaces (mirrors) with free-form optical prescriptions >1 mm, spherical departure with surface figure error <10 nm rms, and roughness <5 Å. 10-cm-diameter blazed optical reflective gratings on free-form surface shapes with >1 mm departure from a best-fit-sphere, and grating spacings from 1 to 100 µm. Larger mirrors are also desired for flagship missions for ultraviolet (UV) and coronagraphic applications, with 10-cm- to 1-m-diameter surfaces having figure error <5 nm rms and roughness <1 Å rms.

- Metrology: Accurate metrology of free-form optical components with large spherical departures (>1 mm), independent of requiring prescription-specific null lenses or holograms.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Optical components—Demonstration, analysis, design, metrology, software, and hardware prototype:

- Phase I deliverables: Report, analysis, demonstration, and prototype.
- Phase II deliverables: Analysis, demonstration, and prototype.

State of the Art and Critical Gaps:
Free-form optics design, fabrication, and metrology for package-constrained imaging systems. This field is in early stages of development. Improving the optical surfaces with large field of view and fast F/#s is highly desirable.

Relevance / Science Traceability:
NASA missions with alternative low-cost science and small-size payload are increasing. However, the traditional interferometric testing as a means of metrology is unsuited to free-form optical surfaces due to changing curvature and lack of symmetry. Metrology techniques for large fields-of-view and fast F/#s in small size instruments are highly desirable—specifically if they could enable cost-effective manufacturing of these surfaces. (CubeSat, SmallSat, and NanoSat). Additionally, design studies for large observatories such as Origins Space Telescope (OST) and Large UV/Optical/IR Surveyor (LUVOIR, currently being proposed for the 2020 Astrophysics Decadal Survey) have demonstrated improved optical performance over a larger field-of-view afforded by free-form optics. Such programs will require advances in free-form metrology to be successful.

References:

1. Applications for Freeforms Optics at NASA: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170010419.pdf
2. Alignment and Testing for a Freeform Telescope: https://ntrs.nasa.gov/citations/20180007557
3. Freeform Surface Characterization and Instrument Alignment for Freeform Space Applications: https://ntrs.nasa.gov/citations/20190025929

Focus Area 11 Spacecraft and Platform Subsystems

The Science Mission Directorate (SMD) will carry out the scientific exploration of our Earth, the planets, moons, comets, and asteroids of our solar system, and the universe beyond. SMD's future direction will be moving away from exploratory missions (orbiters and flybys) into more detailed/specific exploration missions that are at or near the surface (landers, rovers, and sample returns) or at more optimal observation points in space. These future destinations will require new vantage points or would need to integrate or distribute capabilities across multiple assets. Future destinations will also be more challenging to get to, have more extreme environmental conditions and challenges once the spacecraft gets there, and may be a challenge to get a spacecraft or data back from. A major objective of the NASA science spacecraft and platform subsystems development efforts are to enable science measurement capabilities using smaller and lower cost spacecraft to meet multiple mission requirements thus making the best use of our limited resources. To accomplish this objective, NASA is seeking innovations to significantly improve spacecraft and platform subsystem capabilities while reducing the mass and cost that would in turn enable increased scientific return for future NASA missions. A spacecraft bus is made up of many subsystems such as: propulsion; thermal control; power and power distribution; attitude control; telemetry command and control; transmitters/antenna; computers/on-board processing/software; and structural elements. High performance space computing technologies are also included in this focus area. Science platforms of interest could include unmanned aerial vehicles, sounding rockets, or balloons that carry scientific instruments/payloads, to planetary ascent vehicles or Earth return vehicles that bring samples back to Earth for analysis. This topic area addresses the future needs in many of these sub-system areas, as well as their application to specific spacecraft and platform needs. For planetary missions, planetary protection requirements vary by planetary destination, and additional backward contamination requirements apply to hardware with the potential to return to Earth (e.g., as part of a sample return mission). Technologies intended for use at/around Mars, Europa (Jupiter), and Enceladus (Saturn) must be developed so as to ensure compliance with relevant planetary protection requirements. Constraints could include surface cleaning with alcohol or water, and/or sterilization treatments such as dry heat (approved specification in NPR 8020.12; exposure of hours at 115° C or higher, non-functioning); penetrating radiation (requirements not yet established); or vapor-phase hydrogen peroxide (specification pending). The National Academies' Decadal Surveys for Astrophysics, Earth Science, Heliophysics, and Planetary Science discuss some of NASA's science mission and technology needs and are available at https://www.nationalacademies.org/

S13.02 Spacecraft Technology for Sample Return Missions (SBIR)

Lead Center: JPL
Participating Center(s): GRC, GSFC, LaRC, MSFC

Scope Title: Critical Technologies for Sample-Return Missions

Scope Description:
This subtopic focuses on technologies for robotic sample-return (SR) missions that require landing on large bodies (e.g., the Moon, Mars, Vesta, Ceres, Phobos, Europa), as opposed to particulate-class SR missions (e.g., Genesis, Hayabusa) or touch-and-go (TAG) missions to relatively small asteroids or comets (e.g., OSIRIS-Rex, Hayabusa2). The mission destinations envisioned are dwarf planets (e.g., Vesta, Ceres) and planet or planet moons (e.g., Phobos, Europa). These are the most challenging missions in NASA's portfolio but also the most scientifically promising, given the vast array of instruments available on Earth to study the retrieved samples. Specifically, technologies are sought to address the following challenges associated with these SR missions: (1) Mass-efficient spacecraft architectures (e.g., efficient propulsion or materials that significantly reduce the mass of the launch payload required), (2) Sample integrity (e.g., surviving reentry), and (3) Planetary protection/contamination control (PP/CC) (e.g., preventing leakage into the Mars Sample Return (MSR) mission's orbital sample (OS) canister).

The heightened need for mass-efficient solutions in these SR missions stems from their extreme payload mass "gear ratio." For example, the entire MSR campaign will probably require four heavy launch vehicle launches with rough spacecraft mass of 5,000 kg each to bring back multiple samples with an estimated total mass of 0.5 kg. Clearly, any mass savings in the ascent vehicle's gross liftoff mass (GLOM) or in the mass of either the lander or the Earth Return Orbiter, for example, would yield many times more savings in the launch payload mass, enhancing the feasibility of these missions. Examples of propulsion technologies that may reduce overall mass include the development of lightweight, restartable ignition techniques for hybrid and solid rocket motors, lightweight spin motors, lightweight vectoring systems, lightweight insulation materials, and lightweight expandable nozzle designs to increase nozzle area ratios.

Once acquired, samples must be structurally and thermally preserved through safe landing and transport to Johnson Space Center (JSC) for analyses. Sample integrity technology solutions that address the long, high-radiation return trip, as well as the dynamic and high-temperature environment of reentry, are sought.

Potential solutions include near-isotropic and crushable high-strength energy-absorbent materials that can withstand the ballistic impact landing. Materials that offer thermal isolation in addition to energy absorption are highly desirable given the reentry environment. In the case of cryogenically preserved samples, the technical challenge includes development of thermal control systems to ensure volatiles are conserved.

Finally, acquired samples must be chemically and biologically preserved in their original condition. Examples of PP/CC technology solutions sought include:

- Materials selection: selection of metallic materials (non-organic) for the interior of the OS canister as well as materials that allow preferable surface treatments and bake-out sterilization approaches.
- Surface science topics: Adsorber coatings/materials for contaminant adsorption (getter-type materials, such as aluminum oxide, porous polymer resin) and/or low-surface-energy materials to minimize contaminant deposition.
- Characterization of contamination sources on lander, rover, capsule, ascent vehicle, and orbiter, for design of adequate mitigation measures.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.3 Manipulation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:
A Phase I deliverable would be a final report that describes the requisite research and detailed design accomplished under the project.

A Phase II deliverable would be successful demonstration of an appropriate-TRL performance test, such as at representative scale and environment, along with all the supporting analysis, design, and hardware specifications.

State of the Art and Critical Gaps:
The kind of SR missions targeted in this solicitation are those that require landing on an extraterrestrial body. This most challenging kind of SR mission has only been successfully done in the Soviet Luna program that returned 326 g of Moon samples in three missions—out of eleven attempts—in the early 1970s. Hayabusa2 and OSIRIS-Rex are TAG SR missions. The former returned asteroid Ryugu samples to Earth in December 2020; the latter is expected to follow suit in September 2023 from asteroid Bennu. The first segment of NASA's MSR mission is the sample-collection rover Perseverance, which landed on Mars in February 2021. The MSR sample retrieval segment (lander, fetch rover, Mars Ascent Vehicle) is currently in Phase A development and expected to launch in 2028.

The content and breath of this solicitation is informed by lessons learned in MSR over the pre-Phase A years. Future SR missions are in need of technology improvements in each of the critical areas targeted: mass efficiency, sample integrity, and planetary protection.

This solicitation seeks proposals that have the potential to increase the TRL from 3 or 4 to 6 within 5 years, and are within the cost constraints of the Phases I, II, and III of this SBIR Program. Such progress would allow full flight qualification of the resulting hardware within 5 to 10 years.

Relevance / Science Traceability:

Medium- and large-class SR missions address fundamental science questions such as whether there is evidence of ancient life or prebiotic chemistry in the sampled body. Table S.1 of *Vision and Voyages for Planetary Science in the Decade 2013-2022 (2011)* correlates 10 "Priority Questions" drawn from three Crosscutting Science Themes, with "Missions in the Recommended Plan that Address Them." SR missions are shown to address 8 out of the 10 questions and cover every crosscutting theme, including Building New Worlds, Planetary Habitats, and Workings of Solar Systems.

References:

1. Vision and Voyages for Planetary Science in the Decade 2013-2022: http://nap.edu/13117
2. Visions into Voyages for Planetary Science in the Decade 2013-2022: A Midterm Review (2018): http://nap.edu/25186
3. Mars Sample Return (MSR): https://science.nasa.gov/science-pink/s3fs-public/atoms/files/07-GramlingMSR-PAC%2017Aug2020.pdf
4. Comet Nucleus Sample Return (CNSR): https://ntrs.nasa.gov/search.jsp?R=20180002990

S13.03 Extreme Environments Technology (SBIR)

Lead Center: JPL

Participating Center(s): GRC, GSFC, LaRC

Scope Title: Extreme Environments Technology

Scope Description:

This subtopic addresses NASA's need to develop technologies for producing space systems that can operate without environmental protection housing in the extreme environments of NASA missions. Key performance parameters of interest are survivability and operation under the following conditions:

1. Very low temperature environments (e.g., temperatures at the surfaces of Titan and of other ocean worlds as low as -180 °C; and in permanently shadowed craters on the Moon).
2. Combination of low-temperature and radiation environments (e.g., surface conditions at Europa of -180 °C with very high radiation).
3. Very high temperature, high pressure, and chemically corrosive environments (e.g., Venus surface conditions, having very high pressure and a temperature of 486 °C).

NASA is interested in expanding its ability to explore the deep atmospheres and surfaces of planets, asteroids, and comets through the use of long-lived (days or weeks) balloons and landers. Survivability in extreme high temperatures and high pressures is also required for deep-atmospheric probes to the giant planets. Proposals are sought for technologies that are suitable for remote-sensing applications at cryogenic temperatures and in situ atmospheric and surface explorations in the high-temperature, high-pressure environment at the Venusian surface (485 °C, 93 atm) or in low-temperature environments such as those of Titan (-180 °C), Europa (-220 °C), Ganymede (-200 °C), Mars, the Moon, asteroids, comets, and other small bodies.

Also, Europa-Jupiter missions may have a mission life of 10 years, and the radiation environment is estimated at 2.9 Mrad total ionizing dose (TID) behind 0.1-in-thick aluminum. Proposals are sought for technologies that enable NASA's long-duration missions to extreme wide-temperature and cosmic radiation environments. High reliability, ease of maintenance, low volume, low mass, and low outgassing characteristics are highly desirable. Special interest lies in development of the following technologies that are suitable for the environments discussed above:

- Wide-temperature-range precision mechanisms: for example, beam-steering, scanner, linear, and tilting multi-axis mechanisms.
- Radiation-tolerant/radiation-hardened low-power, low-noise, mixed-signal mechanism control electronics for precision actuators and sensors.
- Wide-temperature-range feedback sensors with sub-arcsecond/nanometer precision.

- Long-life, long-stroke, low-power, and high-torque force actuators with sub-arcsecond/nanometer precision.
- Long-life bearings/tribological surfaces/lubricants.
- High-temperature analog and digital electronics, electronic components, and in-circuit energy storage (capacitors, inductors, etc.) elements.
- High-temperature actuators and gear boxes for robotic arms and other mechanisms.
- Low-power and wide-operating-temperature radiation-tolerant/radiation-hardened radio-frequency (RF) electronics.
- Radiation-tolerant/radiation-hardened low-power/ultralow-power, wide-operating-temperature, low-noise mixed-signal electronics for spaceborne systems such as guidance and navigation avionics and instruments.
- Radiation-tolerant/radiation-hardened wide-operating-temperature power electronics.
- Radiation-tolerant/radiation-hardened electronic packaging (including shielding, passives, connectors, wiring harness, and materials used in advanced electronics assembly).

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.2 Mobility

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research
- Analysis

Desired Deliverables Description:
Provide research and analysis for Phase I as a final report. Deliverables for Phase II should include proof-of-concept working prototypes that demonstrate the innovations defined in the proposal and enable direct operation in extreme environments.

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase II contract.

State of the Art and Critical Gaps:
Future NASA missions to high-priority targets in our solar system will require systems that have to operate at extreme environmental conditions. NASA missions to the surfaces of Europa and other ocean worlds bodies will be exposed to temperatures as low as -180 °C and radiation levels that are at megarad levels. Operation in permanently shadowed craters on the Moon is also a region of particular interest. In addition, NASA missions to the Venus surface and deep atmospheric probes to Jupiter or Saturn will be exposed to high temperatures, high pressures, and chemically corrosive environments.

Current state-of-practice for development of space systems for the above missions is to place hardware developed with conventional technologies into bulky and power-inefficient environmentally protected housings. The use of environmental-protection housing will severely increase the mass of the space system and limit the life of the mission and the corresponding science return. This solicitation seeks to change the state of the practice by support technologies that will enable development of lightweight, highly efficient systems that can readily survive and operate in these extreme environments without the need for the environmental protection systems.

All proposals relevant to the scope described above would be eligible to be considered for award. For proposals featuring technologies intended for use in planetary science applications, this year a preference will be given to those proposals that would benefit in situ studies of icy ocean worlds, especially techniques that would be beneficial to systems that will descend through kilometers of cryogenic ice, acquire and communicate scientific observations during descent, and sample and concentrate meltwater and interior oceans.

Relevance / Science Traceability:
Relevance to SMD (Science Mission Directorate) is high.

Low-temperature survivability is required for surface missions to Titan (-180 °C), Europa (-220 °C), Ganymede (-200 °C), small bodies, and comets. Mars diurnal temperatures range from -120 °C to +20 °C. For the Europa Clipper baseline concept with a mission life of 10 years, the radiation environment is estimated at 2.9 Mrad TID behind 0.1-in-thick aluminum. Lunar equatorial region temperatures swing from -180 °C to +130 °C during the lunar day/night cycle, and shadowed lunar pole temperatures can drop to -230 °C.

Advanced technologies for high-temperature systems (electronic, electromechanical, and mechanical) and pressure vessels are needed to ensure NASA can meet its long-duration (days instead of hours) life target for its science missions that operate in high-temperature and high-pressure environments.

References:

1. Proceedings of the Extreme Environment Sessions of the IEEE Aerospace Conference: https://www.aeroconf.org/ or via IEEE *Xplore* Digital Library.
2. Proceedings of the meetings of the Venus Exploration Analysis Group (VEXAG): https://www.lpi.usra.edu/vexag/
3. Proceedings of the meetings of the Outer Planet Assessment Group (OPAG): https://www.lpi.usra.edu/opag/

S13.04 Contamination Control and Planetary Protection (SBIR)

Lead Center: JPL
Participating Center(s): GSFC

Scope Title: Contamination Control (CC) and Planetary Protection (PP) Implementation and Verification

Scope Description:
The CC and PP subtopic develops new technologies or supports new applications of existing technologies to clean spacecraft, instrumentation, or hardware, while assessing for molecular and biological contaminants to improve NASA's ability to prevent forward and backward contamination.

CC prevents the degradation of the performance of space systems due to particulate and molecular contamination. For CC efforts, understanding and controlling particulate and molecular contaminants supports the preservation of sample and science integrity and ensures spacecraft function nominally. NASA is seeking analytical and physics-based modeling technologies and techniques to quantify and validate submicron particulate contamination; low-energy surface material coatings to prevent contamination; modeling and analysis of particles and molecules to ensure hardware and instrumentation meet organic contamination requirements; and improved technologies for the detection and verification of low levels of organic compounds on spacecraft surfaces.

PP prevents forward and backward contamination to protect planetary bodies, including the Earth, during responsible exploration. Forward contamination is the transfer of viable organisms and bacterial endospores from Earth to another planetary body. Backward contamination is the transfer of biological material, with the potential to cause harm, from a planetary body to Earth's biosphere. Understanding potential CC and PP contaminants and preventing the contamination of our spacecraft and instruments in general also supports the integrity of NASA sample science and mitigates other potential impacts to spacecraft function.

NASA is seeking innovative approaches to address these challenges through:

- Improvements to spacecraft cleaning and sterilization that are compatible with spacecraft materials and assemblies.
- Prevention of recontamination and cross contamination throughout the spacecraft lifecycle.
- Advanced technologies for the detection and verification of organic compounds and biologicals on spacecraft, specifically for microbial detection and assessments for viable organism and deoxyribonucleic-acid- (DNA-) based verification technologies and that may encompass sampling devices, sample processing, and sample analysis pipelines.
- Active in situ recontamination/decontamination approaches (e.g., in situ heating of sample containers to drive off volatiles prior to sample collection) and in situ/in-flight sterilization approaches (e.g., UV or plasma) for surfaces.
- Development of analytical and modeling-based methodologies to address bioburden and probabilistic risk assessment biological parameters to be used as alternatives to demonstrate requirement compliance.
- Enabling end-to-end sample return functions to ensure containment and pristine preservation of materials gathered on NASA missions (e.g., development of technologies that support in-flight verification of sample containment or in-flight correctable sealing technologies).

Examples of outcomes:

- End-to-end microbial reduction/sterilization technology for larger spacecraft subsystems.
- Microbial reduction/sterilization technology for spacecraft components.
- Ground-based biological contamination/recontamination mitigation system that can withstand spacecraft assembly and testing operations.
- In-flight spacecraft component-to-component cross-contamination mitigation system.
- Spacecraft sterilization systems for target body ground operations.
- Viable organism and/or DNA sample collection devices, sample processing (e.g., low biomass extraction), and sample analysis (e.g., bioinformatics pipelines for low biomass).
- Real-time, rapid device for detection and monitoring of viable organism contamination on low-biomass surfaces or in cleanroom air.
- Bioburden spacecraft cleanliness monitors for assessing surface cleanliness throughout flight and surface operations during missions.
- DNA-based system to elucidate abundance, diversity, and planetary protection relevant functionality of microbes present on spacecraft surfaces.
- An applied molecular identification technology to tag/label biological contamination on outbound spacecraft.
- Molecular mapping and detection technology for organic contamination on outbound and returned spacecraft and spaceflight hardware.
- Low surface area energy coatings.
- Molecular adsorbers (“getters”).
- Technologies to assess human contamination vectors and safety for missions traveling to the Earth’s Moon and human missions traveling to Mars.
- Experimental technologies for measurement of outgassing rates lower than 1.0×10^{-15} g/cm^2/sec with mass spectrometry, under flight conditions (low and high operating temperatures) and with combined exposure to natural environment (e.g., high-energy radiation, ultraviolet radiation, atomic oxygen exposure).
- Physics-based technologies for particulate and molecular transport modeling and analysis for complex geometries with moving elements (e.g., rotating solar arrays, articulating robotic arms) in continuum, rarefied, and molecular flow environments, with additional physics (e.g., electrostatic, vibro-acoustic, particle detachment and attachment capabilities).

- A ground-based containment system that protects the Earth from restricted Earth-return samples, protects the samples from terrestrial contamination and allows for hardware manipulation and preliminary characterization of samples (e.g., double-walled isolators).

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.3 Mission Operations and Safety

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

- Phase I deliverable: As relevant to the proposed effort—proof-of-concept study for the approach to include data validation and modeling.
- Phase II deliverable: As relevant to the proposed effort—detailed modeling/analysis or prototype for testing.
- Areas to consider for deliverables: technologies, approaches, techniques, models, and/or prototypes, including accompanying data validation reports and modeling code demonstrating how the product will enable spacecraft compliance with PP and CC requirements.

State of the Art and Critical Gaps:
PP state of the art encompasses technologies from the 1960s to 1970s Viking spacecraft assembly and test era along with some more recent advancements in sterilization and sampling technologies. The predominant means to control biological contamination on spacecraft surfaces is to use some combination of heat microbial reduction processing and mechanical removal via solvent cleaning processes (e.g., isopropyl alcohol cleaning). Notably, vapor hydrogen peroxide is a NASA-approved process, but the variability of the hydrogen peroxide concentration, delivery mechanism, and material compatibility concerns still tends to be a hurdle to infuse it on a flight mission with complex hardware and multiple materials for a given component. Upon microbial reduction, during spacecraft integration and assembly, the hardware then is protected in a cleanroom environment (ISO 8 or better) using protective coverings when hardware is not being assembled or tested. For example, terminal sterilization has been conducted with recontamination prevention for in-flight biobarriers employed for the entire spacecraft (Viking) or a spacecraft subsystem (Phoenix spacecraft arm). In addition to the hardware approaches developed for compliance, environmental assessments are implemented to understand recontamination potential for cleanroom surfaces and air. Biological cleanliness is then verified through the NASA standard assay, which is a culture-based method. Although the NASA standard assay is performed on the cleanroom surfaces, DNA-based methodologies have been adopted by some spaceflight projects to include 16S and 18S ribosomal-ribonucleic-acid- (rRNA-) targeted sequencing, with metagenomic approaches currently undergoing development. Rapid cleanliness assessments can be performed, but are not currently accepted as a verification methodology, to inform engineering staff about biological cleanliness during critical hardware assembly or tests that include the total adenosine triphosphate (tATP) and limulus amoebocyte lysate (LAL) assays. Variability in detector performance thresholds in the low biomass limit remain a hurdle in the infusion of ATP luminometers for spaceflight verification and validation. Moreover, with recent missions leveraging probabilistic modeling for biological contamination, modeling has become a key tool in demonstrating compliance and helping to drive biological assurance cases for spacecraft cleanliness. Given the complexity of upcoming missions, this is rapidly becoming an emerging need in the discipline to help define parameters and develop upstream models for understanding biological cleanliness, distributions of biological contamination, behaviors of these biologicals on spacecraft surfaces, transport models, etc. In summary, the

critical PP gaps include the assessment of DNA from low-biomass surfaces (<0.1 ng/µL DNA, using current technologies, from 1 to 5 m^2 of surface); sampling devices that are suitable for reproducible (at a certification level) detection of low biomass and compounds (e.g., viable organisms, DNA) but also compliant with spaceflight environmental requirements (e.g., cleanroom particulate generation, electrostatic discharge limits); quantification of the widest spectrum of viable organisms; enhanced microbial reduction/sterilization modalities that are compatible with flight materials and ground-/flight-/planetary-body-based recontamination prevention/mitigation systems.

CC requirements and practices are also evolving rapidly as mission science objectives targeting detection of organics and life are driving stricter requirements and improved characterization of flight-system- and science-instrument-induced contamination. State-of-the-art CC includes:

- Testing and measurement of outgassing rates down to 3.0×10^{-15} $g/cm^2/sec$ with mass spectrometry, under flight conditions (low and high operating temperatures) and with combined exposure to natural environment (high-energy radiation, ultraviolet radiation, atomic oxygen exposure).
- Particulate and molecular transport modeling and analysis for forward contamination scenarios of simple and complex spacecraft geometries with electrostatic, vibro-acoustic, particle detachment and attachment capabilities in continuum, rarefied, and molecular flow environments.
- Modeling and analysis of particulate flux for assessment of backward contamination scenarios using dynamic approaches (e.g., direct simulation Monte Carlo (DSMC) and Bhatnagar–Gross–Krook (BGK) formulations).

Relevance / Science Traceability:

With increased interest in investigating bodies with the potential for life detection such as Europa, Enceladus, Mars, and maybe other bodies, and the potential for sample return from such bodies, there is increased need for novel technologies associated with planetary protection and contamination control. The development of such technologies would enable missions to be able to be responsive to PP and CC requirements as they would be able to assess viable organisms and other particulate and organic contaminants; establish microbial reduction and protective technologies to achieve acceptable microbial bioburden and organic contamination levels for sensitive life detection in spacecraft and instruments to mitigate risk and inadvertent “false positives”; ensure compliance with sample return planetary protection and science requirements; and support model-based assessments of planetary protection requirements for biologically sensitive missions (e.g., outer planets and sample return).

References:

1. Planetary Protection: https://planetaryprotection.nasa.gov/
2. JPL Planetary Protection Center of Excellence: https://planetaryprotection.jpl.nasa.gov/
3. Handbook for the Microbial Examination of Space Hardware: https://explorers.larc.nasa.gov/2019APSMEX/SMEX/pdf_files/NASA-HDBK-6022b.pdf
4. McCoy, K. et. al.: "Europa Clipper planetary protection probabilistic risk assessment summary," *Planetary and Space Science*, Vol. 196, February 2021, 105139.

S16.04 Unpiloted Aerial Platforms and Technologies for NASA Science Missions (SBIR)

Lead Center: ARC
Participating Center(s): AFRC, GSFC, JPL, LaRC

Scope Title: Unpiloted Aerial Platforms for High-Altitude, Long-Endurance (HALE) Missions

Scope Description:

NASA is interested in increased utilization of innovative, cost-effective, unpiloted, aerial platforms, including ones that are heavier and lighter than air, to perform NASA missions in the stratosphere in order to supplement current piloted and satellite platforms. Unmanned aerial platforms are especially suited for HALE missions that occur at or above 50,000 to 90,000 ft and can support continuous flights of 30 days or more at altitude.

HALE missions enable new Earth and space science applications and an opportunity for testing spaceborne-like measurements in the stratosphere. High spatial and temporal resolution observations from HALE can improve measurements of Earth system processes or phenomena requiring sustained observations, including: air quality monitoring, coastal zone and ocean imaging and monitoring, mapping of geologically active regions, forest and agricultural monitoring, and imaging of polar regions. The NASA Surface Biology and Geology mission, for example, is anticipating the need for measurements of leaf canopy chemistry during the growing season, and significant changes can happen between overpasses of polar orbiting satellites. Similarly, the Surface Topography and Vegetation Incubation team recently released a report citing the need for more frequent observations of areas prone to landslides and other ephemeral or episodic events where time series observations can improve Earth system models.

HALE Platforms offer several key challenges, including solar/battery technologies, operation in regions of harsh radiation and temperatures, vehicle health monitoring, and mission deployment/support at remote locations. Methods for accurate stationkeeping in areas of interest would also have to be developed.

Proposals are solicited for both heavier- and lighter-than-air innovative stratospheric platforms that can operate at an altitude of 60,000 ft or above, for a mission of 30 or more days in duration. The proposed vehicle must be able to carry a scientific instrumentation payload of 22lbs or more on all science missions. The combined system must be able to maintain position within 100 nautical miles of a fixed point on the ground and be able to provide at least 100+ W of sustained power (28 Vdc) to payloads. The platform must also have high band width, line-of-sight payload telemetry, and SATCOM capability to enable beyond visual line of site command and control. Proposals can be based on new design platforms or extensively modified existing platforms to meet the above HALE mission requirements.

The primary focus of proposal should be on vehicle design towards a flight test prototype in Phase II. Other aspects such as concept of operations, vehicle maintenance, vehicle transport and deployment, ground station design, and flight-test planning should also be addressed.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.2 Mobility

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
It is expected that a Phase I effort will consist of a system-level design and a proof-of-concept experiment on one or more key components. Deliverable items for Phase I shall be a final report describing the results of the concept analysis and demonstration of any key component technology developed.

The Phase II effort will focus on the development of a concept prototype and feasibility testing. The Phase II deliverable should include a final report on design concept documentation, test reports, and photos of any prototypes that were built and tested.

State of the Art and Critical Gaps:

NASA Global Hawk unmanned aircraft system (UAS) previously provided HALE capability for NASA Earth Science missions but was retired from this mission in 2020. NASA presently has no UAS platforms serving in this role and is reliant on satellites and piloted aircraft to fly these missions. Currently, NASA Earth Science has needs but no platforms to meet this.

While NASA continues development of super-pressure balloons with extended duration, several lighter-than-air vehicles have recently been developed that can provide capabilities to meet NASA science needs.

Several prototype and proof-of-concept HALE vehicles are under development and flight testing. These next-generation HALE vehicles under development have had a focus on communications, and so payloads relevant to Earth Science have not been demonstrated. These existing platforms, which include both heavier- and lighter-than-air platforms could be modified to meet requirements of this solicitation, or new designs could meet them as well.

Relevance / Science Traceability:
As the impacts of climate change become more pronounced through long-term drought, more frequent and intense wildfires, and an increase in severe weather occurrences, there is increased emphasis on Earth Science missions by NASA, other Government Agencies, and private industry. This includes new technologies and capabilities to enhance our ability to observe and predict effects on the environment and the economy of these more frequently occurring events.

NASA, other Government Agencies, and private companies have also shown increased interest in utilizing UAS platforms, both heavier and lighter than air, for Earth Science data collection, supplementing satellite and piloted Earth Science aircraft. This is largely because of the ability of UAS to perform dull, dirty, difficult, and dangerous missions more easily than other platforms.

There is interest from the highest levels of Government to invest in the domestic UAS manufacturing base to reduce reliance on foreign manufacturers as well as security concerns with foreign UAS platforms and technologies.

References:

1. Airborne Platforms to Advance NASA Earth System Science Priorities: Assessing the Future Need for a Large Aircraft Committee on Future Use of NASA Airborne Platforms to Advance Earth Science Priorities 2021: https://www.nap.edu/catalog/26079/airborne-platforms-to-advance-nasa-earth-system-science-priorities-assessing - see page 142.
2. Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space National Academies of Sciences, Engineering 2018: https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth
3. Observing Earth's changing surface topography and vegetation structure 2021: https://science.nasa.gov/science-red/s3fs-public/atoms/files/STV_Study_Report_20210622.pdf - see page 122.

Scope Title: Unpiloted Aerial Platforms for Extreme Environment Missions on Earth

Scope Description:
NASA is interested in increased utilization of unpiloted aerial platforms, both lighter and heavier than air, for Earth Science missions to supplement current piloted and satellite platforms, taking advantage of unpiloted aerial platforms to perform dull, dirty, difficult, and dangerous missions. These platforms are especially suited for extreme environment missions such as volcano, storm, and wildfire penetration as there would be no risk to humans compared to piloted aircraft.

Numerous Earth Science missions require aircraft to operate in situ or in close proximity to extreme environments. This includes flights into volcano plumes to compare sulfur dioxide concentration measurements with those measured by satellites. Another application is storm penetration where unmanned aircraft system (UAS) platforms are flown into thunderstorms and hurricanes to obtain measures of air pressure, wind conditions, temperatures, and other data used for storm forecasting and weather model development. A third example is operation in wildfires where unmanned aerial vehicles (UAVs) can gather information on emissions and fire behavior.

UAS Platforms designed for operation in extreme environments offer several key challenges to developers. Strong winds in the area of these missions usually ground smaller UAS platforms. Turbulence could cause vehicle upset and loss of control in addition to structural damage. Many UAS platforms are not weather resistant and so cannot operate in visible precipitation. For operation in extremely cold conditions, icing could cause loss of the aircraft.

Proposals are solicited for both heavier- and light-than- air aerial platforms that can operate in the extreme environments described above. Proposed platforms should address the operational challenges described to enable missions to be accomplished with minimal vehicle loss. The proposed vehicle must be able to carry a scientific instrumentation payload on all science missions. The proposal can be based on new design platforms or extensively modified existing platforms to meet the above mission requirements.

The primary focus of the proposal should be on vehicle design. However, other aspects such as concept of operations, vehicle maintenance, vehicle transport and deployment, ground station design, and flight test planning should also be addressed.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.2 Mobility

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
It is expected that a Phase I effort will consist of a system-level design and a proof-of-concept experiment on one or more key components or enabling technologies. Deliverable items for Phase I shall be a final report describing the results of the concept analysis and demonstration of any key component technology developed.

The Phase II effort will focus on the development of a concept prototype and feasibility testing. Phase II deliverables should include a final report on design concept documentation, test reports, and photos of any prototypes that were built and tested.

State of the Art and Critical Gaps:
Currently, most UAS platforms can operate only in the proximity of extreme environments but do not have capability for actual penetration other than with a high probability of vehicle loss. The strong winds and turbulence associated with these environments usually grounds smaller UAS platforms or could cause vehicle upset and loss of control as well as structural damage.

Many UAS platforms are not weather resistant and so cannot operate in precipitation. For operation in extremely cold conditions such as polar regions, icing could cause loss of the vehicle.

Because of the capability and operational limits of current UAS platforms, it may not be possible to capture important Earth Science data in hazardous environments.

NASA ARMD (Aeronautics Research Mission Directorate) and NASA ARMD SBIR technologies as well as technologies developed by universities could be utilized by the proposed to address some of these challenges such as icing detection and removal; gust load alleviation; upset prevention, detection, and recovery; see-and-avoid systems; technologies for beyond visual line of sight operation; and others.

Relevance / Science Traceability:
Because of global warming and associated effects such as long-term drought, more frequent and intense wildfires, and an increase in severe weather occurrences, there is an increased priority of Earth Science missions by NASA, other Government Agencies, and private industry. This includes prediction of, detection of, response to, and measurement of effects on the environment and the economy of these more frequently occurring events.

NASA, other Government Agencies, and private companies have also shown increased interest in utilizing unmanned aircraft system (UAS) platforms, both heavier and lighter than air, for Earth Science data collection, supplementing satellite and piloted Earth Science aircraft. This is largely due to the ability of UAS to perform dull, dirty, difficult, and dangerous missions more easily than other platforms. In addition, simpler UAS platforms could be more easily deployed to quickly respond to events of interest.

In addition, there is interest from the highest levels of government to invest in the domestic UAS manufacturing base to reduce reliance on foreign manufacturers such as DJI as well as security concerns with foreign UAS platforms and technologies.

Historically it has been difficult to operate UAS platforms in the National Airspace, primarily because of safety concerns. A large amount of planning, coordination, and approvals were required, making a quick response nearly impossible. Less restrictive operational requirements as developed by the NASA UAS in the NAS program and advances in UAS Air Traffic Technologies developed under the NASA UAS Traffic Management (UTM) Project have enabled simpler, safer, and more efficient UAS flight operations both for private companies and for NASA Earth Science missions.

Advances in UAS technologies, developed under the NASA Aeronautics Research Mission Directorate (ARMD), have enables more capable, less expensive, and higher performing platforms, resulting in an increase of small, innovative, domestic UAS manufacturers. This pool of UAS companies have the expertise and capabilities to develop UAS platforms for future NASA Earth Science missions as well as to commercialize these platforms for non-NASA users.

References:

1. Airborne Platforms to Advance NASA Earth System Science Priorities: Assessing the Future Need for a Large Aircraft Committee on Future Use of NASA Airborne Platforms to Advance Earth Science Priorities 2021: https://www.nap.edu/catalog/26079/airborne-platforms-to-advance-nasa-earth-system-science-priorities-assessing
2. Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space National Academies of Sciences, Engineering 2018: https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth

Scope Title: Lighter-than-air platform subsystems for Earth and Venus

Scope Description:
1. Venus lighter-than-air platform:

NASA is interested in scientific exploration of Venus using aerial vehicles to perform in situ investigations of its atmosphere and is currently developing concepts for variable-altitude balloons operating at an altitude range between 52 and 62 km.

One concept for a variable-altitude balloon features a super-pressure (SP) balloon located within a zero-pressure (ZP) balloon. The configuration can be described as one small balloon inside a large balloon that are co-located at the bottom. Altitude changes are made by transfer of helium between the two balloons. Pumping helium from the ZP balloon into the SP balloon reduces buoyancy to descend in altitude. Venting helium from the SP balloon into the ZP balloon increases buoyancy to ascend in altitude. Isolating the ZP and SP balloons when neither the pump or vent is operated enables the balloon to float at constant altitude. Details on the variable-altitude balloon system concept can be found in [Hall 2021].

Proposals for an innovative balloon altitude modulation system featuring a lightweight, high-efficiency pump, isolation valves, and venting orifices are desired. The performance requirements of the balloon altitude modulation system will vary depending on the size of the balloon system and payload. For the purposes of adequately scaling this effort, the following specifications represent the requirements for a current Venus balloon concept (the fluid medium is helium gas):

- The pump shall have a nominal flow rate of 250 liters per minute at a pressure rise of 30 kPa.
- The vent shall have a nominal flow rate of 1,000 liters per minute at a pressure drop of 5 kPa.

For reliability purposes, the mission operating lifetime is about 100 days of continuous operations.

Typical commercial pumps with this pressure rise and flow rate have a mass around 15 kg and require 250 W of power. Ground-breaking solutions to reduce pump mass to <7 kg and reduce power to <120 W are goals for the specified flow rate and operating pressure.

The specified pressure and flow requirements are current best estimates and will not change during the Phase I proposal development period but may be updated for Phase II.

Venus features a challenging atmospheric environment that significantly impacts the design and operation of devices on aerial vehicles. Proposers should be familiar with the properties of the Venus atmosphere as described in this call. Additional information on the Venus atmospheric environment can be found in the References section.

2. Earth Lighter-than-air platform:

NASA is also looking for an innovative way to reduce the termination dispersions from a few miles to within 1/2 to 1/4 mile of the predicted termination point by the use of a steerable parachute recovery system (SPRS). The SPRS will need to be able to maneuver around infrastructure (e.g., oil wells, power lines, wind mills), protected areas (e.g., national parks, special habitats), natural resources (e.g., rivers, mountains, lakes), and other areas of interest (e.g., farm land). The SPRS will need to provide real-time maneuverability for a science gondola from a remote operations control room using the communications and telemetry systems provided by the Columbia Scientific Balloon Facility (CSBF). The system should be lightweight—no more than 75 lb—including power.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.6 Vehicle Concepts

Desired Deliverables of Phase I and Phase II:

- Prototype

- Hardware

Desired Deliverables Description:
The deliverables for Phase I include a trade study of the potential systems, a simulation of how each system should work, and a report on the recommendation of one to two systems to be further developed in Phase II. It is anticipated that these products are achievable given the SBIR time and funding constraints.

The deliverables for Phase II include an engineering development unit and flight testing with a report of the results.

State of the Art and Critical Gaps:
1. Venus lighter-than-air platform state of the art:

There are few commercially available pumps in the market today that have the pressure rise and flow rate capabilities needed for a Venus balloon. Most pumps are not built to be lightweight or efficient, which are of critical importance on a balloon mission. Commercial pumps with the targeted flow rate and pressure capability typically have a mass around 15 kg and require 250 W of power. Isentropic pumping power analysis shows that only 80 W of power are required to achieve the desired flow rate and pressure rise. Therefore, the thermodynamic efficiency of commercial pumps is only about 33%. The Venus balloon system desires a system that is at least 65% efficient (2x over commercial products) and half the mass of commercial pump systems to maximize resource availability on the balloon system.

2. Earth lighter-than-air platform state of the art:

A scientific balloon floats at an average altitude of 110,000 ft or more and carries science payloads up to 8,000 lb. At the end of a scientific balloon mission, the science payload on the gondola (“science gondola” from this point on) is separated from the balloon and falls to Earth on a parachute, following the wind currents at the time of release, and then lands on cardboard crush pads. In most cases this allows recovery of the science gondola, although the payload and gondola may be in areas that are hard to reach using conventional recovery trucks. However, there are rare cases where the science gondola falls either into water or in areas that require special equipment or are difficult for recovery (i.e., inaccessible area). Currently, trajectory predictions for termination are within a few miles and are dependent on models, map overlays (showing restricted air space, national/state parks), and observations from a plane on areas along the trajectory to determine the best area to terminate the balloon and bring the science gondola safely to the ground. Some items that are considered during the termination discussions are science mission minimums, trajectory predications (e.g., national or state parks, lakes, mountains, rivers, infrastructure, crop lands), weather conditions, and risk to the public.

Current state of the art does not include steerable systems in balloon parachutes. Success in this endeavor will primarily entail steerability, and will also frequently result in a safety analysis, which will allow more “green lights” for launch than would otherwise be the case.

Relevance / Science Traceability:
1. Venus Lighter-than-air platform relevance:

The Mars Helicopter, Ingenuity, and the Titan Dragonfly mission show there is significant interest in planetary aerial vehicles for science investigations. It is in NASA's interest through the SBIR program to continue fostering innovative ideas to extend our exploration capabilities by developing technologies for Venus aerial mission concepts.

The NASA Jet Propulsion Laboratory's (JPL's) Solar System Mission Formulation Office and Science Mission Directorate's (SMD's) Planetary Science Division advocate Venus aerial vehicle platform development. NASA recently completed the Venus Flagship Mission concept study, which included a balloon system for the Planetary Decadal Survey [Gilmore, 2020].

Science traceability: The 2019 VEXAG Venus Strategic Plan identified several key science investigations that are ideally suited to aerial platforms. The areas of scientific interest include Atmospheric Gas Composition, Cloud and Haze Particle Characterization, Atmospheric Structure, Surface Imaging, and Geophysical Investigations. The variable-altitude aerial vehicle platform is ideal for investigating these science goals and objectives. Building the variable-altitude balloon requires the development of several key components such as the helium transfer system identified in this call.

2. Earth Lighter-than-air platform relevance:

This subtopic will be relevant to any mission directorate, commercial entity, or other government agency that drops payloads from an altitude, including the Balloon Program. Other potentially interested projects include NASA sounding rockets, unmanned aerial vehicles (UAVs), and aircraft programs.

References:

Venus Lighter-than-air platform:

1. Crisp, D.: “Radiative forcing of the Venus mesosphere I: Solar fluxes and heating rates,” *Icarus*, 67, pp. 484-514, 1986.
2. Gilmore, M., et al.: “Venus Flagship Mission Planetary Decadal Study,” Planetary Mission Concept Studies Virtual Workshop, 2020.
3. Hall, J., et al.: “Prototype Development of a Variable Altitude Venus Aerobot”, AIAA Aviation Forum, 2021.
4. Knollenberg and Hunten: "The microphysics of the clouds of Venus: Results of the Pioneer Venus Particle Size Spectrometer Experiment," *JGR*, 85, pp. 8039-8058, 1980, doi:10.1029/JA085iA13p08039.
5. Oschlisniok, J. et al.: "Microwave absorptivity by sulfuric acid in the Venus atmosphere: First results from the Venus Express Radio Science experiment VeRa," *Icarus,* 221, p. 940, 2012.
6. Titov, D., Ignatiev, N. I., K. McGouldrick, Wilquet, V., and Wilson, C. F.: “Venus III: Clouds and hazes of Venus,” *Space Sci. Rev.*, 214, 126, 2018.
7. The VEXAG Strategic Plan 2019: https://www.lpi.usra.edu/vexag/documents/reports/Combined_VEXAG_Strategic_Documents_2019.pdf
8. The Venus Atmospheric Properties are available in Kliore, A. J., Moroz, V. I., Keating G. M., Eds.: “The Venus International Reference Atmosphere,” *Adv. Space Res.*, Vol. 5, No. 11, pp 8+305, 1985, ISBN 0-08-034631-6.

Earth Lighter-than-air platform:

1. JPADS: circumventing GPS for next-gen precision airdrops: https://patents.google.com/patent/EP1463663A4/en https://www.airforce-technology.com/features/featurejpads-circumventing-gps-for-next-gen-precision-airdrops-4872436/

S16.06 Command, Data Handling, and Electronics (SBIR)

Lead Center: GSFC

Participating Center(s): JPL, LaRC, MSFC

Scope Title: Analog-to-Digital Conversion Components

Scope Description:

NASA's space-based observatories, flyby spacecraft, orbiters, landers, and robotic and sample-return missions require robust command and control capabilities. Advances in technologies relevant to command and data handling and instrument electronics are sought to support NASA's goals and several missions and projects under development.

The 2022 subtopic goals are to develop platforms for the implementation of miniaturized highly integrated avionics and instrument electronics that:

- Are consistent with the performance requirements for NASA missions.
- Minimize required mass/volume/power as well as development cost/schedule resources.
- Can operate reliably in the expected thermal and radiation environments.

Successful proposal concepts should significantly advance the state of the art. Furthermore, proposals developing hardware should indicate an understanding of the intended operating environment, including temperature and radiation. Note that environmental requirements vary significantly from mission to mission. For example, some low-Earth-orbit missions have a total ionizing dose (TID) radiation requirement of less than 10 krad(Si), whereas planetary missions can have requirements well in excess of 1 Mrad(Si).

Specific technologies sought by this scope include:

- Radiation-hardened mixed-signal structured application-specific integrated circuit (ASIC) platforms to enable miniaturized and low-power science sensor readout and control, with sufficient capability to implement 12-bit digital-to-analog converters (DACs), monotonic and 12- to 16-bit analog-to-digital converters (ADCs) (<100 kHz 16-bit and 1 to 2 MHz 12-bit), and also charge-sensitive amplifiers for solid-state detectors and readout integrated circuit (ROIC) for silicon photomultipliers.
- Low-power, radiation-hardened ASIC devices to enable direct capture of analog waveforms.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.1 Avionics Component Technologies

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software
- Analysis
- Research

Desired Deliverables Description:
Desired Phase I deliverables include the design, simulation, and analysis to demonstrate viability of proposed component.

Desired Phase II deliverables include a prototype mixed-signal ASIC implemented with a proof-of-concept end-user design. The proof-of-concept design should demonstrate the stated performance capabilities of the ASIC.

State of the Art and Critical Gaps:
There is a need for a broader range of mixed-signal structured ASIC architectures. This includes the need for viable options for mixed ASICs with high-resolution, low-noise analog elements, especially 12-bit DACs and 12- to 16-bit ADCs. The current selection of mixed-signal structured ASICs is limited to 10-bit designs, which do not provide the accuracy or resolution to perform the science required of many of the instruments currently being flown. Mixed-signal structured ASICs can integrate many functions and therefore can save considerable size, weight, and power over discrete solutions—significantly benefiting NASA missions. The lack of parts with high-precision analog is greatly limiting their current application.

Relevance / Science Traceability:
Mixed-signal structured ASIC architectures are relevant to increasing science return and lowering costs for missions across all Science Mission Directorate (SMD) divisions. However, the benefits are most significant for

miniaturized instruments and subsystems that must operate in harsh environments. These missions include interplanetary CubeSats and SmallSats, outer-planet instruments, and heliophysics missions to harsh radiation environments. For all missions, the higher accuracy would provide better science or allow additional science through the higher density integration.

References:

The following resources may be helpful for descriptions of radiation effects in electronics:

1. NASA Technical Reports Server: https://ntrs.nasa.gov/
2. NASA Electronic Parts and Packaging Program: https://nepp.nasa.gov/
3. NASA/GSFC Radiation Effects and Analysis Home Page: https://radhome.gsfc.nasa.gov/top.htm

Scope Title: Low-Cost Data Acquisition System

Scope Description:

Destinations such as Mars, Venus, and Titan pose many challenges for entry, descent, and landing (EDL) data acquisition systems, including radiation, g-loading, and volume constraints. Recent notable examples of such systems are the Mars Entry, Descent, and Landing Instrumentation (MEDLI) and MEDLI2 sensor suites, which successfully acquired EDL data in 2012 and 2021, respectively. The NASA MEDLI and MEDLI2 data acquisition systems were very well designed and robust to the extreme environments of space transit and EDL but came at a great financial burden to these missions. The high cost prohibits smaller mission classes such as Discovery and New Frontiers from using MEDLI-like systems, therefore limits the EDL science that can be conducted by NASA. In an effort to bring EDL instrumentation to all missions, NASA seeks a low-cost, robust, high-accuracy data acquisition system. Wireless data acquisition capability would eliminate external radio-frequency interference coupling effects and represents a significant cost and mass savings opportunity on future NASA missions. For example, the sensor cable mass for the Orion Exploration Flight Test 1 (EFT-1) Developmental Flight Instrumentation (DFI) suite was 700 lb. of the entire 1200-lb DFI system. A wireless option for the low-cost data acquisition system is therefore highly desirable.

Data acquisition requirements:

- Compatibility: Minimum 15 thermocouples (minimum of 2 Type R and minimum of 8 Type K) and 8 pressure transducers (120- or 350-ohm bridge).
- Power: 16 W or less.
- Size: Modularity encouraged, max. module size of 10 cm^3, four modules max.
- Measurement resolution: 12 bit or higher.
- Acquisition rate: 8 Hz or higher.
- Weight: 5 kg or less.
- Accuracy: +/-0.5% of FSR (full scale range).
- Radiation tolerant by design: Minimum of 10 krad (30 krad or better desired).
- Axial loading capability: minimum 15g (Venus missions could require 100g to 400g).
- Temperature capability: -40 to +85 °C.
- Cost: Fully qualified target of ~$1M (recurring).

Optional wireless capability:

- Centralized or distributed architecture.
- Scalable architecture.
- 0.0% packet loss.
- Capable of operating independently for a minimum of 2 years.
- Completely wireless: data acquisition and communication powered by a battery or harvested energy (e.g., solar, thermal).

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.2 Avionics Systems and Subsystems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I deliverables would include electrical system design, trade studies, component selections, requirements definitions, and systems analysis to result in a modeled and analyzed data acquisition system architecture. Early breadboard circuits or prototypes may be included.

Phase II deliverables would include production of a prototype low-cost data acquisition system and results from electrical performance testing. Testing may include some environmental and stress testing.

State of the Art and Critical Gaps:
The NASA MEDLI and MEDLI2 data acquisition systems were very well designed and robust to the extreme environments of space transit and EDL, but this comes at a great financial burden to these missions. The high cost prohibits smaller mission classes such as Discovery and New Frontiers from using MEDLI-like systems, therefore limiting the EDL science that can be conducted by NASA. To bring EDL instrumentation to all missions, NASA seeks a low-cost, robust, high-accuracy data acquisition system.

Relevance / Science Traceability:
This technology would be especially relevant to upcoming Science Mission Directorate (SMD) planetary missions, such as DAVINCI and VERITAS, but low-cost data acquisition systems with these capabilities would also be relevant to the other science lines of business, especially for future cost and volume-constrained and distributed-systems missions.

References:

1. MEDLI2: https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/MEDLI-2
2. MEDLI: https://mars.nasa.gov/msl/spacecraft/instruments/medli/
3. NASA Selects 2 Missions to Study ‘Lost Habitable’ World of Venus: https://www.nasa.gov/press-release/nasa-selects-2-missions-to-study-lost-habitable-world-of-venus
4. NASA to Explore Divergent Fate of Earth’s Mysterious Twin with Goddard’s DAVINCI+: https://www.nasa.gov/feature/goddard/2021/nasa-to-explore-divergent-fate-of-earth-s-mysterious-twin-with-goddard-s-davinci
5. VERITAS: https://www.jpl.nasa.gov/missions/veritas

Scope Title: Printed High Density Interconnects

Scope Description:
As the size of circuit boards continues to shrink and electronic component sizing continues to approach bare die form factors, NASA's need for high-reliability, high-density interconnection solutions is increasing. The ability to connect components or even larger assemblies together without the need for conventional connectors and harnessing stands to offer significant advantages to the size and weight requirements of command, data handling, and electronics systems. High-reliability interconnect methodologies that can operate in space environments (vacuum, vibration) and deliver hundreds of signal/power connections while using as little physical board area as possible are desired.

Chip-scale interconnection methodologies such as wirebonding are size and volume efficient, but present manufacturing, reliability, and handling challenges when applied in an exposed manner on otherwise conventional circuit board assemblies. NASA seeks manufacturing technologies that could be applied at the circuit board assembly level to create high-reliability, high-density electrical connections across three-dimensional (3D) topologies, such as connecting to the top surface of microcircuit die adhered to a substrate. Emerging additively manufactured and printed hybrid electronics technologies offer potential solutions that also address the reliability and handling challenges present with larger assembly implementations, but further development is needed to demonstrate performance and reliability for NASA applications.

Specifically, NASA is seeking:

- Capability to reliably print or produce 400 or more conductive traces, on the order of 50 to 100 µm width, with 100 to 200 µm pitch.
- Capability to reliably print or produce traces that can traverse a vertical shift to an elevated topology shifts of up to 1.5 mm in height. Printing or producing fillets or ramps to accommodate smooth transitions for the vertical topology shifts is acceptable.
- Electrical resistivity of the traces shall be no more than 300 ohm/mm, and isolation to adjacent traces shall be on the order of gigaohms.
- Printed or produced traces shall demonstrate alignment to target features on the substrates and the elevated topology surfaces.
- Demonstrated reliability and workmanship testing performance, such as vibration and thermal cycling.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.2 Avionics Systems and Subsystems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I deliverables would include development of prototype design, materials selection and trade studies, production of necessary equipment fixtures and tooling, and ultimately demonstration of the proposed interconnect manufacturing.

Phase II deliverables would include refinement of prototype designs, demonstration of consistent print production across multiple samples, electrical performance, and results of workmanship and reliability tests of produced designs.

State of the Art and Critical Gaps:
The current assembly process for arrays of die and sensors is wire bonding. However, as die become smaller and die pads become smaller and denser, this pushes the limits of wire bonding capabilities. The next generation of NASA science missions have needs for higher density interconnect solutions. Printed hybrid electronics technologies are emerging; however, they have not yet demonstrated suitable repeatability and reliability for use in NASA applications.

Relevance / Science Traceability:

These technologies would be broadly beneficial to command and data handling (C&DH) architectures on many NASA missions. There is also a crossover need for this technology on high-density detector systems that will be needed for NASA's next-generation science missions.

- Missions/Programs/Projects that could use the technology:
    - Large UV/Optical/IR Surveyor (LUVOIR).
    - Habitable Exoplanet Observatory (HabEx).
    - Cosmic Evolution Through UV Spectroscopy (CETUS).

References:

The following resources may be helpful for descriptions of radiation effects in electronics:

1. NASA Technical Reports Server: https://ntrs.nasa.gov/
2. NASA Electronic Parts and Packaging Program: https://nepp.nasa.gov/
3. NASA/GSFC Radiation Effects and Analysis Home Page: https://radhome.gsfc.nasa.gov/top.htm
4. LUVOIR: https://asd.gsfc.nasa.gov/luvoir/
5. Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/
6. Cosmic Evolution Through UV Spectroscopy (CETUS): https://cor.gsfc.nasa.gov/copag/AAS_Jan2018/Heap_UVisSig_8Jan18.pdf

Scope Title: Intelligent Hardware Supervisors

Scope Description:

The space radiation environment and single-event effects (SEEs) are known to cause errors and interruptions in electronics circuitry. NASA has an increasing need to achieve higher performance processing and microcircuits, and this often requires infusion of commercial electronic parts, which may not be explicitly designed for radiation tolerance. One critical aspect to successfully using these commercial technologies in a space system is being able to recognize when a component has been hit by a SEE and commanding that component to reset itself, without causing major disruption to the entire system.

To this goal, NASA seeks responsive or intelligent hardware supervisor components for SEEs. Ideally, a microcircuit that can monitor the operational profile of other components and intelligently determine what is and is not a latchup or other event versus a computationally intense processing state, especially for consumer/COTS (commercial-off-the-shelf) electronics.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:

Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.1 Avionics Component Technologies

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables would include system design, trade studies, component selections, requirements definitions, and systems analysis to result in a modeled and analyzed system architecture. Early breadboard circuits or prototypes may be included.

Phase II deliverables would include production of a prototype(s) and electrical performance testing. Testing may include some environmental and stress testing.

State of the Art and Critical Gaps:
Existing hardware supervisors do exist, but they do not fully address the needs of NASA missions seeking to infuse modern COTS components. Supervisor methodologies are either too conservative, and overly reset devices causing undue downtime and data loss or are more intelligent to distinguish upsets but require computationally intense processing and power resources to implement. NASA needs supervisor components that can intelligently determine latchups or other events without a computationally intense processing state.

Relevance / Science Traceability:
These technologies would be relevant to increasing science return and lowering costs for missions across all Science Mission Directorate (SMD) divisions. However, the benefits are most significant for miniaturized instruments and subsystems that must operate in harsh environments. These missions include interplanetary CubeSats and SmallSats, outer planets instruments, and heliophysics missions to harsh radiation environments.

References:
The following resources may be helpful for descriptions of radiation effects in electronics:

1. NASA Technical Reports Server: https://ntrs.nasa.gov/
2. NASA Electronic Parts and Packaging Program: https://nepp.nasa.gov/
3. NASA/GSFC Radiation Effects and Analysis Home Page: https://radhome.gsfc.nasa.gov/top.htm

Z2.02 High-Performance Space Computing Technology (SBIR)

Lead Center: JPL
Participating Center(s): GSFC

Scope Title: High-Performance Space Computing Technology

Scope Description:
Most current NASA missions utilize 20-year-old space computing technology that is inadequate for future missions. Newer processors with improved performance are becoming available from industry but still lack the performance, power efficiency, and flexibility needed by the most demanding mission applications. The NASA High-Performance Spaceflight Computing (HPSC) project is addressing these needs. This subtopic solicits technologies that can enable future high-performance, multicore processors, along with the supporting technologies needed to fully implement avionics systems based on these processors.

- Fault-tolerant internet protocol (IP) core supporting Ethernet, Time-Sensitive Networking (TSN), Time-Triggered Ethernet (TTE), and remote direct memory access (RDMA) over converged Ethernet (RoCE) to support processor clustering.
- Compilers that support software-implemented fault tolerance (SIFT) capabilities (e.g., control flow checking, coordinated checkpoint/rollback, recovery block) for multicore processors are desired.
    - Compile-time fault tolerance is desired by NASA for reorganizing execution code to automatically build redundancy in stall cycles without requiring additional development from the user; this would be exceptional for performance optimization of code without putting additional burden on the developers. This is increasingly important with the adoption of more complex and commercial processors in future missions.
- Radiation-tolerant, point-of-load (POL) converters that feature multiple outputs, intelligent communication, or high power.
    - Modern and next-generation processors require multiple voltage supply levels, requiring multiple discrete POL converters occupying valuable processor card real estate. A multiple-output POL would enable smaller and more powerful spaceflight processing platforms.
    - Future spaceflight systems have increased needs for fault detection, tolerance, and command ability. A POL converter capable of communicating with command-and-control architectures to report health status, telemetry, or to adjust parameters is desired.

    - Future high-powered spaceflight processing applications will have a need for high-power POL converters. Specifically, converters capable of providing low voltage, but high currents (tens of amps) are desired.
- Coprocessors to (a) accelerate onboard artificial intelligence applications, or (b) perform digital signal processing (DSP) functions. Specifically, technologies are sought that either enable the reliable use of commercial off-the-shelf (COTS) coprocessors in space systems, or fault-tolerant IP cores that can be implemented in a radiation-hardened field-programmable gate array (FPGA).
- Radiation-tolerant solid-state memory drives (minimum 1-TB capacity) with Peripheral Component Interconnect Express (PCIe) interface, supporting file systems with industry-standard Non-Volatile Memory Express (NVMe) software stack.
- Checkpointing and recovery mechanism for single-process flight software applications.
    - Especially with increased use of COTS processors, single-event functional interrupts (SEFIs) have a high chance the processor will need to reset or incur a kernel panic. NASA desires a way for the flight software to be automatically checkpointed or have some sort of functional save-state to recover before the upset.
    - Current methodologies for resetting and recovering processors and flight software applications can incur considerable downtime and data loss. A more intelligent, rapid method for resetting and recovering is desired. NASA's Core Flight Software (cFS) would be an ideal candidate software to implement this capability.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.X Other Flight Computing and Avionics

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software
- Research

Desired Deliverables Description:
Phase I Deliverables:
For software and hardware elements, a solid conceptual design, plan for full-scale prototyping, and simulations and testing results to justify prototyping approach. Detailed specifications for intended Phase II deliverables.

Phase II Deliverables:
For software and hardware elements, a prototype that demonstrates sufficient performance and capability and is ready for future development and commercialization.

State of the Art and Critical Gaps:
Most NASA missions utilize processors with in-space-qualifiable high-performance computing that has high power dissipation (approximately 18 W), and the current state-of-practice Technology Readiness Level 9 (TRL-9) space computing solutions have relatively low performance (between 2 and 200 DMIPS (Dhrystone million instructions per second) at 100 MHz). A recently developed radiation-hardened processor provides 5.6 GOPS (giga operations per second) performance with a power dissipation of 17 W. Neither of these systems provides the desired performance, power-to-performance ratio, or flexibility in configuration, performance, power management, fault tolerance, or extensibility with respect to heterogeneous processor elements. Onboard network standards exist that can provide >10 Gbps bandwidth, but not everything is available to fully implement them.

Relevance / Science Traceability:
The high-performance spaceflight computing (HPSC) ecosystem is enhancing to most major programs in the Human Exploration and Operations Mission Directorate (HEOMD). It is also enabling for key Space Technology Mission Directorate (STMD) technologies that are needed by HEOMD, including the Safe and Precise Landing - Integrated Capabilities Evolution (SPLICE) project. Within the Science Mission Directorate (SMD), strong mission pull exists to enable onboard autonomy across Earth science, astrophysics, heliophysics, and planetary science missions. There is also relevance to other high-bandwidth processing applications within SMD, including adaptive optics for astrophysics missions and science data reduction for hyperspectral Earth science missions.

References:

1. RISC-V: https://riscv.org/news/2019/09/risc-v-gains-momentum-as-industry-demands-custom-processors-for-new-innovative-workloads/
2. Next Generation Space Interconnect Standard: http://www.rapidio.org/wp-content/uploads/2014/10/RapidIO-NGSIS-Seminar-July-23-2014.pdf
3. He, J., et al. Provably Correct Systems. Formal Techniques in Real-Time and Fault-Tolerant Systems. pp. 288-335. ProCoS. 1994.
4. Reis, G.A. SWIFT: Software Implemented Fault Tolerance. International Symposium on Code Generation and Optimization. IEEE. 2004.
5. Wessman, N., et al. De-RISC: The First RISC-V Space-Grade Platform for Safety-Critical Systems. pg. 17-26. IEEE Space Computing Conference Proceedings. 2021.
6. Franconi, N., et al. Signal and Power Integrity Design Methodology for High-Performance Flight Computing Systems. pg. 17-26. IEEE Space Computing Conference Proceedings. 2021.
7. Yanguas-Gil, A., et al. Neuromorphic Architectures for Edge Computing under Extreme Environments. pg. 39-45. IEEE Space Computing Conference Proceedings. 2021.
8. Sabogal, S., et al. A Methodology for Evaluating and Analyzing FPGA-Accelerated, Deep-Learning Applications for Onboard Space Processing. pg. 143-154. IEEE Space Computing Conference Proceedings. 2021.

Z2.03 Human Interfaces for Space Systems (SBIR)

Lead Center: JSC
Participating Center(s): N/A

Scope Title: Display Systems

Scope Description:
NASA's vision for human spaceflight requires the crew to execute increasingly complex tasks in more demanding and dangerous environments. As a result, advances in avionics technologies relevant to human interfaces for space systems are sought that can be infused into current and future human spaceflight programs, including orbiting spacecraft, surface habitats, surface mobility vehicles, and spacesuits. The 2022 subtopic goals are to advance technologies that increase the reliability of crew interface systems in the radiation environment beyond Low Earth Orbit (LEO), while also increasing the crew’s capabilities and effectiveness in performing mission tasks. Standards-based interfaces are of particular interest to promote interoperability and equipment reuse across spacecraft.

Successful proposal concepts should significantly advance the state of the art. Furthermore, proposals should indicate an understanding of the safety-critical operations performed by spaceflight crews, as well as the intended radiation environment. Note that environmental requirements vary significantly between space systems and missions, with some spacecraft and surface vehicles supporting human operations for days and others supporting periodic crewed missions for 15 or more years.

Specific technologies sought by this subtopic include display systems capable of supporting long-duration human spaceflight beyond low Earth orbit. Multifunctional visual displays provide the highest bandwidth and most versatile means for crew to receive complex information, but unique component technologies with limited radiation performance data prevent high-reliability displays from being developed. The following design parameters and data are sought for display panel and pixel technologies:

- A scalable architecture that permits different levels of performance
- Radiation test data, analysis of failure modes, radiation-tolerant designs, and prototype hardware/software solutions
- A display panel diagonal measurement of at least 14 in. with the capability to render complex graphics, including high-definition video, at a frame rate of at least 20 frames per second.

Design and performance parameters are driven by use cases requiring crewmembers to directly control the spacecraft using live streaming video, such as in-space docking, controlled landing, robotic operations, and surface mobility.

Expected TRL or TRL Range at completion of the Project: 3 to 7

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.2 Avionics Systems and Subsystems

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software
- Analysis

Desired Deliverables Description:
The desired Phase I deliverables include designs, simulations, and analyses to demonstrate the viability of proposed designs and components.

The desired Phase II deliverables for display systems include a prototype demonstration of a custom or modified display panel technology that mitigates radiation failure modes of electronic components. The proof-of-concept design should consider scalability and integration with other display components.

State of the Art and Critical Gaps:
Commercial display technologies have been used in LEO on the International Space Station for decades, but radiation test data for complex electronics beyond LEO are very limited, and existing test data indicate displays may be more susceptible to radiation than other electronic components. As a result, spacecraft designers are forced to take an unquantified risk of equipment failure due to radiation effects and to include backup crew interface systems that take up valuable mass, volume, and power on the spacecraft. While ongoing Government and industry investments seek to improve processor and graphics processing unit (GPU) performance, quantifying and improving the radiation tolerance of display panel components remains unaddressed.

Relevance / Science Traceability:
This subtopic is relevant to human spaceflight programs in the development and planning phases, including Gateway, HLS (Human Landing System), Orion, and xEMU (Exploration Extravehicular Mobility Unit), as well as to lunar and Martian surface habitation systems and rovers. Technology solutions developed under this subtopic have the potential for a direct infusion path as these spacecrafts are designed and developed.

Electronic visual displays are required for human spaceflight (NPR 8705.2C, NASA Human-Rating Requirements for Space Systems) and will be at the center of any spacecraft’s crew interface architecture. By quantifying and improving the reliability of radiation-tolerant displays, spacecraft designers will be able to simplify this architecture by reducing the need for redundancy, sparing, and operational constraints while also reducing mass, volume, and power needs.

References:

1. NASA Electronic Parts and Packaging Program: https://nepp.nasa.gov/NASA/GSFC
2. Radiation Effects and Analysis Homepage: https://radhome.gsfc.nasa.gov/top.htm
3. NASA Cross-Program Design Specification for Natural Environments (DSNE): http://ntrs.nasa.gov/citations/20200000867
4. The Past, Present, and Future of Display Technology in Space: https://arc.aiaa.org/doi/10.2514/6.2010-8915
5. NASA Active Matrix Organic Light Emitting Diode (AMOLED) Environmental Test Report: https://ntrs.nasa.gov/citations/20140003471
6. OLED Technology Evaluation for Space Applications: https://ntrs.nasa.gov/citations/20150016975

Scope Title: Audio Systems

Scope Description:
NASA's vision for human spaceflight requires the crew to execute increasingly complex tasks in more demanding and dangerous environments. As a result, advances in avionics technologies relevant to human interfaces for space systems are sought that can be infused into current and future human spaceflight programs, including orbiting spacecraft, surface habitats, surface mobility vehicles, and spacesuits. The 2022 subtopic goals are to advance technologies that increase the reliability of crew interface systems in the radiation environment beyond Low Earth Orbit (LEO), while also increasing the crew’s capabilities and effectiveness in performing mission tasks. Standards-based interfaces are of particular interest to promote interoperability and equipment reuse across spacecraft.

Successful proposal concepts should significantly advance the state of the art (SOA). Furthermore, proposals should indicate an understanding of the safety-critical operations performed by spaceflight crews, as well as the intended radiation environment. Note that environmental requirements vary significantly across space systems and missions, with some spacecraft and surface vehicles supporting human operations for days and others supporting periodic crewed missions for 15 or more years.

Specific technologies sought by this subtopic include audio systems that provide two-way voice communication between crew members and mission personnel on Earth through all mission phases and crew activities. These systems also must annunciate alarms and may provide a means of controlling systems by voice or record field notes. Robust audio system technologies are sought with the following design and performance parameters:

- Low-latency G.711 and G.729 audio encoding/decoding and routing from multiple simultaneous sources.
- Integrate with Ethernet-based spacecraft networks to route multiple simultaneous audio streams to each user.
- Support ad hoc addition and removal of end systems and in-flight configuration and extensibility.
- Leverage modular and standards-based hardware and software.
- Provide radiation tolerance and fault mitigation.
- Incorporate SOA microphones, speakers, and acoustic echo-canceling technologies that improve speech quality and intelligibility for voice communication and speech recognition in acoustically challenging environments, such as noisy habitable modules and spacesuits. NASA human spaceflight programs typically require a speech intelligibility score of 90% per the ANSI S3.2 standard using the Modified Rhyme Test (MRT) method.

Expected TRL or TRL Range at completion of the Project: 4 to 7

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.2 Avionics Systems and Subsystems

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:
The desired Phase I deliverables include designs, tabletop hardware/software prototypes, and analyses to demonstrate the viability of proposed designs and components.

The desired Phase II deliverables for display systems include a prototype hardware and software audio system that can be tested in NASA network test facilities with at least three simultaneous audio endpoints. The audio system should be tested for radiation tolerance.

State of the Art and Critical Gaps:
Audio systems are not currently available that meet NASA's basic functional requirements and can perform reliably in the spaceflight radiation and acoustic environments.

Relevance / Science Traceability:
This subtopic is relevant to human spaceflight programs in the planning phases, including human landing systems (HLSs) and lunar and Martian surface habitation systems and rovers. Technology solutions developed under this subtopic have the potential for a direct infusion path as these spacecrafts are designed and developed.

Voice communication and auditory alarms have been included in NASA spacecraft since the Mercury Program, but this has not been sufficient to sustain a robust commercial market for space-rated audio systems. As NASA and commercial partners have increased new spacecraft development, the dearth of vendors has resulted in substantial schedule, cost, and technical integration risk.

References:

1. NASA Electronic Parts and Packaging Program: https://nepp.nasa.gov/
2. Radiation Effects and Analysis Home Page: https://radhome.gsfc.nasa.gov/top.htm
3. NASA Cross-Program Design Specification for Natural Environments (DSNE): https://ntrs.nasa.gov/citations/20200000867
4. Space Shuttle Orbiter Audio Subsystem: https://ntrs.nasa.gov/citations/19790056509
5. Technical Aspects of Acoustical Engineering for the ISS: https://ntrs.nasa.gov/api/citations/20090009764/downloads/20090009764.pdf

Focus Area 12 Entry, Descent, and Landing Systems

The SBIR focus area of Entry, Descent and Landing (EDL) includes the suite of technologies for atmospheric entry as well as descent and landing on both atmospheric and non-atmospheric bodies. EDL mission segments are used in both robotic planetary science missions and human exploration missions beyond Low Earth Orbit, and many technologies have application to emerging commercial space capabilities such as lunar landing, low-cost space access, small spacecraft, and asset return.

Robust, efficient, and predictable EDL systems fulfill the critical function of delivering payloads to lunar and planetary surfaces through challenging environments, within mass and cost constraints. Future NASA Artemis and planetary science missions will require new technologies to break through historical constraints on delivered mass, enable sustained human presence, or to go to entirely new planets and moons. Even where heritage systems exist, no two planetary missions are exactly “build-to-print,” leading to frequent challenges from environmental uncertainty, risk posture, and resource constraints that can be dramatically improved with investments in EDL technologies. EDL relies on validated models, ground tests, and sensor technologies for system development and certification. Both new capabilities and improved assessment and prediction of state-of-the-art systems are important facets of this focus area.

The subtopics in this Focus Area generally align with the Entry, Descent, and Landing flight regimes, including the flight instrumentation area. In future solicitations, the intent is to maintain these subtopic titles, and to rotate the content within the subtopics as Agency needs and priorities change and as technologies are matured.

The subtopics and their overarching content descriptions are:

- Z7.01 Entry, Descent and Landing Flight Sensors and Instrumentation: Seeks sensors and components for precision landing and hazard detection, as well as heatshield instrumentation and other EDL flight systems diagnostics and electronics.
- Z7.03 Entry and Descent Systems Technologies: Contains hypersonic materials, aeroshell systems, and modeling advances, including deployable aeroshells for EDL and asset return and recovery. Includes smaller-scale systems appropriate for small spacecraft applications.
- Z7.04 Landing Systems Technologies: Covers landing engines, plume-surface interaction modeling, testing, and instrumentation, and landing attenuation systems.

Please refer to the subtopic write-ups for the specific content and scope solicited this year.

H5.02 Hot Structure Technology for Aerospace Vehicles (SBIR)

Lead Center: MSFC
Participating Center(s): AFRC, JSC, LaRC

Scope Title: Hot Structure Technology for Aerospace Vehicles

Scope Description:
This subtopic deals with the development of hot structure technology for aerospace vehicle structural components that are exposed to extreme heating environments. The hot structure technologies proposed for development must be for reusable, nonmetallic, oxidation-resistant, fiber-reinforced composite structures. Hot structure is an enabling technology for reusability, thus facilitating the development of advanced propulsion systems requiring multiple engine firings and vehicles requiring aerocapture/aerobraking followed by entry, descent, and landing. The development of hot structure technology for (a) combustion-device liquid rocket engine propulsion systems and (b) aerodynamic structures for aeroshells, control surfaces, wing leading edges, and heatshields is of great interest.

Desired hot structure systems encompass multifunctional structures that can reduce or eliminate the need for active cooling, and in the case of aerodynamic structures, separate thermal protection system (TPS) materials. The potential advantages of using hot structure systems in place of actively cooled structures or a TPS with underlying cool structure include reduced mass, increased mission performance (such as reusability and greater thermal efficiency), improved aerodynamics for aeroshell components, improved structural efficiency, and increased ability for nondestructive inspections. These aerospace vehicle applications are unique in requiring the hot structure to carry primary structure vehicle loads and to be reusable after exposure to extreme temperatures during liquid rocket engine firings and/or atmospheric entry. Examples of prior flight-proven hot structures include: (a) the composite nozzle extensions for the Centaur RL10 family of upper-stage rocket engines, and (b) the wing leading edges and control surfaces for the Space Shuttle Orbiter, Hyper-X (X-43A), and/or X-37B.

This subtopic seeks to develop innovative, low-cost, damage-tolerant, reusable, lightweight fiber-reinforced composite hot structure technology adhering to the following:

- At a minimum, the subject hot structures must be capable of operating at temperatures of at least 1,510 °C (2,750 °F)—higher temperatures are of even greater interest, such as up to 2,204+ °C (4,000+ °F).
- Constructed from composite fiber-reinforced materials, such as carbon-carbon (C-C) and ceramic matrix composite (CMC) materials.
- Potential applications of interest for hot structure technology include: (a) propulsion system components (hot gas valves, combustion chambers, nozzles, and nozzle extensions) and (b) primary load-carrying aeroshell structures, control surfaces, leading edges, and heatshields.

Proposals should present approaches to address the current need for improvements in operating temperature capability, toughness/durability, reusability, and material system properties, as well as the need to reduce cost and manufacturing time requirements. Technology focus areas for submitted proposals should address one or more of the following:

- Repeatable materials properties: Improvements in manufacturing processes and/or material designs to achieve repeatable uniform material properties, while minimizing data scatter, that are representative of actual vehicle components: specifically, material property data obtained from flat-panel test coupons should correlate directly to the properties of prototype and flight test articles.
- Improved toughness/durability: Material/structural architectures and multifunctional systems providing significant toughness and/or durability improvements over typical 2D interlaminar mechanical properties while maintaining in-plane and thermal properties when compared to state-of-the-art C-C or CMC materials. Examples include incorporating through-the-thickness stitching, braiding, or 3D woven preforms. Advancements in oxidation resistance that enhance durability are also of interest, and may include matrix inhibition, oxidation resistant matrices, functionally graded material systems, and exterior environmental coatings. The goals here are to eliminate/reduce discontinuities in material properties and to provide robust material systems.
- Reduced cost and/or delivery time: Manufacturing process methods that enable a significant reduction in the cost and time required to fabricate materials and components. There is a great need to reduce cost and processing time for hot structure materials and components—current state-of-the-art materials are typically expensive and have fabrication times often in the range of 6 to 12 months (or longer), which can limit or exclude the use of such materials. Approaches enabling reduced costs and manufacturing times should not lead, however, to significant reductions in material properties. Advanced manufacturing methods may include but are not limited to the following: (a) rapid densification cycles, (b) high char-yield resins, (c) additive manufacturing (AM), and (d) automated weaving, braiding, layup, etc.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.1 Materials

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research
- Analysis

Desired Deliverables Description:

Research, testing, and analysis should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware or prototype demonstrations. Phase I feasibility studies should also address cost and the risks associated with the hot structure technology.

In addition to delivery of a Phase I final report, a representative sample(s) of the material and/or technology addressed by the Phase I project should be provided at the conclusion of the Phase I contract. Examples of representative Phase I sample deliverables include:

- Coupons appropriate for thermal and/or mechanical material property tests.
- Arc-jet test specimens.
- Subelement or subcomponent structures.

Plans for potential follow-on Phase II contracts should include the delivery of manufacturing demonstration units to NASA or a commercial space industry partner during Phase II. Testing of such demonstration articles should be a part of the anticipated Phase II effort. Depending upon the primary application addressed by the Phase II contract, such test articles may include subscale nozzle-extensions, arc-jet specimens, or other representative hot structure components. Opportunities and plans should also be identified and summarized for potential commercialization with at least one aerospace company. Vehicle integration issues (attachment, joining, etc.) should be addressed.

State of the Art and Critical Gaps:

The current state of the art for composite hot structure components is limited primarily to applications with maximum use temperatures in the 1,093 to 1,593 °C (2,000 to 2,900 °F) range. While short excursions to higher temperatures are possible, considerable degradation may occur. Reusability is limited and may require considerable inspection before potential reuse. Critical gaps or technology needs include:

- Increasing operating temperatures to 1,649 to 2,204+ °C (3,000 to 4,000+ °F).
- Increasing resistance to environmental attack (primarily through oxidation).
- Increasing manufacturing technology capabilities to improve reliability, repeatability, and quality control.
- Increasing durability/toughness and interlaminar mechanical properties (for 2D reinforcement) or introducing 3D architectures.
- Decreasing manufacturing cost.
- Decreasing overall manufacturing time requirements.

Relevance / Science Traceability:

Hot structure technology is relevant to the Human Exploration and Operations Mission Directorate (HEOMD), where the technology can be infused into spacecraft and launch vehicle applications. Such technology should provide either improved performance or enable advanced missions requiring reusability, increased damage tolerance, and the durability to withstand long-duration space exploration missions. The ability to allow for delivery and/or return of larger payloads (and crewed vehicles) to various space destinations, such as the lunar South Pole and Mars, is also of great interest.

The Advanced Exploration Systems (AES) Program (https://www.nasa.gov/directorates/heo/aes/index.html) would be ideal for further funding a prototype hot structure system and technology demonstration effort. Commercial space programs, such as the Commercial Resupply Services (CRS) Program, the Commercial Crew Program (CCP), the Commercial Lunar Payload Services (CLPS) Program, and Next Space Technologies for Exploration Partnerships (NextSTEP), are also interested in this technology for flight vehicles. Additionally, NASA HEOMD programs that could use this technology for propulsion upgrades or block changes in the future include the Artemis Space Launch System (SLS), Orion, and Human Landing System (HLS). Hot structure technology is also highly relevant to the NASA Aeronautics Research Mission Directorate's (ARMD's) Hypersonic Technology (HT) Project (https://www.nasa.gov/aeroresearch/programs/aavp/ht). Other relevant efforts include the work done by NASA and the Defense Advanced Research Projects Agency (DARPA) in developing nuclear thermal propulsion (NTP) systems, both for reactor materials and nozzle extensions.

Potential NASA users of this technology exist for a variety of propulsion systems and other applications requiring the use of similar materials, including the following:

- Upper-stage engine systems, such as those for the Artemis SLS.
- In-space propulsion systems, including nuclear thermal propulsion systems.
- Lunar/Mars lander descent/ascent propulsion systems.
- Propulsion systems for the commercial space industry, which is partnering with and supporting NASA efforts.
- Atmospheric entry vehicle aeroshells, such as those for use at Earth, Mars, or other planets and their moons.
- Related applications include the structures required for hypersonic flight vehicles.

Finally, the U.S. Air Force is interested in such technology for its National Security Space Launch (NSSL), ballistic missile, and hypersonic vehicle programs. Other non-NASA users include the U.S. Army, the U.S. Navy, the U.S. Space Force, the Missile Defense Agency (MDA), and DARPA. The subject technology can be both enhancing to systems already in use or under development, as well as enabling for applications that may not be feasible without further advancements in high-temperature composites technology.

References:

Liquid Rocket Propulsion Systems:

1. “Carbon-Carbon Nozzle Extension Development in Support of In-Space and Upper-Stage Liquid Rocket Engines;” Paul R. Gradl and Peter G. Valentine; 53rd AIAA/SAE/ASEE Joint Propulsion Conference, Atlanta, GA; AIAA-2017-5064; July 2017;https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170008949.pdf.
2. “Extreme-Temperature Carbon- and Ceramic-Matrix Composite Nozzle Extensions for Liquid Rocket Engines;” Peter G. Valentine and Paul R. Gradl; 70th International Astronautical Congress (IAC), Washington DC; IAC-19-C2.4.9; October 2019; https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190033315.pdf.

Hypersonic Flight Vehicle Structures:

1. "Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles;" David E. Glass; 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Dayton, OH; AIAA-2008-2682; April-May 2008;https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080017096.pdf.
2. "A Multifunctional Hot Structure Heatshield Concept for Planetary Entry;" Sandra P. Walker, Kamran Daryabeigi, Jamshid A. Samareh, Robert Wagner, and Allen Waters; 20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Glasgow, Scotland; AIAA 2015-3530; July 2015; https://arc.aiaa.org/doi/pdf/10.2514/6.2015-3530.

Note: The above references are all open literature references. Other references exist regarding this technology, but they are International Traffic in Arms Regulations (ITAR) restricted. Numerous online references exist for the subject technology and projects/applications presented here, both foreign and domestic.

Z7.01 Entry, Descent, and Landing Flight Sensors and Instrumentation (SBIR)

Lead Center: JSC

Participating Center(s): ARC, GSFC, JPL, LaRC

Scope Title: Air Data Sensors to Support Entry, Descent, and Landing (EDL) Environment Characterization

Scope Description:

Current NASA state-of-the-art air data sensors for EDL applications are very expensive to incorporate on planetary missions because they must meet functional and performance requirements during and after exposure to loads and environments associated with long-duration spaceflight and atmospheric entry. The dynamic loads and thermal environments encountered prior to arrival at the destination make flight qualification of air data sensors challenging and costly. Scarce commercial options exist for off-the-shelf products with the potential to meet NASA's requirements for accuracy and survivability. To bring more commercial options for air data sensors that can be flown on EDL missions as part of an air data system, NASA seeks proposals in two distinct areas: pressure transducers and lidar sensors.

1. Air Data Pressure Transducers

The Mars Entry, Descent, and Landing Instrumentation 2 (MEDLI2) sensor suites flew supersonic-range pressure transducers on the heat shield that were developed in house at NASA Langley Research Center because there was no commercially available pressure sensor that met the mission's requirements. The hypersonic pressure transducer on the heat shield was a flight spare from the first MEDLI suite, which flew on the Mars Science Laboratory Mission in 2012. In situ pressure measurements on the aerodynamic surfaces of an EDL vehicle capsule—such as the heat shield and backshell—are primarily used to reconstruct the free-stream density and vehicle attitude (angles of attack and sideslip) to isolate aerodynamic performance. NASA seeks pressure transducers that can meet the following requirements:

- Configuration: The pressure transducer shall be hermetically sealed. The design space should consider a nonamplified output configuration or a configuration with embedded electronics for an amplified output. The internal temperature shall be monitored. The pressure transducer shall measure absolute pressure, and the housing must be able to be connected to a flared tube fitting. The pressure transducer should have the capability of being mechanically mounted in a 2- or 3-point configuration.
- Mass: Less than 300 g if no active electronics; less than 400 g for a unit with active electronics.
- Size: Less than 442 c^3.
- Electrical connections: Electrical interface/connector should be configured for power, ground, analog signal, analog return, and temperature sensor accommodation. Electrical connector pin configurations should allow for interchangeability of mating connectors for all pressure transducers.
- Parts, material, and processes used in the construction of the pressure transducer should be controlled by specification or procedure per AS9100 or equivalent. Any soldering should meet NASA-STD-8739.3 or IPC J-STD-001 with space addendum, and any fusion welding should follow AWSD17.1.
- The pressure transducer should meet MIL-STD-461 for electromagnetic interference (EMI) compliance (amplified units only).
- Axial loading capability: Minimum 15 g (Venus missions could require 100 g or higher).
- Temperature capability: Operating temperature range of -120 to 80 °C. It is desired that the unit can survive temperatures as cold as -130 °C in a nonoperating condition. It is also desired that the unit can survive a dry heat microbial reduction temperature of 104 °C for 200 hr, or 110 °C for 100 hr.
- Functional characteristics:
    - Input voltage: Up to 10 Vdc for a nonamplified unit or 12 to 36 Vdc for an amplified unit.
    - Input current: Should not exceed 7 mA for a nonamplified unit or 30 mA for an amplified unit.
    - Output impedance: Should not exceed 10 kilohms for a nonamplified unit or 1 kilohm for an amplified unit.
    - Output voltage: Minimum output of 1.2 mV/V (nonamplified unit).
    - Measurement range: 0 to 1.0 psia for a supersonic range pressure transducer; 0 to 5.0 psia for hypersonic range pressure transducer. Zero psia is considered to be less than 10^{-5} torr.
    - Accuracy: Provide a description of the approach to quantify and demonstrate accuracy of the pressure transducer.

  - Static error band should be no greater than +/- 0.3% of full scale based on an unweighted least-squares straight-line fit. The static error band includes errors due to nonlinearity, hysteresis, and non-repeatability.
- Cost: Fully qualified first-unit target of ~$500K.

2. Air Data Lidar Sensors

Air data lidar sensors have the potential of providing more accurate velocimetry data than pitot tubes for Mars landing and Earth reentry vehicles. Furthermore, a lidar-based air data sensor can eliminate the aerodynamic influences of pitot tubes, particularly in the supersonic velocity regime. NASA seeks proposals for air data lidar sensors that can provide critical air-vector velocity data during the atmospheric entry and descent phases of the spacecraft. An ability to provide other relevant air data, such as atmospheric pressure, is viewed favorably if it can enhance and/or complement the air velocity measurement capabilities. The proposed lidar sensor must be compact and efficient with a clear path to spaceflight units meeting physical and environmental constraints of landing vehicles.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.X Other Entry, Descent, and Landing

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Phase I Goals: Design and proof of concept, including the production approach to achieve the cost goals.

Phase II Goals: Prototype/breadboard validation in laboratory environment.

State of the Art and Critical Gaps:
NASA now requires instrumentation on all EDL missions, including competed science missions, and these cost- and mass-constrained missions cannot use the state-of-the-art instrumentation. Very few commercial options exist for air data sensors that can meet accuracy and survivability requirements.

Relevance / Science Traceability:
EDL instrumentation directly informs and addresses the large performance uncertainties that drive the design, validation, and in-flight performance of planetary entry systems. Improved understanding of entry environments and real-time measurement knowledge could lead to reduced design margins, enabling a greater payload mass-fraction, and smaller landing ellipses for placing advanced payloads onto the surface of atmospheric and airless bodies.

References:

1. H. Hwang, et al. (2016), "Mars 2020 Entry, Descent and Landing Instrumentation 2 (MEDLI2)," 46th AIAA Thermophysics Conference, Washington, D.C., June 2016. AIAA paper No. AIAA 2016-3536.
2. J. Santos, K. Edquist, H. Hwang, et al. (2020), "Entry, Descent, and Landing Instrumentation," White Paper for the Planetary Sciences Decadal Survey, 2023-2032. September 2020.

Scope Title: Novel Lidar Component Technologies Applicable to Guidance, Navigation, and Control (GN&C) for Precise Safe Landing

Scope Description:

NASA is seeking the development of component technologies for advanced lidar sensors that will be utilized within entry, descent, and landing (EDL) and deorbit, descent, and landing (DDL) GN&C systems for precise safe landing on solid solar system bodies, including planets, moons, and small celestial bodies (e.g., asteroids and comets). The EDL phase applies to landings on bodies with atmospheres, whereas DDL applies to landings on airless bodies. For many of these missions, EDL/DDL represents one of the riskiest flight phases. NASA has been developing technologies for precision landing and hazard avoidance (PL&HA) to minimize the risk of the EDL/DDL phase of a mission and to increase the accessibility of surface science targets through precise and safe landing capabilities. One flight instrumentation focus of PL&HA technology has been in the development of lidar technologies that provide either terrain mapping (range point cloud) capability or direct velocity measurement. The continued maturation of these technologies is targeting (1) multimodal operation (i.e., combining mapping and velocimetry functions); (2) reduction of size, mass, and power; and (3) multicomponent integration.

This solicitation is requesting specific lidar system components and not complete lidar solutions. To be considered, all component technologies proposed must show a development path to operation within the applicable EDL/DDL spaceflight environment (radiation, thermal, vacuum, vibration, etc.). The specific lidar component technologies desired include the following (proposals can be to either or both):

1. Dense focal plane arrays for simultaneous ranging and Doppler velocimetry with the following characteristics:
    - Simultaneous measurements from each pixel or from subsets of pixels.
    - Functionality (when integrated into a lidar system) for measuring range up to 8 km.
        - Range precision less than 5 cm, 1-sigma, for 3D image frames up to 1 km.
        - Range precision less than 1 m, 1-sigma, for ranges up to 8 km.
    - Functionality (when integrated into a lidar system) for measuring velocity from 0 to 200 m/sec (or greater) along the line of sight (LOS).
        - Doppler velocity precision on order of 1 cm/sec, 1-sigma, from ranges of 4 km or greater.
    - Rejection of false locks on dust or plumes from the spacecraft exhaust.
    - Implementation for low power, mass, and size.

2. Readout integrated circuit (ROIC) consisting of preamplifiers and switching fabric, capable of operating at cryogenic temperatures, with the following characteristics:
    - Preamplifiers: Array of low-noise transimpedance preamplifiers, one for each detector element.
        - Electrical bandwidth: >150 MHz.
        - Transimpedance gain: >300 kV/A.
        - Input current noise: <1.5 pA/Hz$^{1/2}$.
        - Input voltage noise: <10 nV/Hz$^{1/2}$.
        - Output: Analog pulse waveforms, DC coupling.
        - Electrical power: <2 mW per element.
    - Network switching fabric: Connection of a subarray of the detector elements to the output terminals.
        - Switch speed: >5 MHz with settling time <40 ns.
        - Number of input channels: Up to 2x320.
        - Number of output channels: Subarray of the input signals up to 16 channels.
        - Interchannel isolation: < -37 dB @ 1 GHz.
        - Insertion loss: <1 dB.
        - Total electrical power: <0.05 W.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.X Other Entry, Descent, and Landing

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
The following deliverables are desired for Phase I: (1) Hardware demonstrations of sensor components and applicable support hardware and/or (2) Analysis and software simulations of component proofs of concept within simulated environments. Responses must show a path for the proposed capabilities to be compatible with the environmental conditions of spaceflight.

The following deliverables are desired for Phase II: (1) Hardware demonstrations of sensor components and applicable support hardware and (2) Analysis of components in laboratory or relevant environment (depending on TRL). Phase II products will need to demonstrate a path for the capabilities to be compatible with the environmental conditions of spaceflight.

State of the Art and Critical Gaps:
For more than a decade, the EDL GN&C and sensors community has been developing the technologies to enable precise safe landing. Infusion of these capabilities into spaceflight missions and spinoff into the commercial sector remains the critical gap. Bridging this gap requires additional component technology advancements for specific lidar sensors that enhance operational performance, increase dynamic envelope, reduce size/mass/power/cost, and enable spaceflight qualification.

Relevance / Science Traceability:
GN&C/PL&HA technologies for precise safe landing are critical for future robotic science and human exploration missions to locations with hazardous terrain and/or pre-positioned surface assets (e.g., cached samples or cargo) that pose significant risks to successful spacecraft touchdown and mission surface operations. The PL&HA technologies enable spacecraft to land with minimum position error from targeted surface locations, and they implement hazard-avoidance diverts to land at locations safe from lander-sized or larger terrain hazards (e.g., craters, rocks, boulders, sharp slopes, etc.). PL&HA has maintained consistent prioritization within the NASA and National Research Council (NRC) space technology roadmaps for more than a decade, and multiple planetary landers such as Mars 2020 and upcoming Commercial Lunar Payload Services (CLPS) are starting to infuse some of the PL&HA capabilities.

References:

1. *A. Martin, et al. (2018), "Photonic integrated circuit-based FMCW coherent LiDAR," in Journal of Lightwave Technology, vol. 36, no. 19, 4640-4645, Oct.1, 2018, doi: 10.1109/JLT.2018.2840223.*
2. C.V. Poulton, A. Yaacobi, D.B. Cole, M.J. Byrd, M. Raval, D. Vermeulen, and M.R. Watts (2017), *"Coherent solid-state LIDAR with silicon photonic optical phased arrays," Opt. Lett. 42, 4091-4094.*
3. F. Amzajerdian, G.D. Hines, D.F. Pierrottet, B.W. Barnes, L.B. Petway, and J.M. Carson (2017), "Demonstration of coherent Doppler lidar for navigation in GPS-denied environments," Proc. SPIE 10191, Laser Radar Technology and Applications XXII, 1019102.
4. *X. Sun, J.B. Abshire, J.D. Beck, P. Mitra, K. Reiff, and G. Yang (2017), "HgCdTe avalanche photodiode detectors for airborne and spaceborne lidar at infrared wavelengths," Optics Express, 25: 16589-16602.*
5. *X. Sun,* J. Abshire, M. Krainak, W. Lu, J. Beck, W. Sullivan III, P. Mitra, D. Rawlings, R. Fields, D. Hinkley, B. Hirasuna *(2019), "HgCdTe avalanche photodiode array detectors with single photon*

sensitivity and integrated detector cooler assemblies for space applications," Optical Engineering, 58, pp. 067103.

6. W. Sullivan III, M. Goodwin, J. Beck, C. Kmilar, D. Rawlings, M. Skokan, P. Mitra (2018), "A 5 MHz frame rate 32x30 HgCdTe APD focal plane array with photon counting sensitivity for infrared laser radar technology," Military Sensing Symposium (MSS), March 20, 2018 (unclassified, U.S. citizen only).

Z7.03 Entry and Descent System Technologies (SBIR)

Lead Center: LaRC
Participating Center(s): ARC

Scope Title: Entry and Descent System Technologies

Scope Description:
NASA is advancing deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, and Titan as well as payload return to Earth from low Earth orbit. The benefit of deployable decelerators is that the entry vehicle structure and thermal protection system are not constrained by the launch vehicle shroud. Deployable decelerators have the flexibility to more efficiently use the available shroud volume and can be packed into a much smaller volume for Earth departure, addressing potential constraints for payloads sharing a launch vehicle. For Mars, this technology enables delivery of a very large (20 metric tons or more) usable payload, which may be needed to support human exploration. The technology also allows for reduced-cost access to space by enabling the recovery of launch vehicle assets. Development of efficient gas generator technology is needed for inflation of large inflatable decelerators. NASA is also seeking development of domestic capability for fabricating custom stretch-broken carbon and polymer blended yarns for traditional thermal protection systems for other planetary entry missions. This subtopic area solicits innovative technology solutions applicable to both deployable and traditional entry concepts. Specific technology development areas include (1) gas generators for hypersonic inflatable aerodynamic decelerators (HIAD) and (2) blended phenolic/carbon yarn for 3D woven ablative thermal protection systems.

1. Gas Generators for HIAD

Development of gas generator technologies used as inflation systems that result in improved mass efficiency and system complexity over current pressurized cold gas systems for inflatable structures is desired. Inflation gas technologies can include warm or hot gas generators, sublimating powder systems, or hybrid systems; however, the final delivery gas temperature must not exceed 200 °C. Lightweight, high-efficiency gas inflation technologies capable of delivering gas at 250 to 10,000 standard liters per minute (SLPM) are sought. This range spans a number of potential applications. Thus, a given response need not address the entire range. Additionally, the final delivery gas and its byproducts must not harm aeroshell materials such as the fluoropolymer liner of the inflatable structure. Minimal solid particulate is acceptable as a final byproduct. Water vapor as a final byproduct is also acceptable for lower flow (250 to 4,000 SLPM) and shorter duration missions, but it is undesirable for higher flow (8,000 to 10,000 SLPM) and longer duration missions. Chillers and/or filters can be included in a proposed solution, but they will be included in assessing overall system mass versus amount of gas generated. Gas delivery configurations that rely on active flow control devices are not desired. Long-term mission applications will have inflatable volumes in the range of 1,200 to 4,000 ft^3 with final inflation pressures in the range of 15 to 30 psid. Initial concepts will be demonstrated with small-scale volumes to achieve the desired inflation pressures and temperatures. Focus of Phase I development can be subscale manufacturing demonstrations that demonstrate proof of concept and lead to Phase II manufacturing scaleup for applications related to human-scale Mars entry, Earth return, launch vehicle asset recovery, or the emergent small-satellite community.

2. Blended Phenolic/Carbon Yarn for 3D Woven Ablative Thermal Protection Systems

Development of domestic capability for fabricating custom stretch-broken carbon and polymer blended yarns is desired. Specifically, NASA is interested in the ability to twist and ply stretch-broken fibers into a 4-ply blended yarn of varying carbon/phenolic/thermoset resin ratios (phenolic or other nonbrittle fibers preferred). Challenges include maintaining an intimate blend ratio to maintain consistent linear weight while also fabricating a high-quality yarn free from breaks and large yarn defects (e.g., slubs and flames in the resin phase), with uniformity in diameter such that yarns are capable of being processed into 3D woven preforms for advanced thermal protection systems. Phase I effort shall identify the ability to fabricate these custom yarns and establish the characterization processes and controls that will be necessary to eventually fine-tune the blended yarn properties. Final composition of interest to NASA would be a carbon/phenolic blended yarn—any surrogate polymeric yarn should have similar stretch-breaking and blending performance such that any successful process shown with surrogate yarn is extensible to a carbon/phenolic blend with low risk. Notional Phase II effort would demonstrate blending of stretch-broken carbon/kynol fibers and detailed yarn testing—char, strength, yield, etc.—to meet the following established NASA specifications:

- Carbon to phenolic ratio in the yarn by mass shall be 63 ± 4% carbon to 37 ± 4% phenolic
- Blended yield shall be 1,140 yd/lb +/- 10%.
- Yarn shall have a minimum strength of >13,000 cN and elongation of >1%.
- Yarn shall have a twist in the “S” direction and shall be 115 +/- 15% T/m (twists per meter) (2.92 T/in.).
- Yarn shall be manufactured so as to reduce presence of surface features such as slubs or flames.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.1 Aeroassist and Atmospheric Entry

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Reports documenting analysis and development results, including description of any hardware or prototypes developed. Focus of Phase I development can be material coupons and/or subscale manufacturing demonstrations that demonstrate proof of concept and lead to Phase II scaleup and testing in relevant environments for applications related to Mars and other planetary entry, Earth return, launch asset recovery, or the emergent small-satellite community.

State of the Art and Critical Gaps:
The current state of the art for deployable aerodynamic decelerators is limited due to novelty of this technology. Development of gas generator technologies that improve mass efficiency over current pressurized cold gas systems for inflatable structures is needed. Domestic capability for producing blended phenolic/carbon yarn for 3D woven thermal protection systems is nonexistent, and NASA is interested in developing this domestic capability for future missions.

Relevance / Science Traceability:
NASA needs advanced deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, and Titan as well as payload return to Earth from low Earth orbit. NASA also needs domestic supply of blended phenolic/carbon yarn for 3D woven traditional thermal protection systems. HEOMD (Human Exploration and Operations Mission Directorate), STMD (Space

Technology Mission Directorate), and SMD (Science Mission Directorate) can benefit from this technology for various exploration missions.

References:

1. Hughes, S. J., et al., “Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development Overview,” AIAA Paper 2011-2524.
2. Bose, D. M, et al., “The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Mission Applications Study,” AIAA Paper 2013-1389.
3. Hollis, B. R., “Boundary-Layer Transition and Surface Heating Measurements on a Hypersonic Inflatable Aerodynamic Decelerator with Simulated Flexible TPS,” AIAA Paper 2017-3122.
4. Olds, A. D., et al., “IRVE-3 Post-Flight Reconstruction,” AIAA Paper 2013-1390.
5. Del Corso, J. A., et al., “Advanced High-Temperature Flexible TPS for Inflatable Aerodynamic Decelerators,” AIAA Paper 2011-2510.
6. Cassell, A., et al., “ADEPT, A Mechanically Deployable Re-Entry Vehicle System, Enabling Interplanetary CubeSat and Small Satellite Missions,” SSC18-XII-08, 32nd Annual AIAA/USU Conference on Small Satellites.
7. Cassell, A., et al., “ADEPT Sounding Rocket One Flight Test Overview,” AIAA Paper 2019-2896.
8. Ellerby, D., et al., “Heatshield for Extreme Entry Environment Technology (HEEET) Thermal Protection System (TPS),” Materials Science and Technology (MS&T) 2019, September 29-October 3, 2019, Portland, Oregon.

Z7.04 Landing Systems Technologies (SBIR)

Lead Center: MSFC
Participating Center(s): GRC, LaRC

Scope Title: Plume-Surface Interaction (PSI) Instrumentation, Ground Testing, and Analysis

Scope Description:
As NASA and commercial entities prepare to land robotic and crewed vehicles on the Moon, and eventually Mars, characterization of landing environments is critical to identifying requirements for landing systems and engine configurations, instrument placement and protection, and landing stability. The ability to predict the extent to which regolith is liberated and transported in the vicinity of the lander is also critical to understanding the effects on precision landing sensor requirements and landed assets located in close proximity. Knowledge of the characteristics, behavior, and trajectories of ejected particles and surface erosion during the landing phase is important for designing effective sensor systems and PSI risk mitigation approaches. Mission needs to consider include landers with single and multiple engines, both pulsed and throttled systems, landed mass from 400 to 40,000 kg, and both lunar and Mars destinations.

NASA is seeking support in the following areas:

1. Ground test data, test techniques, and diagnostics across physical scales and environments, with particular emphasis on nonintrusive approaches and methodologies.
2. PSI-specific flight instrumentation, with particular emphasis on in situ measurements of particle size and particle velocity during the landing phase.
3. Solutions to alleviate or mitigate the PSI environments experienced by propulsive landers—not vehicle-specific solutions.
4. Validated, robust, and massively parallel computational fluid dynamics (CFD) models and tools for predicting PSI physics for plumes in low-pressure and rarefied environments, time-evolving cratering and surface erosion, and near-field and far-field ejecta transport.

NASA has plans to purchase services for payload delivery to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant PSI technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics, but the data to be obtained or mitigations to be demonstrated should be broadly applicable to other future landing systems. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services are currently under contract, and flight opportunities are expected to continue well into the future. In future years, it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.3 Landing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Deliverables of all types can be infused into the prospect missions due to early design maturity.

For PSI ground test data, flight instrumentation, diagnostics, and mitigation approaches, Phase I deliverables should include detailed test plans, with prototype and/or component demonstrations as appropriate. Phase II deliverables should include complete data products, fully functional hardware, and validated performance in relevant environments.

For PSI modeling and simulation, Phase I deliverables should demonstrate proof of concept and a minimum of component-level verification, with detailed documentation on future data needs to complete validation of the integrated model and uncertainty quantification methodology. Phase II deliverables must demonstrate verification and validation beyond the component level, with validation demonstrated through comparisons with relevant data and documented uncertainty quantification. Significant attention should be applied to create highly robust and extremely high-performance computational simulation tool deliverables, exploiting leading-edge computational architectures to achieve this performance.

State of the Art and Critical Gaps:
The characteristics and behavior of airborne particles during descent is important for designing descent sensor systems that will be effective. Furthermore, although the physics of the atmosphere and the characteristics of the regolith are different for the Moon, the capability to model PSIs on the Moon will feed forward to Mars, where it is critical for human exploration.

Currently, flight data are collected from early planetary landing, and those data are fed into developmental tools for validation purposes. The validation data set, as well as the expertise, grows as a result of each mission and is shared across and applied to all other missions. We gain an understanding of how various parameters, including different types of surfaces, lead to different cratering effects and plume behaviors. The information helps NASA and industry make lander design and operations decisions. Ground testing (“unit tests”) is used early in the development of the capability in order to provide data for tool validation.

The current postlanding analysis of planetary landers (on Mars) is performed in a cursory manner with only partially empirically validated tools, because there has been no dedicated fundamental research investment in this area. Flight test data does not exist in the environments of interest.

Relevance / Science Traceability:
Current and future lander architectures will depend on knowledge of PSI, such as:

- Artemis human landing system (HLS).
- Commercial robotic lunar landers (CLPS or other).
- Planetary mission landers (Mars Sample Retrieval Lander and others).
- Human Mars landers.

References:

1. Lander Technologies: https://www.nasa.gov/content/lander-technologies
2. Metzger, Philip, et al. (2009). ISRU implications for lunar and Martian plume effects. 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition.
3. Plemmons, D. H., et al. (2008). Effects of the Phoenix Lander descent thruster plume on the Martian surface. Journal of Geophysical Research: Planets, 113(E3).
4. Mehta, M., et al. (2013). Thruster plume surface interactions: Applications for spacecraft landings on planetary bodies. AIAA Journal, 51(12), 2800-2818.
5. Vangen, Scott, et al. (2016). International Space Exploration Coordination Group Assessment of Technology Gaps for Dust Mitigation for the Global Exploration Roadmap. AIAA SPACE 2016. 5423.

Scope Title: Landing Shock Attenuation, Reusability, and In Situ Landing Sensors

Scope Description:
Novel and creative solutions will be required to attenuate the structural loads induced by the landing of crewed spacecraft, commercial cargo payloads, scientific payloads, critical surface assets, and surface habitats on the Moon and Mars. In principle, the mass and scale of these spacecraft, payloads, and assets could range from something akin to a small-satellite class, roughly 10 to 500 kg, to masses on the order of thousands of kg. This capability is critical for landing larger spacecraft near assets already in place.

Current landing system solutions include legs, shock absorbers, inflatables, crushables, sky cranes, pallets, etc., but new technologies, novel combinations of existing technologies, and/or the repurposing of current Earth-based technologies could enable new mission design and feasibility.

Mission concepts requiring the sustainability and reusability of assets and payloads on the surfaces of celestial bodies (including the Moon, Mars, moons of Mars, comets, and/or asteroids) will benefit from the development of reusable landing systems, including consideration of launch plumes for ascent vehicles. Reusability can also be interpreted to include the postlanding adaptation of landing systems to enable mobility or augmented capabilities (e.g., "touch-and-go" mobility, grappling, maneuverability, etc.).

In situ landing sensors that measure the induced loads and shocks experienced within these challenging environments will provide engineers and researchers with valuable in situ data, which will enable improved environmental modeling, landing structure design, and sensor design. Possible applications include advanced touchdown sensors, measurement of payload orientation, stability, and/or landing loads.

Also, of interest are approaches for achieving multifunctional components, repurposing landing structures for postflight mission needs such as payload placement or mobility, and incorporating design features that reduce operating complexity.

Under this subtopic, proposals may include efforts to develop prototypes for flight demonstration of relevant technologies in the lunar environment or in terrestrial testbeds. The Commercial Lunar Payload Services (CLPS) accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2022, and flight opportunities are expected to continue well into the future. In future years, it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.3 Landing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Deliverables and/or prototypes of all types can be infused into the prospective missions due to early design maturity.

Phase I deliverables should include preliminary designs, end-product test plans, and component-level testing and/or demonstrations as appropriate, and Phase II should include a working prototype demonstration in a relevant environment.

State of the Art and Critical Gaps:
Robust landing structures can enable lunar and Mars global access with 20-ton payloads to support human missions.

Mission risks related to hazard avoidance may be partially mitigated by robust landing system accommodation of landing hazards.

Development of exploration technologies to enable a vibrant space economy can be partially addressed with respect to landing technologies related to landing pads and protective and robust landing structures.

Construction and outfitting of assets on the Moon and Mars could be addressed by technologies related to multifunctional and adaptive landing structures for use after landing.

Relevance / Science Traceability:
Current and future lander architectures will depend on landing shock attenuation, reusability, and intelligent landing sensors, such as:

- Artemis human landing system (HLS).
- Commercial robotic lunar landers (CLPS or other).
- Planetary mission landers (Mars Sample Retrieval Lander and others).
- Human Mars landers.
- Scientific investigations of comets and asteroids.

References:

1. Lander Technologies: https://www.nasa.gov/content/lander-technologies
2. Commercial Lunar Payload Services: https://www.nasa.gov/content/commercial-lunar-payload-services
3. Lunar Exploration and Transportation Services: https://www.nasa.gov/nextstep/humanlander3
4. JAXA Hyabusa2: https://www.hayabusa2.jaxa.jp/en/
5. JPL ATHLETE Rover: https://www-robotics.jpl.nasa.gov/systems/system.cfm?System=11
6. SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE)

Focus Area 13 Information Technologies for Science Data

NASA Missions and Programs create a wealth of science data and information that are essential to understanding our earth, our solar system, and the universe. Advancements in information technology will allow many people within and beyond the Agency to more effectively analyze and apply these data and information to create knowledge. For example, modeling and simulation are being used more pervasively throughout NASA, for both engineering and science pursuits, than ever before. These tools allow high fidelity simulations of systems in environments that are difficult or impossible to create on Earth, allow removal of humans from experiments in dangerous situations, provide visualizations of datasets that are extremely large and complicated, and aid in the design of systems and missions. In many of these situations, assimilation of real data into a highly sophisticated physics model is needed. Information technology is also being used to allow better access to science data, more effective and robust tools for analyzing and manipulating data, and better methods for collaboration between scientists or other interested parties. The desired end result is to see that NASA data and science information are used to generate the maximum possible impact to the nation: to advance scientific knowledge and technological capabilities, to inspire and motivate the nation's students and teachers, and to engage and educate the public.

S11.06 Earth Science Decision Support Tools Focused on the Mitigation of Climate Change Impacts (SBIR)

Lead Center: GSFC

Participating Center(s): ARC, JPL, LaRC, MSFC

Scope Title: Earth Science Decision Support Tools Focused on the Mitigation of Climate Change Impacts

Scope Description:

The NASA Earth Science (http://science.nasa.gov/earth-science/) and Applied Sciences (http://appliedsciences.nasa.gov/) programs seek innovative and unique approaches to increase the utilization and extend the benefit of Earth Science research data to better meet societal needs. The focus of this subtopic is to develop digital tools for non-expert end users who are not scientists. These users need analytical tools to make decisions in the context of climate change, specifically related to wildfire mitigation and water management. Tools must be intuitive, and results must be reliable and not subject to misinterpretation. Innovative solutions could range from simple, intuitive mobile applications, to dashboard tools that integrate NASA science data with domain-specific contextual data, to sophisticated decision-support software that merges deep analysis with powerful prediction capabilities to provide insights and the ability to explore "what-if" scenarios.

This subtopic develops core capabilities that can be integrated to build remote-sensing-driven decision support tools (DSTs) customized to the requirements of different users in varied fields who are grappling with current and anticipated impacts from wildfires and inadequacy of fresh water. Proven development and commercialization strategies should be used to meet these objectives. The goal of this solicitation is to directly link what is being done at NASA with the end-user community to support decision making. Responsive proposals must include a clear identification of tools that will be used and a clear end-user or business application to which the tools, systems, and so forth are intended to support. Proposals should explain how the proposed capabilities will address an end-user need, business opportunity, or gap area in decision support capabilities. Proposals should also outline existing capabilities, including software, models, and data that are already implemented at NASA or through related NASA activities, and describe how the proposed activities may leverage, complement, or expand from the existing infrastructure. Proposals should discuss the level of computing resources required for their methods as well as the plan to ensure availability of the resources needed.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.X Other Software, Modeling, Simulation, and Information Processing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:
Research proposed to this subtopic should demonstrate technical feasibility during Phase I, and in partnership with commercial customers (to include other Federal Agencies and state and local governments), show a path toward a Phase II prototype demonstration with significant communication with commercial stakeholders to increase the potential for nongovernmental market penetration.

State of the Art and Critical Gaps:
Currently, creating DSTs that effectively utilize remote-sensing data requires significant efforts by experts in multiple domains. NASA Earth science data, while accessible, is massive in breadth and scope—a true “Big Data” problem. However, the formatting of the data is not easily accessed or readily usable beyond remote sensing experts and the research community, suggesting that application by commercial users is even more challenging. Although the data have commercial use, they are underutilized because of accessibility and translation issues. This creates a barrier to the widespread use of Earth observations by state and local governments, businesses, and the public. This subtopic aims to democratize the creation of Earth-science-driven DSTs related to fire mitigation and freshwater management and encourage DST development that significantly increases the return on investment for Earth science missions.

Relevance / Science Traceability:
NASA Mandate 51 USC Section 60506: ensure the availability and widest possible use of accurate and current data on global warming; also, use practical benefits for society as an important measure of success.

From the 2018 Earth Science Decadal Survey: "While some discoveries are grounded entirely on observations from space, many more depend on combining information from a range of sources, including field campaigns, laboratory experiments, computer modeling, and theoretical studies...Science based on integrating information from several approaches can lead to products where the insights from the whole are much greater than the sum of the parts..."

References:
Proposed decision support tools should leverage NASA’s rich Earth science data:

1. Earth data: https://earthdata.nasa.gov/
2. Earth Science Applied Sciences—Perspective: https://appliedsciences.nasa.gov/

S14.01 Space Weather Research-to-Operations/Operations-to-Research (R2O/O2R) Technology Development (SBIR)

Lead Center: MSFC
Participating Center(s): ARC, GSFC, JPL, JSC, LaRC

Scope Title: Space Weather Research-to-Operations/Operations-to-Research (R2O/O2R) Technology Development and Commercial Applications

Scope Description:
Space weather has the potential to disrupt telecommunications; aircraft and satellite systems; electric power subsystems; and position, navigation, and timing services. Given the importance of these systems to our national well-being, NASA's Heliophysics Division invests in activities to improve the understanding of these phenomena and to enable new monitoring, prediction, and mitigation strategies.

The national direction for this work is organized by the Space Weather Operations, Research, and Mitigation (SWORM) Working Group, which is a Federal interagency coordinating body organized under the Space Weather, Security, and Hazards (SWSH) Subcommittee. The SWSH is a part of the National Science and Technology Council (NSTC) Committee on Homeland and National Security, organized under the Office of Science and Technology Policy (OSTP). The SWORM coordinates Federal Government departments and agencies to meet the goals and objectives specified in the National Space Weather Strategy and Action Plan (NSWSAP) and in the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act.

NASA's role under the NSWSAP and PROSWIFT Act is to provide increased understanding of the fundamental physics of the Sun-Earth system through space-based observations and modeling, the development of new space-based space-weather technologies and missions, and through monitoring of space weather for NASA's space missions. This includes research that advances operational and commercial space-weather science and technology.

This subtopic solicits new, enabling space-weather technologies as part of NASA's response to these national objectives. While this subtopic will consider all concepts demonstrably related to NASA's R2O/O2R responsibilities outlined in the NSWSAP, four areas have been identified for priority development (not in priority order):

(1) Space-weather forecasting technologies, techniques, and applications: Innovative technologies and techniques are solicited that explore and enable the transition of tools, models, data, and knowledge from research to operational environments. This includes the preparation and validation of existing science models that may be suitable for transition to operational use. Coordination with existing NASA capabilities, such as the Space Radiation Analysis Group (SRAG) at Johnson Space Center (JSC), the Community Coordinated Modeling Center (CCMC) at Goddard Space Flight Center (GSFC), and the Short-term Prediction Research and Transition (SPoRT) Center at Marshall Space Flight Center (MSFC), is appropriate and encouraged. Areas of special interest include, but are not limited to:

- Lunar space environment characterization tools that can be employed by NASA to enhance protection of crewed and un-crewed missions to cis-lunar and lunar surface missions.
- Specifications and/or forecasts of the energetic particle and plasma conditions encountered by spacecraft within Earth's magnetosphere, as well as products that directly aid spacecraft anomaly resolution and benefit end users such as spacecraft operators.
- Approaches that potentially lead to 2- to 3-day forecasts of atmospheric drag effects on satellites and improvement in the quantification of orbital uncertainties in low-Earth-orbit (LEO) altitude ranges (up to ~2,000 km).

- Techniques that enable the characterization and prediction of ionospheric variability that induces scintillations, which impact communication and global navigation and positioning systems.
- Longer range (2 to 3 days) forecasting of solar particle events (SPEs) and an improved all-clear, SPE-forecasting capability.

(2) Commercial and decision-making applications for space-weather technologies: Innovative techniques and solutions are solicited that extend to commercial entities the use of new technology and knowledge about space weather. The NSWSAP and the PROSWIFT Act specifically call out the need to test, evaluate, and deploy technologies and devices to mitigate the effects of space weather on communication systems, geomagnetic disturbances on the electrical power grid, or radiation events on satellites. In addition, the policy and legislation include the development of processes to improve the transition of research approaches to operations, to support operational partners, and to serve society. Proposals of interest could include, but are not limited to:

- Descriptions and development of standards and best practices to improve the resilience of equipment to space-weather events.
- Efforts to bridge the gap between heliophysics science and society; these proposals would apply NASA data to the decision-making process of an end user to improve life on Earth. This work will power innovative projects through the use in novel ways of NASA space-weather data and will support decision making by a diverse community of users that NASA may not frequently engage. Integrating NASA data into the decision-making process of a particular user or user community is important for this solicitation.
- A description of a decision that will be the focus of a project, how the organization currently makes that decision, and how NASA data will be integrated into and will benefit that process.

Of specific interest are non-operational applications (i.e., not NOAA or DoD) with nontraditional users (e.g., a user who has not used NASA data before). Success could be an organization using NASA space-weather data to inform a decision they make, so that the use of these data tangibly benefits the performance of the organization. Both commercial applications and noncommercial applications are of high interest and are encouraged.

(3) Space weather advanced data-driven discovery techniques: A particular challenge is to combine the sparse, vastly distributed data sources available with realistic models of the near-Earth space environment. Data assimilation and other cutting-edge, data-driven discovery innovations are solicited that enable tools and protocols for the operational space-weather community. Priority will be given to proposals that:

- Develop data assimilation space-weather applications or technologies desired by established space-weather operational organizations.
- Integrate data from assets that typically do not share similar time series, utilize different measurement techniques (e.g., imaging vs. in situ particles and fields), or are distributed throughout the heliosphere.
- Provide new data-driven operational forecasting tools that can be straightforwardly validated by the CCMC or another equally robust validation methodology.
- Integrate underutilized, unexplored, or nontraditional resources.

Many existing or planned commercial constellations may include useful space-weather-exploitable data (e.g., iridium system magnetometer data or space-based radio occultation for ionospheric specification). Other possible data sources are global-navigation-satellite-system- (GNSS-) equipped constellations (for total electron content (TEC) and/or drag information) and imaging constellations (tapping into unused nighttime observations of aurorae).

(4) Space Weather Instrumentation: Heliophysics science relies on a wide variety of instrumentation for its research and often makes its data available in near real time for space-weather forecasting purposes. Ideas are solicited for instrument concepts, flight architectures, and reporting systems that enable enhanced, more informative, robust, and effective measurements for space-weather monitoring and forecasting systems.

Opportunities for improving measurements include increased spatial and temporal resolution, fidelity, promptness, and measurement-system reliability. This includes the miniaturization of existing systems and/or technologies deployable as an array of CubeSats. To be considered for investment, SBIR technologies should demonstrate comparable, or better, precision and accuracy when compared to the current state of the art. Further, SBIR instrument designs should avoid duplicating current NASA research spacecraft arrays or detector systems, including those currently in formulation or development, such as, but not limited to Interstellar Mapping and Acceleration Probe (IMAP), Geospace Dynamics Constellation (GDC), Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC), Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI), Explorer concepts, Advanced Composite Solar Sail System (ACS3), Heliophysics Environmental and Radiation Measurement Experiment Suite (HERMES), Solar Cruiser, and Global Lyman-alpha Imagers of the Dynamic Exosphere (GLIDE).

Proposals must demonstrate an understanding of the current state of the art, describe how the proposed innovation is superior, and provide a feasible plan to develop the technology and infuse into a specific activity listed within the NSWSAP and the PROSWIFT Act.

Expected TRL or TRL Range at completion of the Project: 3 to 8

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.X Other Software, Modeling, Simulation, and Information Processing

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:
Space weather is a broad umbrella encompassing science, engineering, applications, and operations. The ultimate goal of this SBIR is to generate products or services (“deliverables”) that enable end-user action. The deliverables can be applied, for example, to space-weather hazard assessments, real-time situational awareness, or to plan protective mitigation actions. Deliverables can be in the form of new data, new techniques, new instrumentation, and/or predictive models that are prepared/validated for transition into operations:

- Phase I deliverables are proof-of-concept data and/or detailed technique, instrument, or model development plans that have sufficient fidelity to assess technical, management, cost, and schedule risk. Phase I deliverables should also delineate the scope and benefit of the proposed products that could be realized as a result of Phase II and what further scope and benefit necessarily requires further development after Phase II.
- Phase II deliverables are functioning prototype versions of the proposed technologies that have been tested in a realistic environment or within a standard space-weather-community development and validation framework. The extent of the prototype development and testing will vary with the technology and will be evaluated as part of the Phase II proposal. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and commercial use.

State of the Art and Critical Gaps:

- We do not yet know how to predict what phenomena need to be predicted.
- We do not yet know how quantitatively good/bad are our operational capabilities (metrics).
- Mechanisms do not yet exist to enable a broad range of the community to participate in the improvement of operational models.
- The research environment advances understanding rather than the improvement of operational products.

Space weather poses a constant threat to the Nation’s critical infrastructure, our satellites in orbit, and our crewed and un-crewed space activities. Extreme space-weather events can cause substantial harm to our Nation’s security and economic vitality. Preparing for space-weather events is an important aspect of American resilience that bolsters national and homeland security and facilitates continued U.S. leadership in space. A robust space-weather program and its associated forecasting capabilities are essential for NASA’s future exploration success.

Relevance / Science Traceability:
This SBIR subtopic enables NASA to demonstrate progress against NASA Goal 1.4: Understand the Sun and its interactions with Earth and the solar system, including space weather.

These applied research projects directly address NASA's role within the SWORM Working Group, which is a Federal interagency coordinating body organized under the SWSH Subcommittee. The SWSH is a part of the NSTC Committee on Homeland and National Security, organized under the OSTP. The SWORM coordinates Federal Government departments and agencies to meet the goals and objectives specified in the NSWSAP and in the PROSWIFT Act.

The Heliophysics Space Weather Science Application (SWxSA) establishes an expanded role for NASA in space-weather science under a single element, consistent with the recommendation of the National Research Council (NRC) Decadal Survey and the OSTP/SWORM 2019-NSWSAP. SWxSA competes ideas and products, leverages existing agency capabilities, collaborates with other agencies, and fosters partnership with user communities. SWxSA is distinguishable from other Heliophysics research elements in that it is specifically focused on investigations that significantly advance understanding of space weather; this progress is applied to enable more accurate characterization and predictions with longer lead time. The Heliophysics Living With a Star (LWS) Program has established a path forward to meet NASA’s obligations to the research relevant to space weather and is a significant source of input to SWxSA. Further involvement by the emerging Heliophysics space-weather commercial community has the potential to significantly advance the space-weather application obligations portion of the mandate.

Astronauts in Earth orbit are not protected by the Earth's atmosphere and are exposed to space radiation such as galactic cosmic rays and solar-energetic particles. Further, when astronauts travel outside Earth’s magnetosphere, they are exposed to even more radiation. A robust space-weather program and associated forecasting capabilities is essential for NASA's future exploration success.

References:

1. Public Law 116-181—Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act (PROSWIFT): The PROSWIFTAct was signed into law October 21, 2020. This law establishes the policy of the United States to protect its citizens from the effects of space weather on in-space resources and ground-based infrastructure by supporting space-weather research to include forecasts and predictions. Using a strategy of interagency collaboration, within and outside the Federal Government to include international partners, the PROSWIFT Act seeks to ameliorate social and financial impacts of space-weather events to society.
2. Executive Order 13744 – Coordinating Efforts to Prepare the Nation for Space Weather Events describes the policy of the United States with respect to preparations for space-weather events so that economic loss and human hardship will be minimized.
3. The SWORM Working Group is a Federal interagency coordinating body organized under the SWSH Subcommittee. The SWSH is a part of the NSTC Committee on Homeland and National Security, organized under the OSTP. The SWORM coordinates Federal Government departments and Agencies to meet the goals and objectives specified in the National Space Weather Strategy and Action Plan released in March 2019.
4. National Space Weather Strategy and Action Plan (NSWSAP): The White House Executive OSTP released the NSWSAP on March 26th, 2019, during the National Space Council meeting in

Huntsville, Alabama. This strategy and action plan is an update to the original NSWSAP, released in October 2015.

5. Space Weather Phase 1 Benchmarks is a document created by the SWORM subcommittee, and the benchmarks describe a space-weather event's ability to affect the United States. The purpose of the benchmarks is to provide input for creating engineering standards, to develop risk assessments and estimates, establish thresholds for action, develop mitigation procedures, and enhance planning for response and recovery.
6. An Executive Order (EO) on Coordinating National Resilience to Electromagnetic Pulses (EMPs) was released by the White House on March 26, 2019. The EO identifies the disruptive impacts an EMP has on technology and critical infrastructure systems, whether the EMP is human made or naturally occurring. The EO outlines how the Federal Government will prepare for and mitigate the effects of EMPs by an efficient and cost-effective approach.

S17.02 Integrated Science Mission Modeling (SBIR)

Lead Center: JPL
Participating Center(s): GSFC

Scope Title: Innovative System Modeling Methods and Tools

Scope Description:
NASA seeks innovative systems modeling methods and tools addressing the following needs:

1. Define, design, develop, and execute future science missions by developing and utilizing advanced methods and tools that empower more comprehensive, broader, and deeper system and subsystem modeling while enabling these models to be developed earlier in the lifecycle. Ideally, the proposed solutions should leverage MBSE (model-based systems engineering)/SysML (System Markup Language) approaches being piloted across NASA, allow for easier integration of disparate model types, and be compatible with current agile design processes.
2. Enable disciplined system analysis for the design of future missions, including modeling of decision support for those missions and integrated models of technical and programmatic aspects of future missions.
3. Evaluate technology alternatives and impacts, science valuation methods, and programmatic and/or architectural trades.
4. Specific areas of interest are listed below. Proposers are encouraged to address more than one of these areas with an approach that emphasizes integration with others on the list:
   - Conceptual phase models and tools that allow design teams to easily develop, populate, and visualize very broad, multidimensional trade spaces; also, methods for characterizing and selecting optimum candidates from those trade spaces, particularly at the architectural level. There is specific interest in models and tools that facilitate comprehensive comparison of architectural variants of systems.
   - Capabilities for rapid-generation models of function or behavior of complex systems at either the system or the subsystem level. Such models should be capable of eliciting robust estimates of system performance given appropriate environments and activity timelines, and should be tailored:
     - To support emerging usage of autonomy, both in mission operations and flight software as well as in growing usage of autocoding.
     - To operate within highly distributed collaborative design environments, where models and/or infrastructure that support/encourage designers are geographically separated (including open innovation environments). This includes considerations associated with near-real-time (concurrent) collaboration processes and associated model integration and configuration management practices.
     - To be capable of execution at variable levels of fidelity/uncertainty. Ideally, models should have the ability to quickly adjust fidelity to match the requirements of the simulation (e.g., from broad and shallow to in depth and back again).

- Target models (e.g., phenomenological or geophysical models) that represent planetary surfaces, interiors, atmospheres, etc., and associated tools and methods that allow for integration into system design/process models for simulation of instrument responses. These models may be algorithmic or numeric but should be useful to designers wishing to optimize remote sensing systems for those planets.

Note that this topic area addresses a broad potential range of science mission-oriented modeling tools and methods. This includes the integration of these tools into broader model-based engineering frameworks, and also includes proposals with MBSE/SysML as the primary focus.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.X Other Software, Modeling, Simulation, and Information Processing

Desired Deliverables of Phase I and Phase II:
- Prototype
- Software
- Research

Desired Deliverables Description:
Phase I will result in a final report that describes the methodology and a clear proof of concept demonstrating the relevance of the technology for NASA use and provides insight into the next phase of maturation.

At the completion of Phase II, NASA requires a working prototype suitable for demonstrations with "real" data to make a compelling case for NASA usage. Use and development of the model—including any and all work performed to verify and validate it—shall be documented. Also, at the end of Phase II, there will be a clear indication of the path to commercialization.

State of the Art and Critical Gaps:
There are currently a variety of models, methods, and tools in use across the Agency and with our industry partners. These are often custom, phase-dependent, and poorly interfaced to other tools. The disparity between the creativity in the early phases and the detail-oriented focus in later phases has created phase transition boundaries, where missions not only change teams, but tools and methods as well. We aim to improve this.

As NASA continues its move into greater use of models for formulation and development of NASA projects and programs, there are recurring challenges to address. This subtopic focuses on encouraging solutions to these cross-cutting modeling challenges.

These cross-cutting challenges include greater modeling breadth (e.g., cost/schedule), depth (scalability), variable fidelity (precision/accuracy vs. computation time), trade space exploration (how to evaluate large numbers of options), and processes that link them together. The focus is not on specific tools, but demonstrations of capability and methodologies for achieving the above.

The explosion of MBx (Model-Based Everything) has led to a proliferation of models, modeling processes, and the integration/aggregation thereof. The model results are often combined with no clear understanding of their fidelity/credibility. Whereas some NASA personnel are looking for greater accuracy and "single source of truth," others are looking for the generation and exploration of massive trade spaces. Both greater precision and greater robustness will require addressing the cross-cutting challenges cited above.

Relevance / Science Traceability:

Several concept/feasibility studies for potential large (flagship) astrophysics missions are in progress: Large UV/Optical/IR Surveyor (LUVOIR), Origins Space Telescope (OST), Habitable Exoplanet Observatory (HabEx), and Lynx. Following the 2020 Astrophysics decadal rankings, one of these will likely proceed to early Phase A, where the infusion of new and advanced systems modeling tools and methods would be a potential game changer in terms of rapidly navigating architecture trades, requirements development and flow down, and design optimization.

A variety of planetary missions require significant modeling and simulation across a variety of possible trade spaces. The portions of this topic area focused on breadth and variable fidelity will support them.

References:

1. Large Ultraviolet Optical Infrared Surveyor (LUVOIR): https://asd.gsfc.nasa.gov/luvoir/
2. Origins Space Telescope (OST): https://asd.gsfc.nasa.gov/firs/
3. Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/
4. Lynx: https://wwwastro.msfc.nasa.gov/lynx/
5. Laser Interferometer Space Antenna (LISA): https://lisa.gsfc.nasa.gov/
6. Nancy Grace Roman Space Telescope: https://www.nasa.gov/content/goddard/nancy-grace-roman-space-telescope
7. Mars Exploration/Program & Missions: https://mars.nasa.gov/programmissions/
8. JPL Missions: https://www.jpl.nasa.gov/missions/

S17.04 Application of Artificial Intelligence for Science Modeling and Instrumentation (SBIR)

Lead Center: GSFC

Participating Center(s): ARC, JPL, LaRC

Scope Title: Accelerating NASA Science and Engineering Through the Application of Artificial Intelligence to Data Assimilation

Scope Description:

NASA, the National Oceanic and Atmospheric Administration (NOAA), and other Federal Agencies maintain extensive Earth observation networks and are continuously developing the next-generation remote-sensing platforms. The data from these observations are used in a wide variety of ways, including as input to scientific data analysis and physics-based computer models to make a wide range of forecasts. Most forecast models are driven by data from observing systems; these data contain artifacts of the observing system, such as noise, sparsity of observations, and anomalies that do not affect the overall forecast. Since the quality of the forecast is directly related to the estimation of the initialization state of the physical system, these improvements cannot be achieved without better estimates of state of the system. Data assimilation is a technique for integrating observational data about a physical system with modeling that reflects the understanding of the physical processes in it. It fills the gaps in observations and provides both an estimate of the state of the system as well as the uncertainty in that estimate. Current methods are computationally expensive and as data volumes increase, may not be able to meet the performance needed for timely forecasts.

NASA is looking for proposals that apply artificial intelligence (AI), computer vision (CV), machine learning (ML), and/or deep learning (DL) to data assimilation to improve efficiency and accuracy of model forecast products, driven by remote sensing and, when appropriate, in situ data sources. The result will lead to a better forecast of future states and an understanding of risk for localized extreme atmospheric weather, space weather, and water events and lead to earlier warnings, which will save lives and reduce property damage. As an alternative to traditional data assimilation, the application of AI/CV/ML/DL methods, such as pattern recognition, feature extraction, super resolution, gap filling, and more, have the potential to result in a more complete state of the natural system.

Proposals MUST specify and be in alignment with existing and/or future NASA/NOAA programs. Research proposed to this subtopic should demonstrate technical feasibility during Phase I, and in partnership with scientists and/or engineers, show a path toward a Phase II prototype demonstration, with significant communication with missions and programs to later plan a potential Phase III infusion. It is highly desirable that the proposed projects lead to solutions that will be infused into government programs and projects.

Expected TRL or TRL Range at completion of the Project: **4 to 6**

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.2 Modeling

Desired Deliverables of Phase I and Phase II:

- **Prototype**
- **Software**
- **Research**

Desired Deliverables Description:
Data products developed under this subtopic may be developed for broad public dissemination or used within a narrow scientific community. It is expected that the labeled training data sets, models, and resulting data assimilation products will be publicly accessible.

In general, the desired outcomes for this subtopic include, but are not limited to, the following:

- New methods and approaches for science data assimilation.
- New/improved data assimilation products that can be used and infused into NASA science projects.
- Labeled training data sets and trained models specific to a given problem but that can also be used as a basis for furthering other science and engineering research and development.

More specifically:

- Phase I should be used to establish a proof of concept with deliverables including a final report, any software developed, training sets, etc.
- Phase II will expand on this proof of concept to a full prototype with a very similar set of deliverables, including a final report, software, training sets, etc.

State of the Art and Critical Gaps:
NASA, along with other Federal Agencies and commercial and foreign research organizations that perform science and engineering, is making large strides in the use of artificial intelligence (AI) technologies (which includes computer vision, machine learning, and deep learning). This subtopic is looking to improve this by providing trained models that have the possibility of creating a better initial state of the physical system (i.e., Earth, solar wind, etc.) prior to being used as input for scientific data analysis and as input into physics-based simulations to improve forecasts.

In addition, emerging computational platforms now provide significant improvements in computing capabilities to enable AI to be applied to a wide variety of applications in science and engineering. These emerging computational capabilities have the potential to dramatically speed up AI calculations, and these systems are even being used as the reference architecture for exascale high-performance computing systems.

Relevance / Science Traceability:
Broad applicability across throughout the decadal surveys and satellite development requirements to improve the quality and granularity of system forecasts:

- Improved measurements of the Earth system could provide better gap analysis for future mission requirements.

- Global Modeling and Assimilation Office (GMAO) assimilation: Augment data assimilation to improve computational performance or data quality.
- Carbon Cycle Ecosystems Office (CCOE): Wide variety of applications given the diversity of data sets from sparse in-situ to global satellite measurements.
- Earth Science Technology Office/Advanced Information Systems Technology (ESTO/AIST): New technology and services to exploit NASA and non-NASA data leading to digital twins of physical systems.
- Computational and Information Sciences and Technology Office (CISTO - Code 606): Computational, analytic, and visualization technologies used for new data science.
- NASA Center for Climate Simulation (NCCS - Code 606.2): Building applications toward exascale computing.

References:

1. 2017-2027 Decadal Survey for Earth Science and Applications from Space: https://science.nasa.gov/about-us/science-strategy/decadal-surveys
2. 2013-2022 Decadal Survey in Solar and Space Physics
    - Baker, D. N., A. Char, and T. Zurbuchen: "Science for a Technological Society: The 2013–2022 Decadal Survey in Solar and Space Physics," *Space Weather*, 11, pp. 50–51, 2013, doi:10.1002/swe.20022.
    - National Research Council: *Solar and Space Physics: A Science for a Technological Society*. Washington, DC: The National Academies Press, 2013, https://doi.org/10.17226/13060
3. Global Modeling and Assimilation Office: https://gmao.gsfc.nasa.gov/
4. NASA Goddard Institute for Space Studies: https://www.giss.nasa.gov/
5. NASA Earth Science Data: https://earthdata.nasa.gov/
6. NASA Center for Climate Simulation: https://www.nccs.nasa.gov/
7. NASA High-End Computing (HEC) Program: https://www.hec.nasa.gov/
8. PUBLIC LAW 115–25– Weather Research and Forecasting Innovation Act of 2017 (April 18, 2017)
9. M-19-25, FY 2021 Administration Research and Development Budget Priorities, https://www.whitehouse.gov/wp-content/uploads/2019/08/FY-21-RD-Budget-Priorities.pdf
10. William Lahoz and Philipp Schneider, "Data assimilation: making sense of Earth Observation," *Front. Environ. Sci.*, 28 May 2014, https://doi.org/10.3389/fenvs.2014.00016

In addition, proposers are encouraged to search the NASA Technical Report Server (NTRS) for additional information to help guide potential solutions: https://ntrs.nasa.gov/

Focus Area 15 Materials Research, Advanced Manufacturing, Structures, and Assembly

As NASA embarks on its mission for human exploration of the Moon as a step towards the human mission to Mars, taking full advantage of the potential offered by new and existing technologies will be critical to enabling sustainable Lunar and Mars presence. The Materials Research, Advanced Manufacturing, Structures and Assembly focus area seeks to address challenges such as lowering the cost of exploration, enabling efficient, reliable operations in extreme environments, and accelerating the integration of advanced tools and technologies into next generation structural designs.

Improvement in all these areas is critical to future missions. Since this focus area covers a broad area of interests, specific topics and subtopics are chosen to enhance and/or fill gaps in the space and exploration technology development programs, as well as to complement other mission directorate materials, manufacturing, structures, and in-space assembly needs.

H5.01 Lunar Surface 50 kW-Class Solar Array Structures (SBIR)

Lead Center: LaRC
Participating Center(s): GRC

Scope Title: Lunar Surface 50-kW-Class Solar Array Structures

Scope Description:
NASA intends to land near the lunar South Pole (at S latitudes ranging from 85° to 90°) by 2024 in Phase 1 of the Artemis Program, and then to establish a sustainable long-term presence by 2028 in Phase 2. At exactly the lunar South Pole (90 S), the Sun elevation angle varies between -1.5° and 1.5° during the year. At 85 S latitude, the elevation angle variation increases to between -6.5° and 6.5°. These persistently shallow sun grazing angles result in the interior of many polar craters never receiving sunlight while some nearby elevated ridges and plateaus receive sunlight up to 100% of the time in the summer and up to about 70% of the time in the winter. For this reason, these elevated sites are promising locations for human exploration and settlement because they avoid the 354-hr nights found elsewhere on the Moon while providing nearly continuous sunlight for site illumination, moderate temperatures, and solar power [Refs. 1-2].

Under a recently announced “Game Changing” project in NASA’s Space Technology Mission Directorate (STMD) named Vertical Solar Array Technology (VSAT), several firms are developing relocatable 10-kW vertical solar arrays for initial modular power generation at the lunar South Pole [Refs. 3-4]. These adaptable 10-kW arrays can be retracted and moved as needed to support evolving requirements for initial South Pole human occupation. Their relatively small size (35 m^2 of deployed area) allows them to be used individually or in combination to power loads up to a few tens of kilowatts. However, because the Sun is always near the horizon at lunar polar sites, using numerous small interconnected arrays for electrical power loads >>10 kW can result in excessive shadowing of one array onto another as well as considerable positioning, leveling, and deployment challenges when locating them at optimally illuminated locations.

This subtopic seeks structural and mechanical innovations for relocatable 50-kW-class (40- to 60-kW) lightweight solar arrays near the lunar South Pole for powering second-generation lunar base infrastructure including habitats and laboratories, rechargeable rovers, and in situ resource utilization (ISRU) mining and processing machines, and that can deploy and retract at least 5 times. Increasing the unit solar array size from first-generation 10 kW to second-generation ~50 kW is a logical course of action as power needs increase for new higher-power capabilities such as ISRU or the Foundation Surface Habitat, which can require >>10 kW of power. This increase in size by 5 times while maximizing specific power (>75 W/kg) needs structures and mechanisms innovations and development effort to ensure compact packaging, safe transportation in space and on the lunar surface, reliable deployment, stable operation while sun tracking, and retraction and relocation as needed. Small Business Innovation Research (SBIR) contracts provide important near-term investment to flesh out specific technical requirements and new technical challenges for these larger 50-kW-class solar arrays based on VSAT results for smaller 10-kW arrays and on assumed Design, Development, Test, and Evaluation (DDT&E) schedules.

These 50-kW-class solar arrays are listed in NASA’s HEOMD-405 Integrated Exploration Capabilities Gap List as tier 1 (highest impact) development gap #03-04 for which at least 1 potential solution has been identified, but additional work is required to ensure feasibility of the new and/or novel performance or function in a specific operational application [Ref. 5]. The largest similar lightweight solar array under development is the 30-kW “ROSA” wing for NASA’s Lunar Gateway, but it is considerably smaller than desired for second-generation lunar surface arrays, and it is not designed to retract or to survive the unique lunar gravity, insolation, and dust and terrain environments. Exploration Capabilities Gap #03-04 is described as “Medium-power solar array technology for human-rated missions with specific power (>75 W/kg) and operation in mission specific environment.”

Retraction will allow valuable solar array hardware to be relocated, repurposed, or refurbished and possibly also to minimize nearby rocket plume loads and dust accumulation. Also, innovations to raise the bottom of the solar array by up to 10 m above the surface to reduce shadowing from local terrain are required [Ref. 6]. The ability to be relocated is assumed to be through use of a separate surface-mobility system (i.e., not necessarily part of the solar array system), but design of array structures and mechanisms should accommodate loads likely to be encountered during transport along the lunar surface. Suitable innovations, variations, or combinations of existing 10-kW array components to these much larger 40- to 60-kW arrays including those being developed under the VSAT project are of special interest.

Design guidelines for these deployable/retractable solar arrays are:

- Deployed area: 140 m^2 (40 kW) initially; up to 210 m^2 (60 kW) eventually per unit, assuming state-of-the-art space solar cells.
- Single-axis Sun tracking about the vertical axis.
- Up to 10-m height extension boom to reduce shadowing from local terrain.
- Deployable, stable base for supporting tall vertical array on unprepared lunar surface.
- Base must accommodate a local 15° terrain slope with adjustable leveling to <0.5° of vertical.
- Retractable for relocating, repurposing, or refurbishing.
- Number of deploy/retract cycles in service: >5; stretch goal >10.
- Lunar dust, radiation, and temperature resistant components.
- Specific mass: >75 W/kg and specific packing volume: >20 kW/m^3, including all mechanical and electrical components.
- Factor of safety of 1.5 on all components.
- Lifetime: >10 years.

Suggested areas of innovation include:

- Novel packaging, deployment, retraction, and modularity concepts.
- Novel lightweight, compact components including booms, ribs, solar cell blankets, and mechanisms.
- Novel actuators for telescoping solar arrays such as gear/rack, piezoelectric, ratcheting, or rubber-wheel drive devices.
- Mechanisms with exceptionally high resistance to lunar dust.
- Load-limiting devices to avoid damage during deployment, retraction, and solar tracking.
- Methodology for stabilizing large vertical arrays such as compactly packageable support bases, using regolith as ballast mass, or novel guy wire and surface anchor systems.
- Optimized use of advanced lightweight materials, including composite materials with ultra-high modulus (>280 GPa) combined with low coefficient of thermal expansion (<0.1 m/m/°C).
- Integration of novel structural health monitoring technologies.
- Validated modeling, analysis, and simulation techniques.
- Modular and adaptable solar array concepts for multiple lunar surface use cases.
- Completely new concepts: e.g., thinned rigid panel or 3D-printed solar arrays, nonrotating telescoping “chimney” arrays, or lightweight reflectors to redirect sunlight onto solar arrays or into dark craters.

Proposals should emphasize structural and mechanical innovations, not photovoltaics, electrical, or energy storage innovations, although a complete solar array systems analysis is encouraged. If solar concentrators are proposed, strong arguments must be developed to justify why this approach is better from technical, cost, and risk points of view over unconcentrated planar solar arrays. Solar array concepts should be compatible with state-of-the-art solar cell technologies with documented environmental degradation properties. Design, build, and test of scaled flight hardware or functioning lab models to validate proposed innovations is of high interest.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.2 Structures

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
In Phase I, contractors should prove the feasibility of proposed innovations using suitable analyses and tests. In Phase II, significant hardware or software capabilities that can be tested at NASA should be developed to advance their TRL. TRLs at the end of Phase II of 4 or higher are desired.

State of the Art and Critical Gaps:
This subtopic addresses capability gap #03-04 in the 2021 HEOMD-405 Integrated Exploration Capabilities Gap List titled “50 kW class solar power generation systems.” Gap #03-04 is one of just three tier 1 (highest impact) capability gaps in the 03) Aerospace Power and Energy Storage category, and is considered to be a development gap for which at least one potential solution has been identified but additional work is required to ensure feasibility of the new and/or novel performance or function in a specific operational application.

Deployable solar arrays power almost all spacecraft, but they primarily consist of hinged, rigid panels. This traditional design is too heavy and packages too inefficiently for lunar surface power. Furthermore, there is usually no reason to retract the arrays in space, so self-retractable solar array concepts are unavailable except for rare exceptions such as the special-purpose International Space Station (ISS) solar array wings. In recent years, several lightweight solar array concepts have been developed but none of them have motorized retraction capability either. The critical technology gap filled by this subtopic is a lightweight, vertically deployed, retractable 50-kW-class (40- to 60-kW) solar array for surface electrical power near the lunar South Pole for diverse needs including ISRU, lunar bases, dedicated power landers, and rovers.

Relevance / Science Traceability:
Robust, lightweight, redeployable solar arrays for lunar surface applications are a topic of great current interest to NASA on its path back to the Moon. New this year, the subtopic extends the focus area from human landers to other powered elements of the lunar surface architecture along with refined design guidelines. There are likely several infusion paths into ongoing and future lunar surface programs, both within NASA and also with commercial entities currently exploring options for a variety of lunar surface missions. Given the focus on the lunar South Pole, NASA will need vertically deployed and retractable solar arrays that generate 10 to 20 kW of power for first-generation capabilities and 40 to 60 kW for second-generation capabilities.

References:

1. Burke, J., “Merits of a Lunar Pole Base Location,” in Lunar Bases and Space Activities of the 21st Century, Mendell, W. (editor), 1985, https://www.lpi.usra.edu/publications/books/lunar_bases/
2. Fincannon, J., “Characterization of Lunar Polar Illumination From a Power System Perspective,” NASA TM-2008-215186, May 2008, https://ntrs.nasa.gov/citations/20080045536.
3. NASA Space Tech News, “NASA, Industry to Mature Vertical Solar Array Technologies for Lunar Surface,” March 23, 2021, https://www.nasa.gov/feature/nasa-industry-to-mature-vertical-solar-array-technologies-for-lunar-surface.
4. Pappa, R. S., et al., “Relocatable 10 kW Solar Array for Lunar South Pole Missions,” NASA-TM-20210011743, March 2021, https://ntrs.nasa.gov/citations/20210011743.
5. NASA Human Exploration & Operations, Systems Engineering and Integration, HEOMD-405 Version 1, “2021 Integrated Exploration Capabilities Gap List,” March 19, 2021.
6. Mazarico, E. et al., “Illumination Conditions of the Lunar Polar Regions Using LOLA Topography,” Icarus, February 2011, https://doi.org/10.1016/j.icarus.2010.10.030.

H5.05 Inflatable Softgoods for Next Generation Habitation Systems (SBIR)

Lead Center: MSFC

Participating Center(s): JSC, LaRC

Scope Title: Inflatable Softgoods for Next Generation Habitation Systems: Testing and Structural Health Monitoring

Scope Description:
A key enabling technology for future crewed habitation systems is the development of inflatable softgoods materials and structures. In the past, habitat structures have typically consisted of metal alloys, but larger habitable volumes with lower structural mass will be required for long-duration, exploration-class missions. This subtopic seeks activities to mature inflatable softgoods through integration of sensing capabilities for structural health monitoring (SHM) and development of accelerated testing techniques.

Activities that may be undertaken under a Phase I effort include:

Development of approaches for accelerated materials creep testing, specifically for high-strength materials in inflatable softgoods such as webbings and cords. In implementing these materials in habitation structures, one long-term risk is failure of the structural material due to creep (deformation under sustained loading). Real-time creep testing at the component and subscale levels can take years and new test methods need to be developed to help certify softgoods for flight in their intended use environment. Approaches may include novel test methods to reduce the duration of the test (while still generating meaningful data relative to long term use of a material system in its environment) and/or a combination of test methods and modeling approaches to accelerate generation and capture of relevant lifetime material data. Development of new approaches will help to increase testing throughput and mitigate potentially catastrophic risks in failure of inflatable materials.

Scope of work includes:

- Develop a methodology and test approach that can be validated to produce accurate predicted lifetime creep strain data and time-to-failure (TTF) for high-strength softgoods over a range of percent creep loads (50~90% nominally) within a year. (Within 1 to 3 months would be preferable).
    - "High strength" refers to webbings and cordage of strength nominally in the range 5,000 to 20,000 lbs/in.
- Produce master creep curves for each percent load and failure points.

The second focus area is integrated SHM. Integrated sensing capabilities in inflatable softgoods material systems are needed to monitor the structural performance of the material in situ, measure load/strain on softgoods components, detect damage, and predict further degradation/potential failures. The ability to acquire, process, and make use of this data in real time is an important risk mitigation for potential structural failure modes. The current state of the art in this field are instrumentation systems such as high-resolution strain gauges, fiber optics, accelerometers, and acoustic sensors using flexible electronics. However, there is a technology gap in developing a proven system that can integrate into a softgoods material system and continually monitor performance through its life. For this activity, integration of a system as a proof of concept and preliminary testing on an integrated inflatable softgoods structure are expected as part of the Phase I.

Scope of work includes:

- Develop robust/repeatable integration approach with high-strength softgoods during manufacture or afterwards, that minimizes impact on the performance of the softgoods.
- Develop sensor(s) that are robust to packaging/deployment/handling of the softgoods they are integrated into.
- Repeatable performance and high-accuracy strain measurement (creep strain is typically 0.1 ~ 0.5%) once deployed and over the lifespan of the inflatable module.
- Sensor(s) are inherently able to (or have a defined path to) survive the extreme environment of space.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.2 Structures

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Phase I: Depending on the activity the proposer chooses to focus on, a Phase I effort would result in:

1. Development of accelerated creep test methods for inflatable softgoods at the component level and a laboratory proof of concept.
2. Approach to SHM for inflatable softgoods, a laboratory proof of concept of efficacy of approach, and/or preliminary design, which integrates the SHM approach into test articles.

Phase II: Depending on the activity the proposer chooses to focus on, a Phase II effort would result in:

1. Implementation of accelerated testing methods for evaluation of material creep and comparison with traditional (real-time) testing approaches at the component level.
2. Integration of SHM approach into inflatable softgoods components or subscale inflatable softgoods prototype and preliminary testing under load.

State of the Art and Critical Gaps:
Development of approaches for accelerated materials creep testing. Current state of the art for testing uses straps for real-time creep testing at the component level and subscale (or full-scale) inflatable softgoods test articles for (a) burst and (b) creep-to-burst testing. These tests are needed to understand the behavior of the inflatable softgoods over the mission lifetime and predict failure due to creep, which represents a catastrophic risk. Real-time testing takes months to years to collect data (depending on load level) and predictions require extrapolation from a limited number of data points. Accelerated testing techniques would enable higher fidelity characterization of the performance of the inflatable softgoods system over the entire mission scenario prior to flight and reduce risk.

Integrated SHM. Approaches for SHM in inflatable softgoods are needed to track the performance of the material system in real-time and identify when the structure has incurred damage or is at risk of failure. SHM typically uses strain gauges, digital image correlation, or accelerometers. SHM for inflatable softgoods requires novel approaches, as the material system is multilayer and fundamentally different from many other habitat structures. New techniques, such as flexile electronics, wireless systems, and fiber optics, are also generally unproven in a flight scenario for SHM.

Relevance / Science Traceability:
Technology for inflatable softgoods has historically been developed under Human Exploration Operations Mission Directorate (HEOMD) and Advanced Exploration Systems (AES). Current work on inflatable softgoods is under NASA's Next Space Technologies for Exploration Partnerships (NextSTEP) A: Habitation Systems Broad Agency Announcement opportunity, which has been ongoing since 2016 and focuses on design of next-generation habitat systems for cislunar space, the lunar surface, and Mars transit scenarios. The work under this subtopic will strongly complement ongoing work under the NextSTEP habitat project and increase the potential for the infusion of inflatable softgoods into future habitation concepts by reducing risk associated with understanding and predicting material behavior.

References:

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2. Valle, Gerard, Doug Littiken, and Tom Jones. "Review of Habitable Softgoods Inflatable Design, Analysis, Testing and Potential Space Applications." AIAA SciTech. January 2019.
3. Littiken, Doug. "Inflatable technology: using flexible materials to make large structures." Proceedings of Electroactive Polymer Actuators and Devices. 13 March 2019. https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10966/1096603/Inflatable-technology-using-flexible-materials-to-make-large-structures/10.1117/12.2500091.full?SSO=1
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Z4.05 Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis (SBIR)

Lead Center: LaRC
Participating Center(s): GSFC, MSFC

Scope Title: Nondestructive Evaluation (NDE) for In-Space and Additively Manufactured Materials/Structures

Scope Description:
NASA's NDE SBIR subtopic will address a wide variety of NDE disciplines with a focus on in-space inspection. This SBIR solicitation will focus on aerospace structures and materials systems, including but not limited to Inconel, titanium, aluminum, carbon fiber, Avcoat, Alumina Enhanced Thermal Barrier (AETB), Phenolic Impregnated Carbon Ablator (PICA), and thermal blanket structures. Development efforts should target any set of these materials in common aerospace configurations, such as micrometeoroid and orbital debris (MMOD) shielding, truss structures, and stiffened structures. NDE can target material and material systems in a wrought state or additive manufacturing (AM). In-process or postproduction NDE techniques that could be used to inspect additively manufactured components will be favored. As NASA strives for longer duration space missions, these new tools need to be developed to support in-space manufacturing and assembly.

NDE Sensors and Data Analysis:

Technologies enabling the ability to perform automated inspections on large or complex structures are encouraged. Technologies should provide reliable rapid assessments of the location and extent of damage or defects. Methods are desired to perform inspections in areas with difficult access in pressurized habitable compartments and external environments for flight hardware. Many applications require the ability to see through assembled conductive and/or thermal insulating materials without contacting the surface.

Techniques that can dynamically and accurately determine position and orientation of the NDE sensor are needed to register NDE results to precise locations on the structure with little to no human intervention. Advanced processing and displays are needed to reduce the complexity of operation and interpretation for astronaut crews who need to make important assessments quickly. NDE inspection sensors are needed for potential use on free-flying inspection platforms. Integration of wireless systems with NDE may be of significant utility. It is strongly encouraged that proposals provide an explanation of how the proposed techniques and sensors will be applied to a complex structure. Examples of structural components include but are not limited to multiwall pressure vessels, batteries, tile, thermal blankets, micrometeoroid shielding, International Space Station (ISS) radiators, or aerospace structural components, including the lunar gateway.

Additionally, techniques for quantitative analysis of sensor data are desired. It is also considered highly desirable to develop tools for automating detection of material foreign object debris (FOD) such as lunar dust and/or defects and evaluation of bondline and in-depth integrity for ablative materials, like a heat shield. Typical internal void volume detection requirements for ablative materials are on the order of less than 6 mm, and bondline defect detection requirements are less than 25 mm.

Additive manufacturing is rapidly becoming a manufacturing method capable of producing fracture-critical components; as such, NDE requirements will become more stringent. Additively manufactured components represent a novel challenge for NDE due to the layering nature of the process and its effect on diffracting energy sources. Development of NDE techniques, sensors, and methods addressing these issues would be highly desired. Additionally, in situ inspection systems that support assessment of AM builds will be considered desirable. Most of the aerospace components will be metallic in nature, and critical flaws can be volumetric or fracture-like in nature.

In-Space Inspection:

Technologies sought under this SBIR include those related to in-space NDE. This includes on-orbit NDE (e.g., ISS or Gateway) as well as for future lunar, Mars, or other planetary missions. This could include new NDE tools for astronauts to use in a habitat or in the space environment (i.e., on an extravehicular activity (EVA)) or for automated inspection. Technologies may include fully functional NDE tools developed based on ground-use/laboratory equipment. Consideration will also be given to particularly promising technologies that may not provide turnkey operation but enable the advancement of future NDE inspection capabilities in space (i.e., enabling technologies). Fully functional NDE “tool” designs must address considerations related to size, mass, power, safety, environment, operation and/or automation, and data transfer related to their proposed application. For example, an NDE tool designed for ISS must ultimately be able to meet (after final development) ISS design requirements, launch mass/payload limitations, operational guidelines for crew, etc. If no specific application is outlined in the design, or if the proposal is for development of an enabling technology, then consideration must still be given to system size, mass, power, and data rate, to the extent that it makes the technology feasible in the within the next decade. To that end, consideration may be given to technology developments that are specifically focused on minimizing (or optimizing) these system parameters (e.g., low-mass, compact microfocus x-ray sources).

This solicitation is aimed at technologies for conventional NDE inspection of relevant components in space, meaning detection of commonly known defects in materials (cracks, pores, delamination, FOD, impact damage, etc.), rather than analytical tools aimed at determining chemistry, composition, or other properties of materials. Relevant components to be inspected may include (but are not limited to) spaceflight hardware, protective gear, core/rock samples, structural components, electronics/wiring, pressure vessels, thermal protection systems, etc. Of particular interest are technologies that advance the inspection of AM parts in space. These parts may be manufactured in an AM cabinet system that fits in an ISS EXPRESS (EXpedite the PRocessing of Experiments for Space Station) rack, which results in parts on the scale of 6 in. AM technologies used in such a payload could include fused deposition modeling, bound metal deposition, wire arc additive manufacturing, or other technologies using wire feedstock. Large-scale space structures may be manufactured or assembled in the space environment using AM techniques. Inspection technologies may involve x-ray technology (such as computed tomography), ultrasonic imaging, thermography, or any other NDE methods adapted for space use. NDE tools or enabling technologies that are compact, easy to carry (by astronauts), and work on low or accessible power will be considered.

Expected TRL or TRL Range at completion of the Project: 1 to 6

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I Deliverables: For proposals focusing on NDE sensors: Lab prototype and feasibility study or software package, including applicable data or observation of a measurable phenomenon on which the prototype will be built. For proposals focusing on NDE modeling: Feasibility study, including demonstration simulations and data interpretation algorithms, proving the proposed approach to develop a given product (Technology Readiness Level (TRL) 2 to 4). Inclusion of a proposed approach to develop a given methodology to a TRL of 2 to 4. All Phase I proposals will include minimum of short description for Phase II prototype/software. It will be highly favorable to include a description of how the Phase II prototype or methodology will be applied to structures.

Phase II Deliverables: Working prototype or software of proposed product, along with full report of development, validation, and test results. Prototype or software of proposed product should be of TRL 5 to 6. Proposal should include plan of how to apply prototype or software on applicable structure or material system. Opportunities and plans should also be identified and summarized for potential commercialization.

State of the Art and Critical Gaps:

NASA and the SBIR program are preparing for the next phase of human deep space flight. As such, much of the materials, structures, and subsystem will have to be built or assembled in space. Quantitative and qualitative inspection of these components and structures will be critical to ensure safe spaceflight. Additionally, NDE sensors will be used to determine the health of structures as they age in space.

Relevance / Science Traceability:

Several missions could benefit from technology developed in the area of NDE. Currently, NASA is returning to manned spaceflight. The Artemis program's Orion spacecraft and Space Launch System have had inspection difficulties, and continued development and implementation of NDE tools will serve to keep our missions flying safely. Currently, Orion is using several techniques and prototypes that have been produced under the NDE SBIR topic. The Space Launch System is NASA’s next heavy-lift system, capable of sending hundreds of metric tons into orbit. Inspection of the various systems is ongoing and will continue to have challenges, such as verification of the friction stir weld on the fuel tanks. As NASA continues to push into deeper space, smart structures that are instrumented with structural health monitoring (SHM) systems can provide real-time mission-critical information on the status of the structure. NDE of spaceflight hardware and parts manufactured in space will be key enabling technologies for constant crew presence and long-duration missions.

References:

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2. Burke, E. R.; and Waller, J.: NASA-ESA-JAXA Additive Manufacturing Trilateral Collaboration. Presented at Trilateral Safety and Mission Assurance Conference (TRISMAC), June 4-6, 2018, Kennedy Space Center, Florida.
3. Campbell Leckey, C. A.; Juarez, P. D.; Hernando Quintanilla, F.; and Yu, L.: Lessons from Ultrasonic NDE Model Development. Presented at 26th ASNT Research Symposium 2017, March 13-16, 2017, Jacksonville, Florida.
4. Campbell Leckey, C. A.: Material State Awareness: Options to Address Challenges with UT. Presented at World Federation of NDE Centers Short Course 2017, July 15-16, 2017, Provo, Utah.

5. Campbell Leckey, C. A.; Hernando Quintanilla, F.; and Cole, C.: Numerically Stable Finite Difference Simulation for Ultrasonic NDE in Anisotropic Composites. Presented at 44th Annual Review of Progress in Quantitative Nondestructive Evaluation, July 16-21, 2017, Provo, Utah.
6. Cramer, K. E.; and Klaassen, R.: Developments in Advanced Inspection Methods for Composites Under the NASA Advanced Composites Project. Presented at GE Monthly Seminar Series, April 13, 2017, Cincinnati, Ohio.
7. Cramer, K. E.; and Perey, D. F.: Development and Validation of NDE Standards for NASA's Advanced Composites Project. Presented at ASNT Annual Conference, October 30-November 2, 2017, Nashville, Tennessee.
8. Cramer, K. E.: Current and Future Needs and Research for Composite Materials NDE. Presented at SPIE Smart Structures and NDE 2018, March 4-8, 2018, Denver, Colorado.
9. Cramer, K. E.: Research Developments in Non-Invasive Measurement Systems for Aerospace Composite Structures at NASA. Presented at 2018 International Instrumentation and Measurement Technology Conference, May 14-18, 2018, Houston, Texas.
10. Dehaven, S. L.; Wincheski, R. A.; and Burke, E. R.: X-ray Transmission Through Microstructured Optical Fiber. Presented at QNDE - Review of Progress in Quantitative NDE, July 17-21, 2017, Provo, Utah.
11. Dehaven, S. L.; Wincheski, R. A.; and Burke, E. R.: X-ray Transmission Through Microstructured Optical Fiber. Presented at 45th Annual Review of Progress in Quantitative Nondestructive Evaluation (QNDE), July 15-19, 2018, Burlington, Vermont.
12. Frankforter, E.; Campbell Leckey, C. A.; and Schneck, W. C.: Finite Difference Simulation of Ultrasonic Waves for Complex Composite Laminates. Presented at QNDE 2018, July 15-19, 2018, Burlington, Vermont.
13. Gregory, E. D.; and Juarez, P. D.: In-situ Thermography of Automated Fiber Placement Parts: Review of Progress in Quantitative Nondestructive Evaluation. Presented at QNDE - Review of Progress in Quantitative NDE, July 17-21, 2017, Provo, Utah.
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Z4.07 Advanced Materials and Manufacturing for In-Space Operations (SBIR)

Lead Center: LaRC
Participating Center(s): MSFC

Scope Title: Manufacturing of Materials from Lunar Surface Resources

Scope Description:
As humanity embarks on sustained deep space exploration, starting with the lunar surface, there will be a need for building infrastructure that is based on indigenous resources [1]. Usage of these resources will face limitations that include the available source materials, equipment, and power. Therefore, materials processing and manufacturing approaches are required that are operable within these constraints.

Operations on the lunar surface must consider types of materials available as well as their abundance. Various in situ resource utilization (ISRU) efforts are ongoing to extract and process the raw materials into usable forms. These include some SBIR topics that the prospective proposer is encouraged to investigate. Elements available for extraction from regolith include oxygen, silicon, iron, calcium, aluminum, magnesium, and titanium. From these, and from other materials that may be available in smaller quantities, manufacturing methods are needed to produce components for construction and for the building, replication, and repair of equipment.

Proposals are invited for approaches that utilize the resources available on the Moon to be able to produce structural girders, beams, and pipes that can withstand both tensile and bending forces. These are required in addition to compacted cementitious and sintered materials that can carry mostly compressive loads.

Concepts can include, but are not limited to, production using various metallic materials as well as basalt-fiber-reinforced geopolymers and other combinations that can be produced from lunar resources. Manufacturing methods that capitalize on the lunar environment are of particular interest.

The selection of the material system must consider the potential availability on the lunar surface and a demonstrated or projected ability to support tensile and bending loads. For example, proposed work may include an analysis of lunar material properties and processing methods that yield the required performance characteristics for relevant structures. An example beam would be a structural component for a crane with a 25-ft reach that can support one metric ton (2,200 lb) in lunar gravity. Proposers are pointed to the references provided [2-6] as well as ongoing ISRU activities for the latest and detailed information on the potential availability of various materials on the Moon.

Proposals to the current solicitation can assume the materials extracted and processed in the ISRU activities to be available and ready to use at levels of purity that range from as-dug regolith to separated and refined metals. The quantities available will depend on the lunar abundance of the materials and the effort needed for the processing. As-dug regolith can be expected to be available in large amounts; more refined materials can be expected to be available in quantities that decrease with the level of refinement and the requirements for that refinement, such as energy and any Earth-sourced ingredients.

Proposal elements of interest include but are not limited to:

- Material concepts that can utilize various purities of feedstocks, e.g., concepts that might be able to use a metal at less than 100% purity.
- Manufacturing processes that can take advantage of the lunar environment, such as vacuum, radiation, reduced gravity, etc.
- Equipment required for the manufacturing, including the size scale, power requirements, production rates, and operating environments.
- Preliminary proof-of-concept experiments for feasibility of the proposed material systems, processing methods, and equipment.

Expected TRL or TRL Range at completion of the Project: 4 to 5

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.X Other Manufacturing, Materials, and Structures

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Phase I: Define the material system to be used for manufacturing of relevant components, the processes required, and the equipment needed to process that material. Provide one or more material systems, manufacturing processes, and equipment design concepts for the production of tensile- and bending-force-supporting components on the lunar surface using resources available from ISRU extraction and beneficiation activities. The concept will include analysis of how the material system(s) is/are able to meet the load-carrying requirements and the manufacturing parameters, and how the equipment that is required utilizes/succeeds in operating in the lunar environment.

Phase II would look at scaled/laboratory demonstrations of the material system(s), manufacturing processes, and equipment. These would include designing and building of relevant equipment and potential processing of commercially available regolith simulants or other materials that may match the materials expected to be available on the Moon, either in raw form or from other processes. Test coupons must be built and tested using as close an analog as possible of the lunar material system and a prototype of the proposed manufacturing equipment. Documentation of requirements for the manufacturing process and operation of the equipment, such as power and mass that can be used to evaluate feasibility in trade studies, shall be included.

State of the Art and Critical Gaps:
Sustainable long-term exploration of the Moon will be dependent on the utilization of lunar resources. While various efforts are looking at the excavation and extraction of those resources, there are currently gaps in manufacturing of the material feedstocks that may be available on the Moon into other useful products. Addressing these gaps requires understanding of the fabrication equipment and the full manufacturing cycle as well as the expected impact when the processes are run on the Moon.

Relevance / Science Traceability:
The Artemis program envisions the start of a long-term human presence on the lunar surface for the exploration and development of the Moon by Government as well as commercial companies and international partners. In order to support these missions, it will be essential to utilize resources that can be sourced from the lunar surface. The current solicitation calls for proposals that provide the support for these exploration and development activities. Technologies that are developed in this solicitation may also feature on preparatory missions for Artemis, such as the Commercial Lunar Payload Services Programs, depending on the readiness of the technology.

References:

1. NASA’s Plan for Sustained Lunar Exploration and Development. https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf [accessed 07/23/2021].
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3. R. D. Waldron. Lunar Manufacturing: A Survey of Products and Processes. Acta Astronautica. 1988; 17(7):691-708.
4. Dave Dietzler. Making It on the Moon: Bootstrapping Lunar Industry. NSS Space Settlement Journal, September 2016. https://space.nss.org/wp-content/uploads/NSS-JOURNAL-Bootstrapping-Lunar-Industry-2016.pdf [accessed 07/22/21].
5. I. A. Crawford. Lunar Resources: A Review. Progress in Physical Geography: Earth and Environment. 2015; 39(2):137-167.
6. United States Geological Survey (USGS). Unified Geologic Map of the Moon. https://astrogeology.usgs.gov/search/map/Moon/Geology/Unified_Geologic_Map_of_the_Moon_GIS_v2 [accessed 07/23/2021].

Scope Title: Welding Testbed for Space Manufacturing

Scope Description:
Technology development efforts are required to enable on-orbit servicing, assembly, and manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets.

An in-space material welding capability is an important supporting technology for the long-duration, long-endurance space missions that NASA will undertake beyond the International Space Station (ISS). Historically, structures in space have been assembled using mechanical fastening techniques and modular assembly. Structural designs for crewed habitats, space telescopes, antennas, and solar array reflectors are primarily driven by launch considerations such as payload fairing dimensions and vibrational loads experienced during ascent. An in-space welding capability will greatly reduce constraints on the system imposed by launch, enabling the construction of larger, more complex, and more optimized structures. Welding is an essential complementary capability to large-scale additive manufacturing technologies being developed by NASA and commercial partners. Welding is also a critical capability for repair scenarios (e.g., repair of damage to a structure from micrometeorite impacts).

The development of welding processes for a variety of materials and thicknesses is carried out via a welding destructive testing and nondestructive testing feedback loop. This ensures that a weld procedure is well understood and that it produces welds that have sufficient material properties for their end-use application. While weld procedures are developed on the ground in simulated space environments, it is also necessary to further develop and validate these procedures in the true space environment where they will be applied. To achieve this need, a fully autonomous welding testbed must be created and deployed in space.

This subtopic seeks innovative engineering solutions—both fully autonomous and semiautonomous—to robotically weld materials for manufacturing in the unpressurized space environment. Current state-of-the-art (SOA) terrestrial welding methods such as laser beam, electron beam, and friction stir should be modified with an effort to reduce the footprint, mass, and power requirements for on-orbit applications.

Targeted applications for this technology include joining and repair of components at the subsystem level, habitat modules, trusses, solar arrays, and/or antenna reflectors. The need to repair a damaged structure or build new structures may require the need to not only weld material but to cut and remove material. A process that can weld material is the priority, but a robust process with cutting, removal, and testing capabilities adds value.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.4 Manufacturing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I is a feasibility study and laboratory proof of concept of a robotic welding process and system for on-orbit manufacturing applications. The Phase I effort should provide a laboratory demonstration of the welding process and its applicability to aerospace-grade metallic materials and/or thermoplastics, focusing on joint configurations that represent the priority in-space joining applications identified above. Work under Phase I will inform preliminary design of a mobile welding unit and/or in-space welding testbed. It will also inform a concept of operations for how the system would be deployed and operate in the space environment, with a focus on specific scenarios—for example, repair of a metal panel following micrometeorite damage, longitudinal welding of two metal curved panels, and welding of a truss to an adjacent truss. The Phase I effort should also provide an assessment of the proposed process operational capabilities (e.g., classes of materials that can be welded with the process, joint configurations that can be accommodated, and any expected

impacts of the microgravity environment on joint efficiency relative to terrestrial system operation), volume, and power budget. A preliminary design and concept of operations are also deliverables under Phase I. Concepts for ancillary technologies such as postprocess inspection, in situ monitoring, mechanical testing, or robotic arms for manipulation of structures to be welded may also be included in the Phase I effort.

Development of a prototype with detailed analysis, initial testing, and associated software is desired for Phase I.

Phase II should further develop the prototype from Phase I and provide substantial test data using the prototype in an environment similar to the end application.

State of the Art and Critical Gaps:
A clear demonstrated understanding of the SOA is required. Any proposed technologies should not replicate the SOA and should instead advance the SOA or create an entirely different approach from the SOA. Welding in space has a multitude of applications, from repair to manufacturing, and is necessary to ensure a sustainable human presence in space. The development of space welding technologies is a substantial undertaking and requires years to perfect, so it is of the utmost importance that this process begins now. A welding testbed in space is an integral part of gaining weld property feedback data in an autonomous manner in a high-fidelity environment. The current SOA requires further advancement, and the growth of small business in the field of space welding is the best route to ensure that technological development is unique and that an array of technology providers exists in the future space economy.

Relevance / Science Traceability:
Space welding is necessary for the future sustainability of the space economy. To both build and repair structures in space, on the lunar surface, or on Mars, welding is a valuable tool that will provide agility for astronauts in a location where resources are highly limited. The development of space welding is a significant undertaking, so early development must begin now. The development of systems to autonomously weld structures in space and the ability to develop welding parameters through a closed-feedback-loop space testbed are both required to ensure that welding may be sufficiently applied in space.

References:

1. Tracie Prater et al. Overview of the In-Space Manufacturing Technology Portfolio. 2019. https://ntrs.nasa.gov/api/citations/20190030353/downloads/20190030353.pdf
2. Leigh M. Elrod et al. ISM In-Space Manufacturing. 2019. https://ntrs.nasa.gov/citations/20190033503

Z14.02 Extraterrestrial Surface Construction (SBIR)

Lead Center: MSFC
Participating Center(s): KSC, LaRC

Scope Title: Extraterrestrial Surface Construction

Scope Description:
Lunar and Martian construction of infrastructure from extraterrestrial materials and materials beneficiated or produced from in situ resources has the potential to radically reduce the cost and increase the scale of ambitious future space exploration. Technologies that support development of infrastructure structural elements are sought. Innovative materials and processes technology advancements are required to enable rapid advancement of a lunar or Martian village in a cost-effective manner.

Specific areas of technology development that are of interest include, but are not limited to, the following:

1. Construction technologies shall be based on the use of extraterrestrial materials and limit the need for any terrestrial materials. Development of lunar-construction-relevant materials and processes for infrastructure elements listed in point 2 below are highly encouraged.
   - Materials must have a defined application in a mission context.
   - Proposers are asked to define any consumable materials that must be brought from Earth for construction.

2. Fabrication and assembly of pressurized and unpressurized structural systems, including (for example) landing/launch pads, roads, blast shields, and habitats.
   - Both stationary and mobile fabrication/assembly systems shall be considered.
   - Novel fabrication and assembly methodologies shall be considered.
     - Low-power methods and methods that benefit from the extraterrestrial surface environment are desired.

Technology development shall include design, analysis, fabrication, and testing of components, subsystems, and materials to enable full assessment and accountability of the technology product and fundamental findings with respect to their value toward reaching NASA's goals. Existing design and nondestructive evaluation (NDE) techniques are expected to be used when applicable. A relevant commercially available extraterrestrial simulant that mimics the silicate and oxide minerals in regolith and/or the volatiles in the lunar permanently shadowed regions or Martian surface and atmosphere is expected to be used for structure construction. Lunar materials, components, and systems that would be necessary for the proposed technology must be able to operate on the lunar surface (with thermal mitigations) in temperatures up to 110 °C (230 °F) during sunlit periods and as low as -170 °C (-274 °F) during periods of darkness. Martian materials, components, and systems must be able to operate on the Martian surface in a CO_2-rich atmosphere (with thermal mitigations, if necessary) in temperatures up to 20 °C (70 °F) and as low as -153°C (-225 °F). Systems must also be able to operate for at least 1 year with a goal of 5 years without substantial maintenance in the dusty regolith environment. Proposers should assume that operations involving other systems (e.g., robotics) and future astronauts will be ongoing not more than tens of meters away from the local fabrication and construction activities (i.e., minimization of dust generation is expected).

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.X Other Manufacturing, Materials, and Structures

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I deliverables may be a conceptual design with analysis to show feasibility at relevant scales and/or a small demonstration of the concept.

Phase II deliverables should be hardware demonstrations at a relevant scale.

State of the Art and Critical Gaps:
Planetary surface construction is not a current capability. The state of the art is terrestrial-based construction technology, e.g., cement, wood, and steel forms and terrestrial additive construction.

Relevance / Science Traceability:

The work desired applies to Technology Taxonomy (TX) Area 7: Exploration Destination Systems. It applies to 2018 NASA Strategic Plan Strategic Goal 2: Extend Human Presence Deeper into Space and to the Moon for Sustainable Long-Term Exploration and Utilization. It also applies to the Plan’s Strategic Objective 3.1: Develop and Transfer Revolutionary Technologies to Enable Exploration Capabilities for NASA and the Nation.

References:

1. Werkheiser, M. J., Fiske, M., Edmunson, J., & Khoshnevis, B. (2015). On the Development of Additive Construction Technologies for Application to Development of Lunar/Martian Surface Structures Using In-Situ Materials. In AIAA SPACE 2015 conference and exposition (p. 4451).
2. Moses, R. W., & Mueller, R. P. (2021). Requirements Development Framework for Lunar In Situ Surface Construction of Infrastructure. Earth and Space 2021 (pp. 1141-1155).
3. Gelino, N. J., Mueller, R. P., Moses, R. W., Mantovani, J. G., Metzger, P. T., Buckles, B. C., & Sibille, L. (2020). Off Earth Landing and Launch Pad Construction—A Critical Technology for Establishing a Long-Term Presence on Extraterrestrial Surfaces. Earth and Space 2021 (pp. 855-869).
4. Mueller, R. P., Fikes, J. C., Case, M. P., Khoshnevis, B., Fiske, M. R., Edmunson, J. E., ... & Andersen, C. (September 2017). Additive Construction with Mobile Emplacement (ACME). In 68th International Astronautical Congress (IAC), Adelaide, Australia (pp. 25-29).
5. Edmunson, J., Fiske, M., Alkhateb, H., Johnston, M., & Fikes, J. (2016). Additive Construction with Mobile Emplacement: Planetary.

Focus Area 16 Ground & Launch Processing

Ground processing technology development prepares the agency to test, process, launch, and recover the next generation of rockets and spacecraft in support of NASA's exploration objectives by developing the necessary ground systems, infrastructure and operational approaches for terrestrial and off-planet surface systems.

This topic seeks innovative concepts and solutions for both addressing long-term ground processing and test complex operational challenges and driving down the cost of government and commercial access to space. Technology infusion and optimization of existing and future operational programs, while concurrently maintaining continued operations, are paramount for cost effectiveness, safety assurance, and supportability.

A key aspect of NASA's approach to long term sustainability and affordability is to make test, processing and launch infrastructure available to commercial and other government entities, thereby distributing the fixed cost burden among multiple users and reducing the cost of access to space for the United States.

Unlike previous work focusing on a single kind of launch vehicle such as the Saturn V rocket or the Space Shuttle, NASA is preparing common infrastructure to support several different kinds of spacecraft and rockets that are in development. Products and systems devised at a NASA center could be used at other launch sites on earth and eventually on other planets or moons.

Specific emphasis to substantially reduce the costs and improve safety/reliability of NASA's test and launch operations includes development of ground test and launch environment technology components, system level ground test systems for advanced propulsion, autonomous control technologies for fault detection, isolation, and recovery, including autonomous propellant management, and advanced instrumentation technologies including Intelligent wireless sensor systems.

H10.01 Advanced Propulsion Systems Ground Test Technology (SBIR)

Lead Center: SSC

Participating Center(s): KSC

Scope Title: Advanced Propulsion Test Technology Development

Scope Description:
Rocket propulsion development is enabled by rigorous ground testing to mitigate the propulsion system risks that are inherent in spaceflight. This is true for virtually all propulsive devices of a space vehicle including liquid and solid rocket propulsion, chemical and nonchemical propulsion, boost stage, in-space propulsion, and so forth. It involves a combination of component and engine-level testing to demonstrate the propulsion devices were designed to meet the specified requirements for a specified operational envelope over robust margins and shown to be sufficiently reliable prior to its first flight.

This topic area seeks to develop advanced ground test technology components and system-level ground test systems that enhance chemical and advanced propulsion technology development and certification. The goal is to advance propulsion ground test technologies to enhance environment simulation; minimize test program time, cost, and risk; and meet existing environmental and safety regulations. It is focused on near-term products that augment and enhance proven, state-of-the-art propulsion test facilities. This project is especially interested in ground test and launch environment technologies with potential to substantially reduce the costs and improve safety/reliability of NASA's test and launch operations.

In particular, current technology needs include advanced computational simulation capabilities for robust and rapid modeling of large-scale high-speed chemical reacting multiphase flows, and advanced instruments and monitoring systems capable of operating in those extreme temperature and harsh environments. For example, this might include applications such as launch or test stand rocket plume deflectors which involve shock-laden rocket exhaust plumes impinging and mixing with water sprays and pools.

This subtopic seeks innovative technologies in the following areas:

- Development of innovative rocket test facility components (e.g., valves, flowmeters, actuators, tanks, etc.) for ultra-high pressure (>8,000 psi), high flow rate (>100 lbm/sec), and cryogenic environments.
- Robust and reliable component designs that are oxygen compatible and can operate efficiently in high-vibroacoustic environments.
- Computational tools which can robustly, accurately, and efficiently capture unsteady sharp gradients in rocket flows such as propagating shock and blast waves, free surfaces at liquid/gas interfaces, etc. Specifically, new nondissipative flux techniques to fully eliminate the carbuncle phenomena that occur in Roe/HLLE-based schemes is of interest (numerical routines to solve governing fluid equations). In addition, more efficient and novel adaptive meshing techniques for unsteady, large-scale applications is desired.
- Improved capabilities to predict and model the behavior of components (valves, check valves, chokes, etc.) during the facility design process are needed. This capability is required for modeling components in high pressure (to 12,000 psi), with flow rates up to several thousand pounds per second, in cryogenic environments and must address two-phase flows. Challenges include accurate, efficient, thermodynamic state models; cavitation models for propellant tanks, valve flows, and run lines; reduction in solution time; improved stability; acoustic interactions; and fluid-structure interactions in internal flows.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 13 Ground, Test, and Surface Systems
Level 2: TX 13.1 Infrastructure Optimization

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

- Software

Desired Deliverables Description:
For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I as a final report and show a path toward Phase II hardware/software demonstration, with delivery of a demonstration unit or software package for NASA testing at the completion of the Phase II contract.

State of the Art and Critical Gaps:
This subtopic seeks to provide technological advances that provide the ability to test next generation rocket propulsion systems while reducing costs, increasing efficiencies, and improving safety/reliability within the static rocket engine test environment. Specifically, the goal is to reduce costs of propellants and other fluids, reduce logistics costs, reduce times required for ground processing and launch, reduce mission risk, and reduce hazards exposure to personnel.

There is a broad range of technologies needed to support rocket propulsion testing. Dynamic fluid flow simulation is used to characterize and model the facility performance in a highly dynamic environment with NASA, Department of Defense (DOD), and commercial customers. Multiple issues remain with modeling combustion instabilities and component/facility performance. These issues can have catastrophic results if not understood completely. New test programs will require the materials to withstand extreme temperatures and harsh environments. Next-generation testing requires the ability to produce very high-temperature hydrogen at high near-continuous flow rates to verify component and facility performance. The extreme and harsh environment also requires advancements in mechanical components and instrumentation.

Relevance / Science Traceability:
This subtopic is relevant to the development of liquid propulsion systems development and verification testing in support of the Human Exploration and Mission Operations Directorate (HEOMD), all test programs at Stennis Space Center (SSC), and other propulsion system development centers.

References:

1. https://www.nasa.gov/centers/stennis/home/index.html
2. https://technology.ssc.nasa.gov/
3. CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences - NASA Technical Reports Server (NTRS)

H10.02 Autonomous Operations Technologies for Ground and Launch Systems (SBIR)

Lead Center: KSC
Participating Center(s): ARC, LaRC, SSC

Scope Title: Autonomous Operations Technologies for Ground and Launch Systems

Scope Description:
For the scope of this solicitation, ground systems are considered to be the planetary or lunar surface-based infrastructure and processes used to assemble, validate, support, load, and maintain launch vehicles and payloads (including non-spacecraft payloads) in preparation for flight. Launch systems are considered to be the planetary or lunar surface-based infrastructure and processes used to transition launch vehicles to flight operation.

Autonomous operations technologies (AOT) are required to manage ground and launch systems activities where human intervention/interaction/presence needs to be minimized or eliminated, such as in hazardous locations/operations and in support of remote operations. AOT are required to reduce operations and maintenance (O&M) costs of flight system and payload processing operations on the ground, and to increase ground systems availability to support mission operations. AOT will also be required for extended surface O&M on the Moon and Mars.

AOT performs functions such as system and component fault prediction and diagnostics, anomaly detection, fault detection and isolation, and enables various levels of autonomous control and recovery from faults, where recovery may include system repair and/or reconfiguration. AOT are enabled by Health Management (HM) technologies, methodologies, and approaches; command, monitoring and control architectures; computing architectures; software for decision making and control; and intelligent components and devices.

AOT will be integrated into activities performed by rocket engine test facilities, propellant servicing systems, and processing and launch of vehicles and payloads. AOT will enable surface O&M, which requires a high degree of autonomy and reliability for unattended operations during extended periods of time. AOT will complement in situ resource utilization (ISRU) operations by supporting ISRU ground systems infrastructure with O&M autonomy. AOT enables Autonomous Propellant Management (APM), which requires unattended or minimally attended storage, transfer, monitoring, and sampling of cryogenic propellants, or other propellants used in launch vehicles and maneuvering systems. APM includes preplanned nominal processes, such as vehicle fill and drain, as well as contingency and off-nominal processes, such as emergency safing, venting, and system reconfiguration.

AOT solutions may enable the autonomous command, monitoring, and control of entire integrated systems, such as a propellant loading system and all other associated support systems involved in the loading process. AOT will also support tasks such as systems setup, testing and checkout, troubleshooting, maintenance, upgrades, and repair. These additional tasks drive the need for autonomous element-to-element interface connection and separation, multielement inspection, and recovery of high-value cryogenic propellants and gases to avoid system losses.

AOT software may include prerequisite control logic (PCL) and reactive control logic (RCL), and it may also utilize machine learning or other forms of artificial intelligence to manage nominal system behavior and adapt to off-nominal conditions.

In addition to propellants, propellant management systems may utilize additional commodities to prepare a vehicle for launch, such as high-pressure gases for purging, pressurization, or conditioning. Propellant management systems may also include power and data interfaces with the vehicle to configure vehicle valves or other internal systems and observe vehicle states during propellant management operations.

Specifically, this subtopic seeks the following:

- Development of technologies for automated/autonomous propellant (including cryogenic propellants) management and the servicing of commodities for launch vehicles and payloads.
- Development of high-fidelity physics-based cryogenic-thermal models and ground process simulations capable of real-time and faster than real-time performance.
    - Development of automated/autonomous algorithms for ground systems applications.
    - Machine learning environments (simulation and learning agent) for ground systems processes and applications.
    - Development of high-fidelity models and simulations for complex payload system processing, servicing, maintenance, etc.
    - Development of test and evaluation (T&E), and verification and validation (V&V) methods for automated/autonomous algorithms, models, and simulations.
- Development of technologies for ground systems Health Determination and Fault Management.
    - Prediction, prognosis, and anomaly detection algorithms and applications.
    - Detection, isolation, and recovery of system and component faults and degradation.
    - Development of T&E, and V&V methods for Health Determination and Fault Management algorithms and applications.
- Development of technologies for automated/autonomous planning and scheduling (P&S).

    - Automated/autonomous assets management tools and applications.
    - Scheduling and prioritization algorithms and applications.
    - Human-machine information interactions and intent inferencing.
- Development of technologies for automated/autonomous inspection, maintenance, and repair (IM&R).
    - Use of robotic caretakers for IM&R needs.
    - Self-diagnosis in systems and components to inform condition-based maintenance.
    - Software to aid robotic agents or systems to learn IM&R functionality.
- Development of technologies for enhanced logistics and reliability.
    - Optimization and/or reduction of logistics needs (design for maintainability, commonality, and reusability).
    - Commonality of maintenance equipment, tools, and consumables.
    - Automated/autonomous asset management.
    - Automated/autonomous personnel location and condition determination.
    - Intelligent devices (sensors, actuators, and electronics with self-diagnosis capabilities, calibration on demand, self-healing capabilities, etc.).
- Standardization of architectures and interfaces for ground and launch systems.
- Standardization of ground systems design (design for maintainability, commonality, and reusability).

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I, show a path toward Phase II demonstration and deliver a demonstration package for NASA testing in operational or analog test environments at the completion of the Phase II contract. Successful Phase II technologies will be candidates for integration and demonstration in the existing Advanced Ground Systems Maintenance (AGSM) Integrated Health Management (IHM) Architecture, deployed at Kennedy Space Center (KSC).

Expected TRL or TRL Range at completion of the Project: 5 to 8

Primary Technology Taxonomy:
Level 1: TX 04 Robotics Systems
Level 2: TX 04.6 Robotics Integration

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I deliverables: Research, identify, and evaluate candidate technologies or concepts for systems and components fault detection, isolation and recovery, fault prediction and diagnosis, and decision-making algorithms to enable autonomy of ground systems. Demonstrate technical feasibility and show a path towards a demonstration. Concept methodology should include the path for adaptation of the technology, infusion strategies (including risk trades), and business model. It should identify improvements over the current state of the art and the feasibility of the approach in a multi-customer environment. Bench or lab-level demonstrations are desirable. Deliverables shall include a report documenting findings.

Phase II deliverables: Emphasis should be placed on developing, prototyping, and demonstrating the technology under simulated operational conditions using analog ground systems hardware and processes. Deliverables shall include a report detailing performance testing results, a plan for maturing and applying the technology to mission-worthy systems, and other relevant documentation. Delivery of a functional prototype (software and hardware) is expected at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a TRL of 6 or higher.

State of the Art and Critical Gaps:
There are presently critical gaps between state-of-the-art and needed technology maturation levels as follows:

1. High-fidelity, physics-based, cryogenic-thermal simulations with real-time and faster than real-time performance (Current TRL is 5; Required TRL is 9).
2. Simulation component libraries to support rapid prototyping of cryogenic-thermal models (Current TRL is 5; Required TRL is 9).
3. Supervisory control software for autonomous control and recovery of propellant loading systems and infrastructure (Current TRL is 5; Required TRL is 9).
4. Software development tools to support rapid prototyping of autonomous control applications (Current TRL is 5; Required TRL is 9).
5. Architecture for integrated autonomous operations (Current TRL is 5; Required TRL is 9).

Relevance / Science Traceability:
In addition to reducing O&M costs in ground operations, this subtopic provides Human Exploration and Operations Mission Directorate (HEOMD) with an on-ramp for technologies that enable the unattended setup, operation, and maintenance of ground systems and systems on the surfaces of other planets and moons. The directive from the President to accelerate the timeline for landing astronauts on the Moon, with the goal of a sustainable lunar presence after 2028, has made these technologies even more relevant to mission success. These technology development areas are identified in the 2020 NASA Technology Taxonomy, published by the Office of the Chief Technologist, under TX04 - Robotic Systems, TX10 - Autonomous Systems, and TX13 - Ground, Test, and Surface Systems.

This subtopic also produces technologies useful to the Space Technology Mission Directorate (STMD).

References:

1. NASA Technology Taxonomy (https://www.nasa.gov/offices/oct/taxonomy/index.html)
2. NASA Strategic Space Technology Investment Plan (https://www.nasa.gov/offices/oct/home/sstip.html)

Focus Area 17 Thermal Management Systems

From the smallest satellite to the most complicated human rated spacecraft, thermal is seen as an enabling function to a vehicle. Temperatures must be maintained within design limits, whether those be cryogenic systems for science instruments, or comfortable shirt sleeve operations temperatures for crew missions. As missions evolve and waste energy rejection becomes more of a demand, NASA seeks novel solutions, components, and system design techniques, for both active and passive thermal systems. Such solutions participate in the completion of the thermal cycle which includes waste energy acquisition, transport, rejection/storage, and insulation. The intended goal for any advanced thermal development is to enable new mission concepts while maintaining minimal impact to thermal system mass, volume, and power to maintain a spacecraft at specific temperature limits.

S16.05 Thermal Control Systems (SBIR)

Lead Center: GSFC
Participating Center(s): JPL, JSC, LaRC, MSFC

Scope Title: Coatings for Lunar Regolith Dust Mitigation for Thermal Radiators and Extreme Environments

Scope Description:
Thermal coatings are an integral part of a space mission and are essential to the survivability of the spacecraft and instrument. Radiator surface coatings with desired emissivity and absorptivity provide a passive means for instrument temperature control. The utilization of variable-emittance devices further enables active control of

the instrument temperature when the heat output from the instrument or the thermal environment of the radiator changes. With NASA's new initiative to return to the Moon, a new coating technology that will keep surfaces clean and sanitary is needed. New coating formulations utilizing durable, anticontamination, and self-cleaning properties that will disallow the accumulation of dust, dirt, and foreign materials are highly desirable. These coatings can have low absorptance and high infrared (IR) emittance properties or be transparent for use on existing thermal coating systems. The goal of this technology is to preserve optimal long-term performance of spacecraft and habitation components and systems. Furthermore, coatings that can survive and operate in extreme environments (cryogenic or high temperature) are desirable.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.3 Thermal Protection Components and Systems

Desired Deliverables of Phase I and Phase II:
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Phase I Deliverables:
- Successful development of coating formulations that lead to the desired dust mitigation.
- Deliverable of coupon.
- Samples of the hardware for further testing at NASA facilities.
- Final report.

Phase II Deliverables:
- Results of performance characterization tests.
- Results of stability test of the coating formulations and their mechanical durability test under the influence of simulated space and lunar environmental conditions.
- Test coupon.
- Final report.

State of the Art and Critical Gaps:
There are limited options for durable, stable thermal control coatings that are dust shedding in charging environments. Current state-of-the-art, sprayable radiation-stable coatings are able to coat complex, irregular surfaces, but they are porous and will become imbedded with dust and particulates. Other surface films tend to be less optically stable and may charge in the plasma environment, thereby attracting lunar regolith to their surfaces. Mirrors have the limitations of requiring flat surfaces and are not conformal in nature. Currently, no single thermal control surface appears to provide stability, durability, and meet optical property requirements for sustained durations in space and lunar environments.

Relevance / Science Traceability:
Many Science Mission Directorate (SMD) missions will greatly benefit from this dust mitigation thermal coating technology: any lunar-related project and projects involved with robotic science rovers and landers.

References:

1. References for dust mitigation coatings such as lotus thermal coatings: https://ntrs.nasa.gov/search.jsp?R=20150020486
2. References for extreme environment coatings: https://vfm.jpl.nasa.gov/files/EE-Report_FINAL.pdf
3. References in Subtopic Z13.01, Active and Passive Dust Mitigation Surfaces.

Scope Title: Heat Pumps for High-Temperature Sink Environments

Scope Description:
Operations in extreme environments where the environment sink temperature exceeds spacecraft hardware limits will require active cooling if long-duration survivability is expected. Robotic science rovers operating on the lunar surface over diurnal cycles face extreme temperature environments. Landers with clear views of the sky can often achieve sufficient heat rejection with a zenith or, if sufficiently far from the equator, an anti-Sun-facing radiator. However, science rovers must accommodate random orientations with respect to the surface and Sun. Terrain features can then result in hot environment sink temperatures beyond operating limits, even with shielded and articulated radiator assemblies. Lunar dust degradation on radiator thermo-optical properties can also significantly affect effective sink temperatures. During the lunar night, heat rejection paths must be turned off to preclude excessive battery mass or be properly routed to reclaim nuclear-based waste heat.

Science needs may drive rovers to extreme terrains where steady heat rejection is not otherwise possible. The paradigm of swarms or multiple smaller rovers enabled by commercial lander opportunities will need to leverage standard rover bus designs to permit flexibility. A heat pump provides the common extensibility for thermal control over the lunar diurnal. Active cooling systems or heat pumps are commonly used on spacecraft. Devices used include mechanical cryocoolers and thermoelectric coolers. For higher loads, vapor compression systems have been flown, and more recently, reverse turbo-Brayton-cycle coolers are being developed under NASA's Game Changing program for high-load, high-temperature-lift cryocoolers. However, technology gaps exist for midrange heat pumps that are suitable for small science rovers where internal heat dissipation may range from 20 to 100 W.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.X Other Thermal Management Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

- Conceptual design (Phase I).
- Physics-based analysis or model (Phase I).
- Proof-of-concept hardware (Phase I).
- Proof-of-concept hardware tested against simulated loads in proposed environments (Phase II).
- Final report (Phase I, Phase II).

State of the Art and Critical Gaps:
Specifically, heat pump systems are needed with the following:

- Temperature lift from a cold side at <50 °C to an environmental sink temperature as high as 75 °C (temperature lift of 50 °C or heat rejection rate of 230 W/m^2), with a system coefficient of performance >2.5.
- Tolerance to being powered down during the lunar night and restarted during the day reliably over multiple diurnals.
- Minimal exported vibrations, if any, for compatibility with science instruments.

Novel heat-pump systems are desired. Enabling improvements to state-of-the-art systems are also welcome.

Relevance / Science Traceability:
NASA's lunar initiative and Planetary Science Division form the primary customer base for this technology. Missions that directly address the National Research Council Planetary Science Decadal Survey may be users of this technology.

References:

1. Apollo Lunar Roving Vehicle Documentation: https://www.hq.nasa.gov/alsj/alsj-LRVdocs.html
2. Apollo Experience Report—Thermal Design of Apollo Lunar Surface Experiments Package: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720013192.pdf
3. Thermal Considerations for Designing the Next Lunar Lander: https://aip.scitation.org/doi/10.1063/1.2437438

Scope Title: Advanced Manufacturing of Loop Heat Pipe Evaporator

Scope Description:
A loop heat pipe (LHP) is a very versatile heat transport device that has been used on many spacecrafts. At the heart of the LHP is the evaporator and reservoir assembly. During the manufacturing, tedious processes are required to machine the porous primary wick and insert it into the evaporator, and both ends of the wick need to be sealed for liquid and vapor separation. One commonly used method for vapor seal is to use a bimetallic knife-edge joint, which is more prone to failure over long-term exposure to thermal cycles and shock and vibration. These tedious manufacturing processes add to the cost of the traditional LHP. A new manufacturing technique that will allow the primary wick to be welded directly to the reservoir without the use of a knife-edge seal is needed to reduce the cost and enhance the reliability.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.X Other Thermal Management Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

- Successfully develop advanced techniques to manufacture the LHP evaporator and reservoir assembly (Phase I).
- Demonstrate the performance of the evaporator/reservoir performance in an LHP setup (Phase I).
- Demonstrate the performance of the evaporator/reservoir performance in an LHP setup optimized to operate in simulated realistic environments with appropriate cycling (Phase II).
- Final report (Phase I, Phase II).

State of the Art and Critical Gaps:
The LHP evaporator contains a porous wick, which provides the capillary pumping capability to sustain the fluid flow in the loop. The smaller the pore size of the wick, the higher its capillary pumping capability. However, a smaller pore size results in a higher flow resistance that must be overcome by the capillary force. Traditional sintered metal wicks have a pore size on the order of 1 µm and porosity around 0.4 to 0.6. To replace the traditional porous wick, the new wick produced by the advanced manufacturing technology must have comparable pore size and porosity. The smallest pore size currently produced by direct metal laser sintering is on the order of 10 µm.

Relevance / Science Traceability:

Traditional LHPs are used on many NASA missions including the Ice, Cloud, and Land Elevation Satellite (ICESat), ICESat-2, Swift, Aura, Geostationary Operational Environmental Satellite (GOES), Geostationary Operational Environmental Satellite-R Series (GOES-R), and Surface Water and Ocean Topography (SWOT). Similar future Science Mission Directorate (SMD) missions, especially those using small satellites, can greatly benefit from this technology.

References:

1. Richard, Bradley, et al.: "Loop Heat Pipe Wick Fabrication via Additive Manufacturing," NASA Thermal & Fluid Analysis Workshop, August 21-25, 2017, Marshall Space Flight Center, Huntsville, AL.

Scope Title: Approaches and Techniques for Lunar Surface Payload Survival

Scope Description:
The lunar environment poses significant challenges to small, low-power (~100 W or less) payloads, rovers, and landers required for lunar science. The lunar day/night cycle is approximately one Earth month. During that time, surface temperatures on the lunar surface can reach 400 K at local solar noon or drop to below 100 K during the lunar night—and even colder in permanently shadowed regions. These hot and cold conditions can last several Earth days, because of the slow rotation of the Moon, or permanently in shadowed craters. Lunar dust deposited on heat-rejection surfaces and coatings will increase the heat absorbed from the Sun, thus reducing the effectiveness of radiators for heat rejection. The lunar gravity, which is 1/6th of the Earth's, will limit the ability of typical low-power heat transport devices, but the gravity field may provide advantages that could be utilized. Higher heat dissipation capacity should be addressed in Z2.01. This call seeks to solicit innovative proposals to enable lunar science in the difficult lunar environment. Example technologies may include, but are not limited to, active loops that may be turned off and are freeze tolerant, zero- or low-power non-consumable/regenerative heat generation sources, high-thermal-capacitance thermal storage, advanced insulation, and passive switching with high turndown ratios (e.g., >400:1). Furthermore, small form factors are also desired. Technologies should show substantial increase over the state of the art. Technology proposals should address power usage in day and night/shadow, mass, heat transport when turned on, heat leak when turned off, temperature drops through the system, heat storage/release amount, sensitivity to lunar topography and orientation, and so forth.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.2 Thermal Control Components and Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Thermal management approaches, techniques, and hardware components to enable the accommodation of temperature extremes encountered in the lunar environment. Concept model deliverable for Phase I and prototype demonstration in relevant environment in Phase II.

State of the Art and Critical Gaps:
Missions like Surveyor and Lunokhod hibernated during the night or reduced operational power near noon, in attempts to survive single or multiple lunar cycles. ALSEPs (Apollo Lunar Surface Experiments Packages) were deployed on several Apollo missions and had select experiments that operated for many lunar cycles. However, both Lunokhod and ALSEP benefited from radioisotope heat and power sources, which are either

too expensive or not likely to be available for near-term future lunar science experiments. In fact, most modern lunar surface mission planning is based on solar power and batteries and typically avoids the challenges associated with surviving the full lunar cycle or shadowed regions. Because interest in lunar science and the development of abilities to deliver payloads to the lunar surface is resurgent, the capability to operate through the entire lunar environment is critical. In the absence of perpetual power supplies like radioisotope thermoelectric generators (RTGs), thermal management approaches to accommodate the lunar extremes, extended day/night cycles, and shadowed regions are seen as enabling.

Relevance / Science Traceability:
Science Mission Directorate (SMD) lunar surface science investigations will employ small, low-power payloads that will require advanced thermal control approaches and techniques to survive and operate for extended duration through extreme thermal environments on the lunar surface.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2021, and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References:
1. NASA Prepares for Performing New Science on the Moon: https://www.jpl.nasa.gov/news/news.php?release=2007-068
2. The Surveyor Program: https://history.nasa.gov/TM-3487/ch2-1.htm
3. The Surveyor Program: https://www.lpi.usra.edu/lunar/missions/surveyor/(link is external)
4. Missions - Lunokhod 01: https://solarsystem.nasa.gov/missions/lunokhod-01/in-depth/
5. Missions - Lunokhod 02: https://solarsystem.nasa.gov/missions/lunokhod-02/in-depth/

Z2.01 Spacecraft Thermal Management (SBIR)

Lead Center: JSC
Participating Center(s): GRC, GSFC, JPL, MSFC

Scope Title: Spacecraft Thermal Management

Scope Description:
NASA seeks new technologies that will facilitate low-mass and highly reliable thermal control systems for the exploration of our solar system. This solicitation specifically targets proposals for new technologies and methods that clearly address one of the following areas:
1. Lunar surface habitat thermal technologies
2. High-temperature heat acquisition and transport for nuclear electric propulsion (NEP)
3. Topology optimization of thermal control systems

These areas are considered of equal priority, and no award preference is expected for one area over another.

1. Lunar Surface Habitat Thermal Technology Development

NASA is seeking focused efforts to develop thermal control technologies that will enable crewed habitats for extended stays on the lunar surface. Technologies should address a gap associated to long-duration habitation on the lunar surface, where temperatures range from -193 °C or lower in shadow regions (including night) to 120° C at the equatorial subsolar point. Technologies are needed that allow a single mobile habitat to operate in all these environments. Technologies should address reduction in mass, volume, and power usage relative to current solutions. The addition of heaters can lead to increased vehicle mass due to additional power generation and storage requirements and is not considered a novel architecture approach. Proposed radiator technologies should also address micrometeoroid and orbital debris (MMOD) robustness and protection potential where appropriate.

Examples of other challenges to address in this area include the deposition of dust on radiators leading to degraded optical properties, contamination-insensitive evaporators/sublimators to enable long mission life, self-healing coolant tubes for MMOD-impact resilience, and passive gas traps for removing gas bubbles from internal thermal control system loops that use low-surface-tension non-water coolants. Technologies should be suitable for use with habitats having variable heat loads averaging between 2 and 6 kW. All technologies should support a minimum operational duration of 5 years and be compatible with encountered environments.

Alternatively, technologies that utilize the conditions provided by the lunar environment to provide a critical function may also be considered; for example, air-water separator technologies that leverage the gravity field of the lunar surface, or concepts that explore the viability of utilizing the lunar surface regolith to provide long-duration thermal control function. As appropriate, such systems should also address functional capability in the microgravity environment that will be experienced prior to lunar surface operations.

2. High-Temperature Heat Acquisition and Transport for Nuclear Electric Propulsion (NEP)

NASA is seeking the development of thermal transport systems for NEP. This application requires the transfer of large amounts of thermal energy from a nuclear reactor to a power conversion system. NASA desires a high-temperature heat transfer system capable of transferring 4 to 10 MW of thermal power from a nuclear reactor, at a supply temperature of 1,200 to 1,400 K and a flux on the order of 0.3 MW/m^2 with a goal of 1 MW/m^2, to the hot-end heat exchangers of an electric power conversion system. The target distance for the power conversion system is 5 m from the reactor, but transport distances up to 10 m may be required. The system will need to be gamma- and neutron-radiation tolerant, be single-fault tolerant (a single leak should not render the system inoperable) and have an operating life of 15+ years. System mass and reliability should be addressed as part of the proposal.

Example solutions include, but are not limited to, liquid metal heat pipes or pumped fluid loops. Special consideration should be given to interfaces (both at the nuclear reactor and at the power conversion system) to maximize heat transfer. Integration with the reactor may include solutions that run through the reactor core. For integration with the power conversion system, a helium-xenon working fluid in a Brayton cycle system may be assumed but is not required.

3. Topology Optimization of Thermal Control Systems

Advanced design and manufacturing are rapidly transforming engineered systems. The advent of reliable additive manufacturing techniques coupled with robust optimization algorithms is facilitating the development of new high-performance systems. To date, the advanced design community has primarily focused on optimized structural systems that minimize mass and volume while meeting structural performance requirements. While some work has been done to develop advanced design tools for thermal control systems, considerable work remains to make it standard practice. This solicitation requests the development of a topology optimization (TO) tool that can optimize a thermal-fluid component (e.g., a heat exchanger). Specific goals include minimizing component (heat exchanger) mass, minimizing pressure drop, and maximizing heat transfer efficiency. Because of the inherent multiphysics characteristics of the problem (coupled structural/thermal/fluids behavior), proposals are encouraged to leverage existing TO software (e.g., see Watkins (2019) and other TO references below) that can already handle structural and thermal conduction optimization, and extend the code to handle systems that include single-phase laminar convective heat transfer.

This solicitation requests the development of TO software capable of minimizing heat exchanger mass while meeting envelope volume, heat transfer, and pressure drop targets. The initial target is optimization for laminar single-phase flow. An extended goal is to be able to optimize a heat exchanger for turbulent single-phase flow while accommodating manufacturing constraints to ensure the heat exchanger design is manufacturable.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 14 Thermal Management Systems
Level 2: TX 14.2 Thermal Control Components and Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I awards in this area are expected to demonstrate analytical and/or empirical proof-of-concept results that demonstrate the ability of the organization to meet the goals stated in the solicitation.

At the conclusion of a Phase II contract, deliverables are expected to include a functioning prototype (or better) that demonstrates the potential to meet the performance goals of the technology or software. Any delivered math models should include supporting data that validates the assumptions used within the model.

State of the Art and Critical Gaps:
These focus areas strive to reduce mass, volume, and power of a thermal control system in the next generation of robotic and human-class spacecraft and to enable long-term missions to the Moon and Mars. These improvements may come through either novel hardware solutions or modernization of software tools. The current state of the art in thermal control systems is vehicle power and mass impact of greater than 25 to 30% due to old technologies still in use. Furthermore, as missions become more variable (dormancy, environments, etc.), the need for intelligent design and control (both actively and passively) within the thermal control system becomes more apparent. For topology optimization (TO) in particular, it has become a well-established structural design tool, but it has yet to penetrate the thermal design community. Multiple research efforts have shown that TO of thermal-fluid systems is possible and can be successfully implemented to obtain optimized designs; however, a robust commercial code that can do this is yet to be demonstrated. Additionally, science payloads will continue to decrease in size, increase in power, and require precise temperature control, all of which cannot be readily provided by traditional thermal control methods due to vehicle-level impacts of overall performance, mass/volume, and power.

Relevance / Science Traceability:

- Long-duration habitats (Moon, Mars, etc.).
- Lunar surface power.
- Mars transit vehicles.
- SmallSats/CubeSats.
- Rovers and surface mobility.
- Nuclear electric propulsion (NEP) systems.

References:

1. Stephan, R. "Overview of the Altair Lunar Lander Thermal Control System Design and the Impacts of Global Access," AIAA 2011-5001, 2011.
2. Ewert, M. K. "Investigation of Lunar Base Thermal Control System Options," SAE Transactions, J. of Aerospace, 102(1), 829-840, 1993.
3. Leimkuehler, T. O., et al. “Operational Experience with the Internal Thermal Control System Dual-Membrane Gas Trap,” 33rd International Conference on Environmental Systems (ICES), Vancouver, British Columbia, Canada, July 2003.
4. Leimkuehler, T. O., et al. “Effects of Surfactant Contamination on the Next Generation Gas Trap for the ISS Next Generation Gas Trap for the ISS Internal Thermal Control System,” 34th International Conference on Environmental Systems (ICES), Colorado Springs, CO, July 2004.
5. Wetch, J. R., et al. “Megawatt Class Nuclear Space Power Systems (MCNSPS) Conceptual Design and Evaluation Report,” Volumes I-IV, NASA CR-179614, September 1988.
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12. Stone, J. R. “Alkali Metal Rankine Cycle Boiler Technology Challenges and Some Potential Solutions for Space Nuclear Power and Propulsion Applications,” NASA Technical Memorandum 106593, July 1994.
13. Demuth, S. F. “SP 100 Space Reactor Design,” Progress in Nuclear Energy, Volume 42, Number 3, 2003.
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18. Watkins, Ryan. "Topology Optimization: A Shift Towards Computational Design," 2016.
19. Kambampati, Sandilya, and Hyunsun A. Kim. "Level Set Topology Optimization of Load Carrying Heat Dissipation Devices," AIAA Aviation 2019 Forum, 2019.
20. Kambampati, Sandilya, and H. Alicia Kim. "Level Set Topology Optimization of Cooling Channels Using the Darcy Flow Model," Structural and Multidisciplinary Optimization (2020): 1-17.
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Focus Area 18 Air Vehicle Technology

This focus area includes tools and technologies that contribute to both the Advanced Air Vehicles Program (AAVP) and the Transformative Aeronautics Concepts Program (TACP) encompassing technologies in all six Strategic Thrusts within the NASA Aeronautics Mission Directorate (ARMD). AAVP develops knowledge, technologies, tools, and innovative concepts to enable safe new aircraft that will fly faster, cleaner, and quieter and use fuel far more efficiently than in the past.   AAVP advanced, integrated technologies and capabilities improve vehicle performance and intrinsic safety by reducing fuel usage, noise, and emissions. Fuel efficiency and environmental factors will play an increasingly significant role as the aviation market grows in capacity.

Partnering with industry, academia, and other government agencies, AAVP pursues mutually beneficial collaborations to leverage opportunities for effective technology transition. TACP encourages revolutionary concepts, creates the environment for researchers to experiment with new ideas, performs ground and small-scale flight tests, and drives rapid turnover into potential future concepts to enable aviation transformation. Research is organized to aggressively engage both the traditional aeronautics community and non-traditional partners. Although TACP focuses on sharply focused studies, the program provides flexibility for innovators to assess new-technology feasibility and provide the knowledge base for radical aeronautics advances.

A1.01 Aeroelasticity and Aeroservoelastic Control (SBIR)

Lead Center: LaRC
Participating Center(s): AFRC

Scope Title: Aeroelasticity and Aeroservoelasticity for Advanced Configurations

Scope Description:
The technical discipline of aeroelasticity is a critical ingredient necessary in the design process of a flight vehicle for maintaining optimal performance while ensuring freedom from aeroelastic and aeroservoelastic instabilities. This discipline requires a thorough understanding of the complex interactions between a flexible structure and the steady and unsteady aerodynamic forces acting on the structure, with interactive control systems for flight vehicle performance and stability. This fundamental aeronautics work is focused on active/adaptive aerostructural control for lightweight flexible structures, specifically related to load distribution, flutter prediction and suppression, gust load prediction and alleviation, and aeroservoelasticity for Ultra-Efficient and Supersonic Commercial Vehicles.

The program's work on aeroservoelasticity includes conduct of broad-based research and technology development to obtain a fundamental understanding of aeroelastic and unsteady aerodynamic phenomena experienced by aerospace vehicles in subsonic, transonic, supersonic, and hypersonic speed regimes.

The program content includes theoretical aeroelasticity, experimental aeroelasticity, and advanced aeroservoelastic concepts. Of interest are:

- Aeroelastic, aeroservoelastic, and unsteady aerodynamic analyses at the appropriate level of fidelity for the problem at hand.
- Aeroelastic, aeroservoelastic, and unsteady aerodynamic experiments to validate methodologies and to gain valuable insights available only through testing.
- Development of computational fluid dynamic (CFD), computational aeroelastic, and computational aeroservoelastic analysis tools that advance the state of the art in aeroservoelasticity through novel and creative application of aeroelastic knowledge.

Specific subjects to be considered include:

- Development of aerostructural control design methodologies that include CFD steady and unsteady aerodynamics, flexible structures, and active control systems.
- Development of efficient methods to generate mathematical models of wind tunnel models and flight vehicles for performing aeroservoelastic studies.
- Development of CFD-based methods (reduced-order models) for aeroservoelastic models and simulation that can be used to predict gust loads, ride quality issues, flight dynamics stability, and aerostructural control issues.
- Development of novel aeroservoelastic sensing and control approaches, including active/adaptive control concepts and architectures that employ smart materials embedded in the structure and aerodynamic sensing and control schemes for suppressing aeroelastic instabilities and improving performance.
- Development of techniques that support simulations, ground testing, wind tunnel tests, and flight experiments for aerostructural control of aeroservoelastic phenomena.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.1 Aerosciences

Desired Deliverables of Phase I and Phase II:

- Hardware
- Software

Desired Deliverables Description:
This subtopic seeks technologies for

- Development of CFD, computational aeroelastic, and computational aeroservoelastic analysis tools that advance the state of the art in aeroservoelasticity through novel and creative application of aeroelastic knowledge.
- Development of aerostructural control design methodologies that include CFD steady and unsteady aerodynamics, flexible structures, and active control systems.
- Development of efficient methods to generate mathematical models of wind tunnel models and flight vehicles for performing aeroservoelastic studies.
- Development of CFD-based methods (reduced-order models) for aeroservoelastic models and simulation that can be used to predict gust loads, ride quality issues, flight dynamics stability, and aerostructural control issues.
- Development of novel aeroservoelastic sensing and control approaches, including active/adaptive control concepts and architectures that employ smart materials embedded in the structure and aerodynamic sensing and control schemes for suppressing aeroelastic instabilities and improving performance.
- Development of techniques that support simulations, ground testing, wind tunnel tests, and flight experiments for aerostructural control of aeroservoelastic phenomena.

Expected Phase I and Phase II Deliverables:

Phase I: Develop the infrastructure for the analysis tool(s), methods, methodologies, and/or simulation/test techniques, then demonstrate/verify feasibility via prototype or proof of concept.

Phase II: Complete development of the Phase 1 effort, demonstrating/verifying the tool(s), methods, methodologies, and/or simulation/test techniques via model(s)/structure(s) of appropriate complexity and interest to NASA.

State of the Art and Critical Gaps:
Aeroelastic prediction and testing methods must evolve and expand together with new and emerging aircraft, structural, and material concepts. The use of lightweight flexible structures, the development of new airframes (truss-braced wings, blended-wing bodies, etc.), and the intentional exploitation of aeroelastic response phenomena require a comprehensive understanding of the aeroelasticity involved if they are to succeed. Both enhancements to current methodologies/codes and new methodologies/codes that enable evaluation and understanding of new concepts are needed to keep pace with the state of the art in vehicle technology and to fill critical gaps in understanding those vehicles. Code development and performance prediction typically lag behind vehicle conceptual development, so while the most popular computational methods in use today, which were developed under Small Business Innovation Research (SBIR) awards, work well for yesterday's configurations, they will have to be modified or rethought entirely to capture the behavior of today's and tomorrow's evolutionary and revolutionary vehicles.

Relevance / Science Traceability:

Predicting the aeroelastic response of emerging evolutionary and revolutionary vehicle concepts is not an easy task. Aeroelastic prediction and testing methods must evolve and expand with the concepts themselves, which include new vehicle configurations, new structures, and new materials. The use of lightweight flexible structures, the development of new airframes (truss-braced wings, blended-wing bodies, etc.), and the intentional exploitation of aeroelastic response phenomena require a comprehensive understanding of the aeroelasticity involved if they are to succeed. The Boeing 787, for example, has the most flexible wing of any transport built thanks to composites and aggressive aeroelastic optimization of the structure. Some specific NASA programs/projects/topics that will greatly benefit from the expansion of aeroelastic knowledge, tools, and test techniques are under the Aeronautics Research Mission Directorate (ARMD), including (a) the Advanced Air Vehicles Program (AAVP), specifically, the Aerosciences Evaluation and Test Capabilities (AETC) project, the Advanced Air Transportation Technologies (AATT) project with the Performance Adaptive Aeroelastic Wing (PAAW) and Passive Aeroelastically-Tailored Wing (PATW) subprojects, and the Commercial Supersonic Technology (CST) project; (b) the Transformative Aeronautics Concepts Program (TACP), specifically, the Convergent Aeronautics Solutions (CAS) project and the Transformational Tools and Technologies (TTT) project; (c) the Integrated Aviation Systems Program (IASP), specifically, the Flight Demonstrations and Capabilities (FDC) project; (d) N+3; (e) the X-56A flight project; and (f) the work with new ultra-efficient and supersonic commercial vehicles.

References:
Links to program/project websites:

1. ARMD's Advanced Air Vehicles Program (AAVP): https://www.nasa.gov/aeroresearch/programs/aavp
2. ARMD's Transformative Aeronautics Concepts Program: https://www.nasa.gov/aeroresearch/programs/tacp
3. ARMD's Flight Demonstrations and Capabilities (FDC) project under the Integrated Aviation Systems Program (IASP): https://www.nasa.gov/aeroresearch/programs/iasp/fdc
4. X-56 Flight Project: https://www.nasa.gov/centers/armstrong/research/X-56/index.html

Information related to evolutionary and revolutionary flight vehicle concepts/configurations that are on the drawing board or already being tested:

1. Truss-Braced Wing: https://www.sae.org/news/2019/01/boeing-and-nasa-unveil-lightweight-ultra-thin-more-aerodynamic-transonic-truss-braced-wing-concept
2. Blended Wing Body: https://www.nasa.gov/centers/dryden/multimedia/imagegallery/X-48C/ED12-0255-51.html
3. Joined Wing: https://www.nasa.gov/centers/langley/multimedia/iotw-tdt-wing.html
4. X-57: https://www.nasa.gov/image-feature/milestone-achieved-as-x-57-mod-ii-takes-shape
5. X-59: https://www.nasa.gov/image-feature/a-look-inside-the-x-59-quesst-cockpit

A1.02 Quiet Performance - Aircraft Propulsion Noise (SBIR)

Lead Center: GRC
Participating Center(s): LaRC

Scope Title: Aircraft Propulsion Noise

Scope Description:
Innovative methods and technologies are necessary for the design and development of efficient and environmentally acceptable aircraft. In particular, the impact of aircraft noise on communities around airports is the predominant limiting factor on the growth of the nation's air transportation system. Reductions in aircraft noise could lead to wider community acceptance, lower airline operating costs where noise quotas or fees are employed, and increased potential for air traffic growth on a global scale. In support of the Advanced Air Vehicles Program (AAVP), Integrated Aviation Systems Program (IASP), and Transformative Aeronautics Concepts Program (TACP), improvements in propulsion noise prediction, diagnostics, and reduction are needed for subsonic and supersonic aircraft. Innovations in the following areas are solicited:

Prediction:

- High-fidelity fan and turbine broadband noise prediction models, fan and turbine 3D acoustic transmission models for tone and broadband noise.
- Accurate models for prediction of installed noise for jet-surface interaction, fan inlet distortion, and open rotors.

Diagnostics:

- Tools/technologies for quantitative characterization of fan in-duct broadband noise in terms of its spatial and temporal content.
- Phased array and acoustical holography techniques to measure realistic propulsion noise sources in low signal-to-noise ratio wind tunnel environments.
- Characterization of fundamental jet noise sources and structures.

Reduction:

- Advanced liners including broadband liners (i.e., liners capable of appreciable sound absorption over at least two octaves) and low-frequency liners (i.e., liners with optimum absorption frequencies half of the current ones but without increasing liner depth).
- Low-noise propulsor concepts that are significantly quieter than the current generation fans and open rotors.
- Concepts for active control of broadband noise sources including fan, open rotor, jet, compressor, combustor, and turbine.
- Adaptive flow and noise control technologies including smart structures for inlets, nozzles, and low-drag liners.
- Concepts to mitigate the effects of distorted inflow on propulsor noise.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.3 Aero Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Tools and technologies that enable prediction, diagnostics, and reduction of propulsion noise at component or system level for subsonic and supersonic aircraft.

Phase I deliverables can include: (1) demonstration of the utility of new tools for predicting realistic model problems in propulsion noise, (2) proof-of-concept demonstration of advanced noise diagnostic techniques for propulsion noise identification and characterization, and (3) laboratory demonstration of propulsion noise reduction concepts or technologies.

Phase II deliverables can include maturation of such tools, capabilities, and technologies for realistic propulsion components or systems.

State of the Art and Critical Gaps:
Efficient high-fidelity computational tools that enable timely evaluations of multiple engine configurations and operating conditions are lacking. Availability of such tools is essential at the design stage or for system-level

assessment. Accurate and robust diagnostic tools for source identification and characterization do not exist for most of the important propulsion noise sources such as fan, combustor, and turbine. State-of-the-art technologies for propulsion noise reduction are generally passive and tend to be designed for a specific operating condition. Adaptive materials and mechanisms that can modify their acoustic performance based on the noise state of the engine are highly desirable. New prediction tools, diagnostic capabilities, and noise reduction technologies would enable development of quieter propulsion systems for aircraft.

Relevance / Science Traceability:
AAVP: The Advanced Air Transport Technology (AATT) and Commercial Supersonic Technology (CST) Projects would benefit from more accurate propulsion noise prediction capabilities, more robust propulsion noise diagnostic tools, and more effective propulsion noise reduction technologies. These could lead to quieter propulsion systems that can help reduce the aircraft noise footprint at landing and takeoff. New engine architectures and new airframe-engine integration concepts could also benefit from an infusion of new tools and technologies to assess their acoustic performance in early design stages.

TACP: The Transformational Tools and Technologies (TTT) Project would benefit from tool developments to enhance the ability to consider acoustic considerations earlier in the aircraft propulsion system design process. The TTT Project would also benefit from the development and demonstration of simple material systems, such as advanced liner concepts with reduced drag or adaptive material and/or structures that reduce propulsion noise, as these component technologies could have application in numerous vehicle classes in the AAVP portfolio, including subsonic and supersonic transports and, potentially, vertical lift vehicles.

References:

1. AAVP - Advanced Air Transport Technology (AATT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/aatt
2. AAVP - Commercial Supersonic Technology (CST) Project: https://www.nasa.gov/aeroresearch/programs/aavp/cst
3. TACP - Transformational Tools and Technologies (TTT) Project: https://www.nasa.gov/aeroresearch/programs/tacp/ttt

A1.03 Low Emissions/Clean Power - Environmentally Responsible Propulsion (SBIR)

Lead Center: GRC
Participating Center(s): LaRC

Scope Title: Environmentally Responsible Propulsion - Aircraft Combustor Tools and Technologies

Scope Description:
Innovative tools and technologies are required to address several challenges to improving combustor operability and durability and minimizing the impact of aircraft emissions on human health and the environment. Overcoming these challenges is important to both next-generation subsonic aircraft and potential future high-speed commercial aircraft. Particulate matter emissions from aircraft gas turbine engines, consisting primarily of ultrafine soot, contribute to adverse health and climate impacts, and new international standards on nonvolatile particulate matter emissions will start in 2023. Next-generation single-aisle aircraft are pushing towards smaller engine cores and higher overall pressure ratios, leading to challenges in combustor cooling design. Future high-speed (supersonic) aircraft also face significant combustor cooling challenges due to the need for maximizing the air available to combust with the fuel (to provide ultralow emissions of oxides of nitrogen that mitigate ozone depletion at stratospheric cruise altitudes) while operating at the harshest thermal condition during long-duration cruise. Conventional gas turbine engines operating at higher overall pressure ratios and future hybrid-electric or high-speed aircraft concepts that use the fuel as a heat sink may experience fuel injection behavior outside of current understanding and modeling capabilities.

Aviation goals to reduce climate impacts from aviation will drive increased use and blending ratios of sustainable aviation fuels. To address these challenges, innovations in the following specific areas are solicited:

- Nonintrusive optical techniques to measure near-wall velocities, temperature, and/or turbulence variables for experiments with liquid-spray injection operating over a range of pressures (1 atm to at least 30 atm).
- Tools and technologies to improve combustor durability and optimize cooling in the combustor for smaller core subsonic application and/or long-duration cruise supersonic applications.
- Approaches that tightly couple convection, conduction, and radiation heat transfer in a computationally efficient manner applicable to time-accurate eddy-resolving simulations of combustion flows with liquid-spray injection.
- Fuel-sensitive soot-precursor chemistry models applicable to Jet-A and various blending ratios of Jet-A with sustainable aviation fuels.
- For multicomponent hydrocarbon fuels (conventional jet fuel and sustainable aviation fuels), models for the transition from two-phase (liquid-vapor regime with surface tension) behavior to a single-phase behavior (where no surface tension exists) that may be encountered for fuels injected into high-pressure and high-temperature combustor chamber conditions, and/or for heated fuels.

Development of measurement techniques for characterizing aircraft engine particle emissions in the 10- to 200-nm particle diameter size range and their interactions with contrails and contrail-cirrus clouds. Complete instrument systems are desired, including features such as remote/unattended operation and data acquisition and minimum size, weight, and power consumption. Instrument prototypes as a deliverable in Phase II proposals and/or field demonstrations are encouraged. Desired measurement capabilities include:

- Size-dependent number and mass concentrations at 1-Hz time resolution that differentiate volatile/nonvolatile particles or elemental/organic carbon fractions, consistent with the measurement definitions given by the standard SAE ARP6320A (https://www.sae.org/standards/content/arp6320a/). Note that the ARP is referenced only for measurement referencing and terminology; this subtopic seeks proposals for research-grade instruments that go significantly beyond the current state of the art and the baseline measurement requirements of the ARP.
- Open-path, aircraft cloud probes suitable for measuring the number and size distribution of near-field small contrail ice crystals down to a nominal 0.1- to 0.3-µm diameter lower size limit.
- Aircraft-mounted water vapor, dew point, or relative humidity probe with small enough size, weight, and power footprint that it would be suitable for integration on a commercial aircraft. Instrument should be optimized for upper tropospheric ambient measurements (nominally 20-ppm minimum sensitivity for water vapor, -40 to -70 °C static air temperature, 150- to 300-mbar static air pressure).
- Aircraft-mounted temperature probe suitable for measuring static air temperature with accuracy at or better than 0.1 °C under upper tropospheric flight conditions.
- Measurements carried out at high sample line pressures relevant for sector combustor studies and low pressures relevant for flight studies.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.3 Aero Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software
- Hardware

Desired Deliverables Description:
A major deliverable will be computer simulation software to predict the best and most effective combustor configurations. Sensor development for monitoring engine emissions would be another deliverable.

Phase I should successfully demonstrate fabrication/testing of a laboratory breadboard system, overcoming a major system or subsystem technical hurdle, or foundational work that lays the groundwork for the Phase II work plan, which should be summarized in the Phase I report.

Phase II deliverables such as instrument prototypes and/or field demonstrations are highly encouraged.

State of the Art and Critical Gaps:
Combustion involves multiphase, multicomponent fuel, turbulent, unsteady, 3D, reacting flows where much of the physics of the processes are not completely understood. Computational fluid dynamics (CFD) codes used for combustion do not currently have the predictive capability that is typically found for nonreacting flows. Low-emissions combustion concepts require very rapid mixing of the fuel and air with a minimum pressure loss to achieve complete combustion in the smallest volume. Areas of specific interest where research is solicited include:

- Development of laser-based diagnostics for quantitative spatially and temporally resolved measurements of fuel/air ratio in reacting flows at elevated pressure.
- Development of optical techniques for soot measurement and characterization for combustor flametube and sector tests (non-prevaporized liquid combustion, fuel Jet-A, pressures 3 to 80 atm; flame temperatures up to 2,250 K, soot diameters on the order of 10 to 100 nm)
- Development of ultrasensitive instruments for determining the size-dependent mass of combustion-generated particle emissions.
- Low-emissions combustor concepts for small high-pressure engine cores.

Relevance / Science Traceability:
All of Aeronautics Research Mission Directorate (ARMD), Transformational Tools and Technologies (TTT), etc.

Achieving low emissions and finding new pathways to cleaner power are critical for the development of future air vehicles. Vehicles for subsonic and supersonic flight regimes will be required to operate on a variety of certified aircraft fuels and emit extremely low amounts of gaseous and particulate emissions to satisfy increasingly stringent emissions regulations. Future vehicles will be more fuel efficient, which will result in smaller engine cores operating at higher pressures. Future combustors will also likely employ lean-burn concepts, which are more susceptible to combustion instabilities.

Infusion/Commercial Potential: These developments will impact future aircraft engine combustor designs (lower emissions, improve operability, control instabilities) and may have commercial applications in other gas-turbine-based industries, such as power generation and industrial burners. The modeling and results can be and will be employed in current and future hydrocarbon rocket engine designs (improving combustion efficiency, ignition, stability, etc.).

References:

1. Advances Air Vehicles Program - Advanced Air Transport Technology (AATT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/aatt
2. Advances Air Vehicles Program - Commercial Supersonic Technology (CST) Project: https://www.nasa.gov/aeroresearch/programs/aavp/cst
3. Transformative Aeronautics Concepts Program - Transformational Tools and Technologies (TTT) Project: https://www.nasa.gov/aeroresearch/programs/tacp/ttt
4. NASA Glenn Combustor Facilities: https://www1.grc.nasa.gov/facilities/erb/combustor/
5. NASA Langley Aerosol Research Group: https://science-data.larc.nasa.gov/large/aeronautics.html

6. Procedure for the Continuous Sampling and Measurement of Non-Volatile Particulate Matter Emissions from Aircraft Turbine Engines (ARP6320): https://www.sae.org/standards/content/arp6320/

A1.04 Electrified Aircraft Propulsion (SBIR)

Lead Center: GRC
Participating Center(s): AFRC, LaRC

Scope Title: Electrified Aircraft Propulsion (EAP)

Scope Description:
Technical proposals are sought for the development of enabling power systems, that will be required for aircraft using turboelectric, hybrid-electric, or all-electric power generation as part of the propulsion system. This subtopic is targeted towards megawatt-class vehicles. For the 100- to 200-kW realm targeted to electric vertical takeoff and landing (eVTOL) vehicles, please go to subtopic A1.06: Vertical Lift Technology for Urban Air Mobility -Electric Motor Fault Mitigation Technology.

Specifically, novel developments are sought in these areas:

- Superconducting wire or cables compatible with the NASA High Efficiency Megawatt Motor (HEMM) and at a temperature of 62 K that have properties exceeding: engineering current density >205 A/mm^2, cost per performance <$1.10/(A-m), and shear stress in all three axis >20 MPa. Information on HEMM can be found in the publication “High Efficiency Megawatt Motor Preliminary Design”, Jansen et al. https://ntrs.nasa.gov/citations/20190029589
- Lightweight alternating current (AC) and direct current (DC) electrical fault management systems and protective devices (such as circuit breakers). Technology should scale to aircraft circuits operating in the 1,000- to 3,000-V range at 500 to 2,000 A. Prototypes can be built at the 100- to 500-V at 10- to 100-A range or at full scale. The circuit breaker technology proposals will be evaluated on the metrics of: speed to isolate circuit, specific power (kW/kg), and efficiency (1-(W loss/ W conducted)). The performance objective is to exceed 200 kW/kG and 99.5% at full scale.
- Converters (inverters/rectifiers) used to convert AC to AC frequency AC to DC. Technology should scale to aircraft circuits operating in the 1,000- to 3,000-V range at 500 to 2,000 A. Prototypes can be built at the 100- to 500-V at 10- to 100-A range or at full scale. The converters will be evaluated on the metrics of: specific power (kW/kg) and efficiency with objective to exceed 20 kW/kG and 99.5% at full scale.
- Electric machines for aircraft propulsion used for direct-drive propulsion of fans or propellers or as generators coupled to internal combustion engines, turboprops, or turbofans. Technology should scale to aircraft applications in the 1- to 5-MW range. The electric machines will be evaluated on the metrics of: specific power (kW/kg) and efficiency with objective to exceed 20 kW/kG and 98% at full scale.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.3 Aero Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Deliverables vary considerably within the subtopic, but ideally proposals would identify a technology pull area (with a market size estimate), how the proposed idea addresses the needs of the technology pull area and then deliver a combination of analysis and prototypes that substantiate the idea's merit.

For Phase I, it is desirable that the proposed innovation clearly demonstrates that it is commercially feasible and addresses NASA's needs.

Deliverables for a Phase II should be focused on the maturation, development, and demonstration of the proposed technical innovation.

State of the Art and Critical Gaps:
The critical technical need is for lightweight, high-efficiency motors, distribution systems, and fault management. Typically, the weight needs to be reduced by a factor of 2 to 3 and efficiency needs to be improved. Higher efficiency reduces losses and makes thermal management more achievable in an aircraft.

Technologies that address these gaps enable EAP, which enables new aircraft configurations and capabilities for the point-to-point on-demand mobility market and a new type of innovation for transport aircraft to reduce fuel consumption and emissions.

Relevance / Science Traceability:
EAP is an area of strong and growing interest in the Aeronautics Research Mission Directorate (ARMD). There are emerging vehicle level efforts in urban on-demand mobility, the X-57 electric airplane being built to demonstrate EAP advances applicable to thin and short haul aircraft markets, and an ongoing technology development subproject to enable EAP for single-aisle aircraft. Additionally, NASA is starting the new Electrified Powertrain Flight Demonstration (EPFD) project to enable a megawatt-class aircraft.

Key outcomes NASA intends to achieve in this area are:

- Outcome for 2015 to 2025: Markets will begin to open for electrified small aircraft.
- Outcome for 2025 to 2035: Certified small-aircraft fleets enabled by EAP will provide new mobility options. The decade may also see initial application of EAP on large aircraft.
- Outcome for >2035: The prevalence of small-aircraft fleets with electrified propulsion will provide improved economics, performance, safety, and environmental impact, while growth in fleet operations of large aircraft with cleaner, more efficient alternative propulsion systems will substantially contribute to carbon reduction.

Projects working in the vehicle aspects of EAP include:

- Advanced Air Vehicles Program (AAVP)/Advanced Air Transport Technology (AATT) Project
- Integrated Aviation Systems Program (IASP)/Flight Demonstrations and Capabilities (FDC) Project
- AAVP/Revolutionary Vertical Lift Technology (RVLT) Project
- Transformative Aeronautics Concepts Program (TACP)/Convergent Aeronautics Solutions (CAS) Project
- TACP/Transformational Tools and Technologies (TTT) Project

References:

1. EAP is called out as a key part of Thrust 3 in the ARMD strategic plan: https://www.nasa.gov/aeroresearch/strategy
2. Overview of NASA's EAP Research for Large Subsonic Aircraft: https://ntrs.nasa.gov/search.jsp?R=20170006235
3. Electrified Powertrain Flight Demonstration (EPFD); https://www.nasa.gov/aeroresearch/programs/iasp/epfd
4. NASA X-57 Project: https://www.nasa.gov/aeroresearch/X-57/technical/index.html

5. “High Efficiency Megawatt Motor Preliminary Design”, Jansen et al. https://ntrs.nasa.gov/citations/20190029589

A1.05 Computational Tools and Methods (SBIR)

Lead Center: LaRC
Participating Center(s): ARC, GRC

Scope Title: Unstructured Meshes for Scale-Resolving Simulations

Scope Description:
Computational fluid dynamics (CFD) plays an important role in the design and development of a vast array of aerospace vehicles, from commercial transports to space systems. With the ever-increasing computational power, usage of higher fidelity, fast CFD tools and processes will significantly improve the aerodynamic performance of airframe and propulsion systems, as well as greatly reduce nonrecurring costs associated with ground-based and flight testing. Historically, the growth of CFD accuracy has allowed NASA and other organizations, including commercial companies, to reduce wind tunnel and single engine component tests. Going forward, increased CFD fidelity for complete vehicle or engine configurations holds the promise of significantly reducing development costs, by enabling certification by analysis (CbA). Confidence in fast, accurate CFD and multidisciplinary analysis tools allow engineers to reach out of their existing design space and accelerate technology maturation schedules. Uncertainty quantification is a key technology in enhancing confidence in the prediction capability of the computational tools. NASA’s CFD Vision 2030 Study (https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140003093.pdf) highlighted the many shortcomings in the existing computational technologies used for conducting high-fidelity simulations, including multidisciplinary analysis and optimization, and made specific recommendations for investments necessary to overcome these challenges. A more recent study provided a long-term vision and a technology development roadmap to enable CbA for aircraft and engine certification (see https://ntrs.nasa.gov/citations/20210015404).

During the current cycle, proposals are solicited in the following mesh generation area for CFD simulations:

Unstructured Meshes for Scale-Resolving Simulations: Mesh generation for high-fidelity simulations is a critical area of research. The focused grid-related area for which proposals are being solicited is automated and scalable mesh generation for wall-modeled large eddy simulations (WMLES). Unstructured approaches can be used to discretize highly complex flow configurations but, in addition to automation, there is need to generate the mesh robustly and efficiently regardless of geometric complexity. The mesh quality aspect is especially critical for scale-resolving simulations where numerical methods benefit significantly from element regularity and alignment for accuracy considerations, while maintaining an optimal number of cells for solver efficiency. Isotropic meshing is preferred and a combination of hex grid (near solid boundaries) and tetrahedral (further away) may provide the best compromise between solution accuracy and solver efficiency. The goal of the solicited work is to encourage development of such mesh generation software that can be interfaced and integrated with NASA CFD solvers. The requirements for the solicited mesh software include: (1) it should be able to efficiently handle arbitrarily complex geometries; (2) the software should be Message Passing Interface (MPI) parallel, scalable to billion+ cell meshes as are typical for NASA applications; (3) the mesh generation process needs to take a water-tight bounding volume definition as input, where the surface of the bounding volume can be marked with prescribed mesh resolution(s), in addition to any user-prescribed volume refinement metrics (such as adjoint-based error metrics, prescribed volumes, etc.). Such mesh technology has the potential to drastically improve turnaround time for scale-resolving simulations for complex configurations and enabling wider use of high-fidelity CFD analysis for challenging turbulent flow problems. This research effort is expected to enable NASA solvers to interface with the resulting tool. The meshing tool should be designed to perform well on the emerging high-performance computing hardware. An additional area of research may include adaptive mesh refinement while a WMLES is progressing. Demonstration of mesh generation coupled with NASA CFD solvers (e.g., the unstructured grid code FUN3D) is considered essential for the solicited research.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.1 Aerosciences

Desired Deliverables of Phase I and Phase II:

- Software
- Research
- Analysis

Desired Deliverables Description:
Phase I:

1. Demonstrate fully automated unstructured mesh generation for canonical geometries as proof of concept.
2. Demonstrate accuracy and efficiency of the developed capability, using a NASA CFD solver (e.g., FUN3D).
3. Provide an executable of the mesh generation code and an Application Programming Interface (API to interface with NASA solvers for independent testing.

Phase II:

1. Further develop the mesh generation capability for WMLES and demonstrate on more complex topologies (e.g., NASA Common Research High-Lift Model (HLPW-4 configuration), NASA juncture flow model, multistream chevron nozzle (TMP17)).
2. Demonstrate solution accuracy.
3. Demonstrate weak and strong scaling of the mesh generation software pushing the capability limits.
4. Further mature coupling with NASA CFD solvers.
5. Deliver executable of mesh generation solver along with the API to NASA for its internal use.

State of the Art and Critical Gaps:
NASA's CFD Vision 2030 Study identified several impediments in computational technologies and this solicitation addresses one of those related to application of scale-resolving simulations needed for expanding the scope of application of CFD across the aircraft flight envelope, particularly in the prediction of maximum lift. This solicitation also addresses meshing needs to enable such computations.

Relevance / Science Traceability:
Various programs and projects of NASA missions use CFD for advanced aircraft concepts, launch vehicle design, and planetary entry vehicles. The developed technology will enable design decisions by Aeronautics Research Mission Directorate (ARMD) and Human Exploration and Operations Mission Directorate (HEOMD).

References:

1. https://www.nasa.gov/aeroresearch/programs/aavp
2. https://www.nasa.gov/aeroresearch/programs/tacp
3. NASA’s CFD Vision 2030 Study: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140003093.pdf
4. NASA's A Guide for Aircraft Certification by Analysis Study: https://ntrs.nasa.gov/citations/2021001540
5. FUN3D: https://software.nasa.gov/software/LAR-19638-1

Scope Title: Unstructured Mesh Generation for Icing

Scope Description:
Computational fluid dynamics (CFD) plays an important role in the design and development of a vast array of aerospace vehicles, from commercial transports to space systems. With the ever-increasing computational power, usage of higher fidelity, fast CFD tools and processes will significantly improve the aerodynamic performance of airframe and propulsion systems, as well as greatly reduce nonrecurring costs associated with ground-based and flight testing. Historically, the growth of CFD accuracy has allowed NASA and other organizations, including commercial companies, to reduce wind tunnel and single-engine component tests. Going forward, increased CFD fidelity for complete vehicle or engine configurations holds the promise of significantly reducing development costs, by enabling certification by analysis (CbA). Confidence in fast, accurate CFD and multidisciplinary analysis tools allow engineers to reach out of their existing design space and accelerate technology maturation schedules. Uncertainty quantification is a key technology in enhancing confidence in the prediction capability of the computational tools. NASA’s CFD Vision 2030 Study (https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140003093.pdf) highlighted the many shortcomings in the existing computational technologies used for conducting high-fidelity simulations, including multidisciplinary analysis and optimization, and made specific recommendations for investments necessary to overcome these challenges. A more recent study provided a long-term vision and a technology development roadmap to enable CbA for aircraft and engine certification (see https://ntrs.nasa.gov/citations/20210015404).

During the current cycle, proposals are solicited in mesh generation for the following CFD application:

Unstructured Mesh Generation for Icing: Another topic for which proposals are solicited is the study of icing effect on aircraft performance. Icing plays an important role in aircraft design and the certification process and, therefore, modeling and quantification of icing effects on aerodynamic performance (e.g., aircraft CLmax) is required, as pointed out in the CbA report referred to previously. This solicitation invites proposals for grid generation with imposed icing shapes to enable high-fidelity CFD analysis of relevant configurations. The objective is to use the developed capability with NASA unstructured grid CFD solvers and, therefore, the proposer will address such coupling along with the capability demonstration. The proposer will collect available icing data and use it to demonstrate the unstructured grid capability as well as simulate icing effect on aerodynamic performance particularly during high-lift flight configuration. Breakdown of the proposed work, including the strategy for capability demonstration, will be a critical factor in the evaluation process. The goal of this research is to provide an automated, efficient, and accurate tool for the intended purpose. Deliverables must include an Application Programming Interface (API) to interface the meshing tool with NASA CFD solvers, in particular FUN3D.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.1 Aerosciences

Desired Deliverables of Phase I and Phase II:

- Analysis
- Research
- Software

Desired Deliverables Description:
Phase I:

1. Demonstrate fully automated unstructured mesh generation for canonical wing geometries as proof of concept.

2. Demonstrate accuracy and efficiency of the developed capability, using a NASA CFD solver (e.g., FUN3D), for prediction of icing effect.
3. Provide an executable of the mesh generation code and an API to interface with NASA solvers for independent testing.

Phase II:

1. Further develop the mesh generation capability including icing and demonstrate on more complex topologies (high-lift applications are of particular interest).
2. Demonstrate solution accuracy.
3. Deliver executable of mesh generation tool, including icing effect, along with the API to couple with NASA unstructured grid solvers.

State of the Art and Critical Gaps:
NASA's CFD Vision 2030 Study identified several impediments in computational technologies and this solicitation addresses one of those related to application of scale-resolving simulations needed for expanding the scope of application of CFD across the aircraft flight envelope, particularly in the prediction of maximum lift. NASA's more recent study "A Guide for Aircraft Certification by Analysis" identified the need for computation of icing effects on aerodynamic performance. This solicitation also addresses meshing needs to enable such computations.

Relevance / Science Traceability:
Various programs and projects of NASA missions use CFD for advanced aircraft concepts, launch vehicle design, and planetary entry vehicles. The developed technology will enable design decisions by Aeronautics Research Mission Directorate (ARMD) and Human Exploration and Operations Mission Directorate (HEOMD).

References:

1. https://www.nasa.gov/aeroresearch/programs/aavp
2. https://www.nasa.gov/aeroresearch/programs/tacp
3. NASA’s CFD Vision 2030 Study: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140003093.pdf
4. NASA's Aircraft Certification by Analysis Study: https://ntrs.nasa.gov/citations/20210015404

A1.06 Vertical Lift Technology for Urban Air Mobility -Electric Motor Fault Mitigation Technology (SBIR)

Lead Center: GRC
Participating Center(s): AFRC, ARC, LaRC

Scope Title: Electric Vertical Takeoff and Landing (eVTOL) Electric Motor Fault Mitigation Technologies

Scope Description:
The expanding Urban Air Mobility (UAM) vehicle industry has generated a significant level of enthusiasm among aviation designers and manufacturers, resulting in numerous vehicle configurations. The majority of the prototype UAM vehicles have more than 4 rotors or propellers, have electric propulsion, carry 2 to 6 passengers, fly more like a helicopter (vertical take-off and landing) than a fixed-wing aircraft and will fly relatively close to the ground and near buildings. There are many technical challenges facing industry’s development of safe, quiet, reliable, affordable, comfortable, and certifiable UAM vehicles and vehicle operations. One of those challenges is the subject of this SBIR subtopic, namely, safe and reliable operation of electric motors (100- to 200-kW class) for eVTOL vehicles to accomplish UAM mission (numerous daily operations; hover-cruise-hover loading cycle) [Ref. 1].

[Megawatt electric propulsion systems for CTOL transport aircraft is addressed in the A1.04 Electrified Aircraft Propulsion subtopic.]

The application of the requested technologies should be relevant to the NASA Revolutionary Vertical Lift Technology (RVLT) Project’s reference concept vehicles [Refs. 2-3], which embody the key vehicle characteristics of the UAM vehicle configurations being designed throughout industry. Technologies proposed for this solicitation should be relevant to 100-kW-class motor-rotor powertrain elements with scalability in the 20- to 500-kW class. Due to the power levels envisioned for UAM vehicles, most will require high-voltage (>540 V) bus operation, with the corresponding high-voltage direct current (DC) protection devices to ensure safe systems [Ref. 4].

Through this solicitation, NASA is seeking advanced technologies supporting electric/hybrid-electric propulsion for the advance air mobility and specifically the UAM mission (concept of operations) in the areas of:

- Electric Machine/Motor Fault Detection and Fault Mitigation: This solicitation is seeking technology advancements that will address the fault detection and fault mitigation for electric machines used in eVTOL vehicle propulsion systems. There are several key faults that are typical for electric machines: electrical, mechanical, and magnetic. Through this Small Business Innovative Research (SBIR) solicitation, technologies are being sought that would preclude common electric machine faults and/or detect and mitigate the faults to ensure safe vehicle operations. Technologies targeting the mitigation of turn-to-turn and turn-to-ground stator short circuit faults in a permanent magnet aircraft generator and/or motor are of especially high interest. Technologies are sought that either allow a motor/generator to continue operating in the event of a stator short circuit or enable quick shut down of the motor/generator before the fault enters a thermal runaway condition.
- Electric Motor Performance Improvement Technology: Single Fluid Motor with High Power Density and High Reliability: Novel and innovative efforts are sought to develop high-performance electric drive motors that utilize a fluid as both the motor coolant and bearing lubricant. Vertical lift propulsion using electric motors to drive rotors and/or propellers offer the potential for lightweight and high efficiency partly through the elimination of ancillary systems found on conventional aircraft. Amongst these systems are hydraulic fluids and lubricating oils. For example, a direct-drive electric motor or those that utilize noncontact magnetic gearing (i.e., flux modulation machines) [Refs. 5-9] could function without lubricating oil provided their bearings could operate solely using the water-based coolants used for motor thermal management. Conventional steel-based ball and roller bearings are susceptible to corrosion and wear when operated using water. NASA has developed newly emerging NiTi (nickel-titanium) alloy bearings [Refs. 10-11] that are impervious to corrosion and have been shown to operate reliably when immersed in water. While a single-fluid electric motor utilizing oil could be conceived, the high viscosity of oils and their low heat capacity tend to limit electric motor power density. It is further recognized that magnetic, electrical, and rotordynamic characteristics of such machines are critical to success and are influenced by material selections. The use of emerging bearing material technologies, such as NiTi and ceramics, for bearings to operate well using a single fluid (such as water, water-based with additives, or appropriate dielectric fluid) [Refs. 12-13] could provide needed tribological, thermal, and electrical performance while achieving power density and reliability comparable to existing conventional designs. However, proposers will need to consider and address several considerations including bearing wear, bearing fatigue, strategy for robustness to debris carried by the fluid stream (including debris arising from bearing fatigue or wear), and bearing stiffness as these will influence the rotor-shaft-bearing subsystem. This topic specifically seeks electric motors using liquid-lubricated bearings. Electric motor concepts using grease-lubricated bearings are not within the scope of this topic.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.3 Aero Propulsion

Desired Deliverables of Phase I and Phase II:

- Analysis
- Research
- Prototype

Desired Deliverables Description:
Phase I of the SBIR should develop design concepts for specific technology advancements supported by analytical studies including modeling and simulation. Phase I effort should establish Phase II goals and should quantify projections of technology performance in the detection and mitigation of motor faults.

Phase II of the SBIR should further develop the designs and validate achievement of goals through additional analysis, modeling, and simulation and through system/component functionality experiments. Phase II incorporates experiments with aircraft relevant hardware available commercially or through partnership with an aircraft component supplier and modified with innovative technology from this SBIR effort.

State of the Art and Critical Gaps:
There are over 200 UAM vehicle concepts in varying stages of development. The immediate focus of the vehicle developers is overcoming obstacles on the path to certification. The public has experience flying in large transport and regional fixed-wing aircraft and are calibrated to associated safety levels for commercial air transportation. Detailed certification requirements for UAM vehicles are still under development by the relevant certifying authorities. For UAM aircraft, research is needed that addresses safety and reliability expectations of the traveling public and certifying authorities for the UAM mission. The concepts of operations for the UAM mission consists of numerous flights per day with power system/powertrain loading associated with vertical flight (hover) and forward flight for each flight. This concept of operations establishes unique safety and reliability challenges for the power system/powertrain. Technology advancements are required to achieve these challenges.

Relevance / Science Traceability:
This subtopic is relevant to the Aeronautics Research Mission Directorate (ARMD) Revolutionary Vertical Lift Technology (RVLT) Project under the Advanced Air Vehicle Program. The goal of the RVLT Project is to develop and validate tools, technologies, and concepts to overcome key barriers for vertical lift vehicles. The project scope encompasses technologies that address noise, speed, mobility, payload, efficiency, environment, and safety for both conventional and nonconventional vertical lift configurations. This subtopic directly aligns with the mission goals and scope in addressing safety and reliability of nonconventional vertical lift configurations. RVLT along with other ARMD projects are pursuing technologies, tools, and research that will enable new aviation markets to address the operational and vehicle requirements for the advance air mobility missions and specifically the UAM (air taxi) mission for VTOL vehicles.

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3. Johnson, W., Silva, C., and Solis, E., “Concept Vehicles for VTOL Air Taxi Operations,” AHS Specialists’ Conference on Aeromechanics Design for Transformative Vertical Flight, San Francisco, CA, 2018.
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7. Tallerico, T. F., Cameron, Z. A., and Scheidler, J. J., “Design of a Magnetic Gear for NASA’s Vertical Lift Quadrotor Concept Vehicle,” GRC-E-DAA-TN70579, 22 August 2019
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A1.08 Aeronautics Ground Test and Measurement Technologies (SBIR)

Lead Center: LaRC
Participating Center(s): ARC, GRC

Scope Title: Electromagnetic Interference (EMI) Detection and Mitigation in Higher Voltage/Higher Power Applications

Scope Description:
NASA is developing electric-powered aircraft under both the Electrified Aircraft Propulsion Technologies (EAPT) and Revolutionary Vertical Lift Technology (RVLT) projects, where testbeds are being used to investigate system interactions and power quality (PQ) to feed associated standards for these classes of vehicles. NASA is also working with the Federal Aviation Administration (FAA) to provide pertinent data for drafting of the certification processes. As part of the testbed development, NASA needs EMI and PQ test equipment for higher voltage/higher power applications, which does not currently exist. Additionally, NASA is investigating the use of fiber-Bragg-grating- (FBG-) based temperature sensors for monitoring temperatures in electric-powered vehicles, both in the electric motors and in the aircraft thermal management systems being developed. While the fiber optic sensing of temperature is immune to EMI, the interrogators used to send the broadband pulses of light down the fiber and process the reflected return signals to measure the temperature at the FBG locations along the fiber are currently not immune to EMI. The objective of the Small Business Innovation Research (SBIR) subtopic is twofold: first to develop EMI and PQ test equipment, and secondly, to develop EMI immune optical interrogators for use on electrified aircraft. For RVLT applications, the requirements are to develop EMI equipment (power amplifiers, isolation transformers, ripple and surge injection units, etc.) and power equipment (power amplifiers, isolation transformers, fault injection units, dynamic load banks, and wide bandwidth emulators/power supplies) capable of testing systems/loads with

operating voltages of at least 650 Vdc (1 kV preferred), 150 A (300 A preferred), with minimum bandwidths of direct current (DC) to 250 kHz (although may vary depending on application), and operating up to altitudes of 15,000 ft. The 250 kHz is of interest for investigation of EMI noise. For EAPT applications, the requirements are to develop similar EMI and power equipment capable of testing systems/loads with operating voltages of at least 1 kVdc and 1 kA, with a bandwidth of DC to 50 kHz and operating at altitudes up to 35,000 ft. EAPT also seeks to develop optical interrogators with a nominal optical bandwidth of at least 40 nm and a high spectral resolution (1 pm) that are immune to EAPT-specified level of EMI above. These high-EMI environments are endemic to both ground- and flight-based hybrid electric systems, and, hence, will have applicability to both test regimes. Initial systems for ground testing will not be constrained by weight, however, future flight-based systems should also be designed for minimized system weight and size.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.3 Aero Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
The desired deliverables for Phase I would be, at a minimum, detailed design and analysis of proposed equipment. An added benefit would be the build of breadboard units to validate the proposed approach.

The desired deliverables for Phase II would be prototype hardware validated through test.

State of the Art and Critical Gaps:
EMI and PQ test equipment for these higher voltage/higher power applications does not exist. With the advent of electrified aircraft efforts, this type of test equipment will be critical in evaluating safety and system interaction aspects for the myriad of designs being proposed for the urban air mobility market.

Relevance / Science Traceability:
This scope ties directly to Aeronautics Research Mission Directorate (ARMD) via the RVLT project by providing technology critical for evaluating architectures under investigation at NASA, and most likely would also have application to the larger aircraft testbed under development through EAPT.

References:

1. ARMD Strategic Implementation Plan: https://www.nasa.gov/aeroresearch/strategy

Scope Title: Flow Diagnostics for High-Speed Flows

Scope Description:
Spatially and temporally resolved, molecular-based diagnostics are sought for high-speed wind tunnel flows (supersonic, hypersonic), both with and without combustion. Improved measurement capabilities are needed for velocity, temperature, density, and/or species concentrations in harsh wind tunnel environments, from short-duration (~msec) to long-duration (~min) flow facilities. Measurement systems should be reliable and robust and preferably would be able to be implemented in multiple wind tunnel facilities and facility types including blowdown tunnels, combustion-heated tunnels, shock tubes, shock tunnels, and arc jets. Planar or volumetric, spatially resolved measurements are preferred. Ability to measure multiple parameters simultaneously is desirable. The ability to time-resolve unsteady flows so that frequency spectra of the

measured phenomena can be obtained is also desirable. Measurement systems should be validated against accepted standards (thermocouples, calibration flames, etc.) to determine measurement accuracy and precision. Proposals should project anticipated accuracies and precisions of the proposed measurement system(s) based on prior cited or demonstrated work.

One area of emphasis is measurement of temperature, water vapor concentrations, and velocity at the nozzle exit of large (up to 8-ft diam.) hypersonic tunnels to quantify facility performance and to determine test article inflow conditions. Such flow fields may contain water droplets and the size, quantity, and distribution of these droplets is also of interest to NASA. Measurements are needed at high repetition rates (tens of kilohertz) and should be able to operate continuously or repeatedly for a duration of several minutes to obtain appropriate amount of data to improve statistical error and provide detailed information about the time varying nature of these flow fields. The technologies described above are all critical for evaluating and analyzing high-speed vehicle concepts and technologies in support of several different NASA missions.

Expected TRL or TRL Range at completion of the Project: 4 to 7

Primary Technology Taxonomy:
Level 1: TX 13 Ground, Test, and Surface Systems
Level 2: TX 13.X Other Ground, Test, and Surface Systems

Desired Deliverables of Phase I and Phase II:

- Hardware
- Prototype
- Analysis
- Research
- Software

Desired Deliverables Description:
The deliverables for the Phase I research should include proof of concept of proposed idea along with a design for the comprehensive system that would be developed in Phase II, including detailed analysis of the expected performance (spatial resolution, time response, accuracy, precision, etc.).

The expected deliverables at the end of the Phase II effort is a usable system to be deployed in a NASA facility and training for NASA personnel. Demonstration of the measurement system in a NASA facility would be beneficial and strongly encouraged.

State of the Art and Critical Gaps:
There are very limited technologies for measuring nozzle exit conditions in hypersonic facilities. Some systems exist but there have been very limited applications. A technology that can measure nozzle exit conditions could also be used for engine inlet and outflow conditions as well. A promising technology was developed and used to study aircraft engine outflow plumes using Air Force Small Business Innovation Research (SBIR) support. This included using an array of laser beams to perform absorption spectroscopy at the exit of a J-85 jet engine. Temperature and water vapor concentrations were measured over an ~1- by 1-m area. A gap in this technology is that the gas velocity, a highly desirable parameter, was not measured. Another gap that exists is the need expressed by facility managers and customers at some of the larger combustion-heated hypersonic facilities at NASA to measure water vapor droplet size and concentration (water droplets are an undesirable consequence of combustion heating and can affect engine performance).

Relevance / Science Traceability:
The target application of this technology is in facilities like the 8-Foot High-Temperature Tunnel at NASA Langley. However, the technology also has other applications such as measuring inflow or outflow for engines being tested at NASA Glenn. The technology could also be applied to measure inflow conditions in other types of facilities like shock tube and shock tunnels as well as conventional aeronautical testing facilities.

References:

1. ARMD Strategic Implementation Plan: https://www.nasa.gov/aeroresearch/strategy

Focus Area 19 Integrated Flight Systems

This focus area includes technologies that contribute to the Integrated Aviation Systems Program's (IASP) objectives. IASP conducts flight-oriented, system-level research and technology development to effectively mature and transition advanced aeronautic technologies into future air vehicles and operational systems, including urban air mobility. IASP focuses on the rigorous execution of highly complex flight campaigns and related experiments for the benefit of the country and U.S. flying public. IASP often works collaboratively with other ARMD programs (e.g., Advanced Air Vehicles Program) to facilitate cross-cutting flight test activities. One such demonstration is the Advanced Air Mobility National Campaign, which will provide key knowledge and data to both the aviation community and the FAA to inform regulations and standards for this new market.

A2.01 Flight Test and Measurement Technologies (SBIR)

Lead Center: AFRC

Participating Center(s): ARC, GRC, LaRC

Scope Title: Flight Test and Measurement Technologies

Scope Description:

NASA continues to use flight research as a critical element in the maturation of technology. This includes developing test techniques that improve the control of in-flight test conditions, expand measurement and analysis methodologies, and improve test data acquisition and management with sensors and systems that have fast response, low volume, minimal intrusion, and high accuracy and reliability. By using state-of-the-art flight test techniques along with novel measurement and data acquisition technologies, NASA and the aerospace industry will be able to conduct flight research more effectively and also meet the challenges presented by NASA and industry’s cutting-edge research and development programs.

NASA's Flight Demonstrations and Capabilities (FDC) Project supports a variety of flight regimes and vehicle types ranging from low-speed, subsonic applications and electric propulsion through transonic and high-speed flight regimes. Therefore, this solicitation can cover a wide range of flight conditions and vehicles.

NASA also requires improved measurement and analysis techniques for acquisition of real-time, in-flight data used to determine aerodynamic, structural, flight control, and propulsion system performance characteristics. These data will be used to provide information necessary to safely expand the flight and test envelopes of aerospace vehicles and components. This requirement includes the development of sensors for both in situ and remote sensing to enhance the monitoring of test aircraft safety and atmospheric conditions during flight testing.

Flight test and measurement technologies proposals may significantly enhance the capabilities of major government and industry flight test facilities. Proposals may address innovative methods and technologies to reduce costs and extend the health, maintainability, communication, and test techniques of flight research support facilities to directly enhance flight test and measurement.

Areas of interest emphasizing flight test and measurement technologies include:

- Measurement technologies for in-flight steady and unsteady aerodynamics, juncture flow measurements, propulsion airframe integration, structural dynamics, stability and control including related to turbulence, and propulsion system performance in order to validate and improve flight modeling for next-generation vertical takeoff and landing (VTOL) vehicles.
- Advancement of miniaturization or portability of in situ and/or onboard sensing and/or integrated secured remote services for use in real-time decision making.

- Prognostic and intelligent vehicle health monitoring for hybrid and/or all-electric propulsion systems using an adaptive embedded control systems. Note: Only sensors to detect failures and for vehicle health monitoring will be considered. Proposals relating to flight control changes and other algorithms that respond to health issues and damage detected by sensors are covered under Subtopic A2.02 and will be declined in this subtopic.
- Improved ruggedized single-longitudinal mode wideband wavelength-sweeping laser system design for in situ flight structural health monitoring to be operated in aircraft, specifically for optical frequency domain reflectometry (OFDR) technology utilized in NASA's fiber optics sensing system (FOSS).
- Sensing technologies, such as wireless sensors, that can be used for flight test instrumentation and flight modeling verification for manned and unmanned aircraft. Emphasis should be on developing a variety of specialized low-profile sensors that are capable of participating in a synchronized, high data rate, and high data volume diverse wireless sensor measurement network with a capability to deliver time-stamped/encrypted data to a central node. For example, an interrogation unit should support the wireless sensor itself and also communicate with the flight unit. This area also includes wireless (nonintrusion) power transferring techniques and/or wirelessly powering remote sensors.

The emphasis here is for articles to be developed for flight test and flight test facility needs.

The technologies developed for this subtopic directly address the technical challenges in the Aeronautics Research Mission Directorate (ARMD) Integrated Aviation Systems Program (IASP) and the Electrified Powertrain Flight Demonstration (EPFD) and FDC Projects. The FDC Project conducts complex flight research demonstrations to support multiple ARMD programs. FDC is seeking to enhance flight research and test capabilities necessary to address and achieve the ARMD strategic plan. Technologies for this subtopic could also support Advanced Air Vehicle Program (AAVP) projects: Commercial Supersonic Technology (CST) and Revolutionary Vertical Lift Technology (RVLT), as well as the Aerosciences Evaluation and Test Capabilities (AETC) Portfolio Office.

For technologies focused on ground testing or operations, please consider submitting to subtopic A1.08 Aeronautics Ground Test and Measurement Technologies, as ground testing technologies will be considered out of scope for this A2.01 subtopic.

For technologies with space-only applications, please consider submitting to a related space subtopic as space-only technologies will be considered out of scope for this A2.01 subtopic.

Proposals relating to flight control changes and other algorithms that respond to health issues and damage detected by sensors are covered under subtopic A2.02 and will be declined in this subtopic

Proposals that focus solely on flight vehicle development rather than focusing on technologies applicable to flight test and measurement will be considered out of scope for the A2.01 subtopic.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.2 Flight Mechanics

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
For a Phase I effort, the small business is expected to develop a proof-of-concept demonstration of a technology and generate a midterm report showing progress of the work. A summary report is expected at the end of Phase I that describes the research effort's successes, failures, and the proposed path ahead.

For a Phase II effort, the small business should show a maturation of the technology that allows for a presentation of a thorough demonstration. Most ideally, a delivery of a prototype that includes beta-style or better hardware or software that is suitable to work in ground testing and can be proven, via relevant environment testing, to be working in flight environment. This relevant environment testing would satisfy NASA's technical readiness level expectations at the end of Phase II.

State of the Art and Critical Gaps:
Current atmospheric flight systems cover a large range of uses from point-to-point drones, to high-performance small aircraft, to large transports, to general aviation. In all areas, advancements can be possible if insights can be gained, studied, and used to create new technologies. New insights will require an evolution of current testing and measurement techniques, as well as novel forms and implementations. Known gaps include: wireless instrumentation for flight, advanced telemetry technique, intelligent internal state monitoring for air and space vehicles, techniques for studying sonic booms, advanced techniques for capturing all dimensions of system operation and vehicle health (spatial/spectral/temporal), and extreme environment high-speed large-area distributive sensing techniques. Along with these comes secure telemetry of data to ensure informed operation of the flight system.

Relevance / Science Traceability:
The technologies developed for this subtopic directly address the technical and capability challenges in ARMD's FDC Project. FDC conducts complex flight research demonstrations to support different ARMD programs. FDC is seeking to enhance flight research and test capabilities necessary to address and achieve ARMD’s strategic plan. Also, they could support IASP and EPFD projects as well as CST and RVLT projects and the AETC Portfolio Office.

References:

1. NASA’s Low-Boom Flight Demonstration mission: https://www.nasa.gov/X59
2. NASA Armstrong Fact Sheet: NASA X-57 Maxwell: https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-109.html
3. NASA Armstrong Fact Sheet: Fiber Optic Sensing System: https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-110-AFRC.html
4. Schlieren Images Reveal Supersonic Shock Waves: https://www.nasa.gov/centers/armstrong/features/shock_and_awesome.html
5. NASA’s Commercial Supersonic Technology (CST) project: https://www.nasa.gov/aeroresearch/programs/aavp/cst
6. NASA’s Revolutionary Vertical Lift Technology (RVLT) project: https://www.nasa.gov/aeroresearch/programs/aavp/rvlt
7. NASA’s Aerosciences Evaluation and Test Capabilities (AETC) Portfolio Office: https://www.nasa.gov/aetc

A2.02 Enabling Aircraft Autonomy (SBIR)

Lead Center: AFRC
Participating Center(s): ARC, GRC, LaRC

Scope Title: Enabling Aircraft Autonomy

Scope Description:

The increased use of automation on aircraft offers significant advantages over traditional manned aircraft for applications that are dangerous to humans, long in duration, and/or require a fast response and high degree of precision. Some examples include remote sensing, disaster response, delivery of goods, industrial inspection, and agricultural support. Advanced autonomous functions in aircraft can enable greater capabilities and promise greater economic and operational advantages. Some of these advantages include a higher degree of resilience to off-nominal conditions, the ability to adapt to dynamic situations, and less reliance on humans during operations.

There are many barriers that are restricting greater use and application of autonomy in air vehicles. These barriers include, but are not limited to, the lack of methods, architectures, and tools that enable:

- Cognition and multi-objective decision making.
- Cost-effective, resilient, and self-organizing communications.
- Prognostics, survivability, and fault tolerance.
- Verification and validation technology and certification approaches.

NASA and the aviation industry are involved in research that would greatly benefit from breakthroughs in autonomous capabilities that could eventually enable the Advanced Air Mobility (AAM) mission. A few of the areas of research and missions are listed below:

- Remote missions utilizing one or more unmanned aircraft systems (UAS) would benefit from autonomous planning algorithms that can coordinate and execute a mission with minimal human oversight.
- Detect and avoid algorithms, sensor fusion techniques, robust trajectory planners, and contingency management systems can enable AAM and higher levels of UAS integration into the National Airspace System (NAS).
- Fault detection, diagnostics, and prognostics capabilities can inform autonomous contingency management systems.

This subtopic is intended to break through these and other barriers with innovative and high-risk research, enabling greater use of autonomy in NASA research, civil aviation, and, ultimately, the emerging AAM market. It is important to note that any proposals for UAS development and sensors for vehicle health/failure detection will not be considered.

The following two research areas are the primary focus, and any submissions must show a strong relevance to these areas to be considered.

- Prognostics, survivability, and fault tolerance: Techniques are required that can understand vehicle health and critical failures, anticipate failures, and autonomously replan or execute emergency landings safely. Prognostics technologies capable of providing accurate predictions in a computationally constrained environment, such as that expected for small vehicles, are also needed. Examples include, but are not limited to, new, efficient approaches and algorithms and hybrid edge/cloud approaches. Proposals for vehicle health and failure detection are covered under Subtopic A2.01 and will be declined under this subtopic.
- Verification and validation technology and certification approaches: New methods of verification, validation, and certification need to be developed to enable application of complex systems to be certified for use in the NAS. Proposed research could include novel hardware and/or software architectures that expedite or enable alternates to traditional verification and validation requirements. Proposals should reference material on emerging standards for autonomy certification, including the American Society for Testing and Materials (ASTM) autonomy guidelines and emerging Federal Aviation Administration (FAA) considerations for small aircraft, UAS, and UAM. For example, proposals could reference standards coming out of ASTM AC377.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 10 Autonomous Systems
Level 2: TX 10.X Other Autonomous Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I deliverables should include, but are not limited to:

- A technology demonstration in a simulation environment that clearly shows the benefits of the technology developed.
- A final report clearly stating the technology challenge addressed, the state of the technology before the work was begun, the state of technology after the work was completed, the innovations that were made during the work period, the remaining barriers in the technology challenge, a plan to overcome the remaining barriers, and a plan to infuse the technology.
- A written plan to continue the technology development and/or to infuse the technology. This may be part of the final report.

Phase II deliverables should include, but are not limited to:

- A useable/workable prototype of the technology (or software program), such as toolboxes, integrated hardware prototypes, training databases, or development/testing environments, are highly desired.
- A technology demonstration in a relevant flight environment that clearly shows the benefits of the technology developed.
- A final report clearly stating the technology challenge addressed, the state of the technology before the work was begun, the state of technology after the work was completed, the innovations that were made during the work period, the remaining barriers in the technology challenge, a plan to overcome the remaining barriers, and a plan to infuse the technology developments.
- There should be evidence of infusing the technology or a clear written plan for near-term infusion of the technology. This may be part of the final report.

State of the Art and Critical Gaps:
Current autonomous systems have limited capabilities, have poor perception of the environment, require human oversight, and need special clearances to fly in the NAS. Future autonomous systems with higher degrees of autonomy will be able to freely fly in the NAS but will require certifiable software that ensure a high degree of safety assurance. Additionally, advanced sensors and more sophisticated algorithms that can plan around other UAS/AAM vehicles and obstacles will be needed. Therefore, the technologies that will be required to advance the state of the art are as follows:

1. A certification process for complex nondeterministic algorithms.
2. Prognostics, vehicle health, and sensor fusion algorithms.
3. Decision making and cooperative planning algorithms.
4. Secure and robust communications.

Relevance / Science Traceability:
This subtopic is relevant to the NASA Aeronautics Research Mission Directorate (ARMD) Strategic Thrust 5 and Strategic Thrust 6.

- Transformative Aeronautics Concepts Program (TACP): https://www.nasa.gov/aeroresearch/programs/tacp

- Airspace Operations and Safety Program (AOSP): https://www.nasa.gov/aeroresearch/programs/aosp
- Integrated Aviation Systems Program (IASP): https://www.nasa.gov/aeroresearch/programs/iasp

References:

1. Strategic Implementation Plan for NASA's ARMD: https://www.hq.nasa.gov/office/aero/pdf/armd-strategic-implementation-plan.pdf
2. Autonomous Systems: NASA Capability Overview (2018 presentation by Terry Fong, Senior Scientist): https://www.nasa.gov/sites/default/files/atoms/files/nac_tie_aug2018_tfong_tagged.pdf
3. Unmanned Aircraft Systems Integration in the National Airspace System (UAS Integration in the NAS) Project, Concluded Sept 2020: https://www.nasa.gov/aeroresearch/nasa-explores-smart-data-for-autonomous-world
4. Explore Flight: We're With You When You Fly: https://nari.arc.nasa.gov/aero-autonomy

A2.03 Advanced Air Mobility (AAM) Integration (SBIR)

Lead Center: HQ
Participating Center(s): LaRC

Scope Title: Support Community AAM and Community Engagement Planning

Scope Description:
AAM is a concept for safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions. AAM includes many potential mission types (e.g., passenger transport, aerial work, and cargo transport) that may be accomplished with many different aircraft types (e.g., manned and unmanned; conventional, short, and/or vertical takeoff and landing; all electric and hybrid electric; etc.) and are envisioned to bring aviation into people's daily lives. Although passenger-carrying urban air mobility (UAM) is an AAM mission with much investment, other AAM missions, including but not limited to "thin haul"/regional air mobility, small package delivery, and medical transport, are also of interest. Responses to this subtopic are not limited to strictly any single AAM mission.

The AAM ecosystem can be viewed as being comprised of three pillars: vehicle, airspace, and community. For this discussion community consists of governmental decision makers and those that support them. Significant investment is being made in local vehicle manufacturing companies, and some investment is being made into local airspace companies, while local and tribal AAM planning entities are having to prioritize their AAM efforts amongst their other funding obligations.

The integration of AAM into a multimodal transportation system is a complicated endeavor involving leveraging existing infrastructure, working with existing and new stakeholders in an evolving regulatory environment. The purpose of this SBIR is to energize an industry around supporting the local community AAM planning efforts while recognizing that these local communities may not have the resources to conduct the planning needed to enable AAM at UAM maturity level-4 (UML-4) on the timeline desired by the entities in the other two pillars. Activities proposed by companies desiring to enter this market shall fill a gap in the communities' current planning efforts.

Three areas of near-term community need have surfaced from NASA conversations with state and city departments of transportation. These include (1) meeting AAM educational and outreach needs, (2) support for planning demonstrations, and (3) AAM system planning.

Educational: A clear and pressing need for education of both local decision makers and the local flying and nonflying public has been identified. The goal of companies proposing to this Small Business Innovation Research (SBIR) would be to enable a robust and cost-conscious capability available to local decision makers to support them effectively providing a broad range of materials at various levels of detail for their use when engaging entities such as local city councils, mayors, planning boards, and infrastructure planning teams. The company would also be able to provide materials and be able to support organizations that directly engage with and inform the public such as Metropolitan Planning Organizations (MPOs), science museums, and Science, Technology, Education, and Mathematics (STEM)-focused organizations. The company should also be capable of providing materials and outreach capabilities not readily available to these organizations, such as locally targeted virtual reality simulations of AAM operations. The company should also have a detailed and sustained familiarity with the local or state culture, nuances, customs, and values to be able to provide a long-term resource to these planning officials and to be able to craft outreach materials that connect citizens with information and in ways relevant to their local situation. Phase I would be to begin executing the plan in the proposal and developing the materials described as part of the plan. Ideally, the plan would include an initial target local partner (customer). Phase I would also include identifying and making contact with a regional or statewide customer base. Phase II would be to provide services to these regional or statewide customers and cementing relationships and a sustainable business.

AAM Demonstrations: Conducting AAM demonstrations is a complicated and involved process that could be markedly easier with expertise associated with having experience and the federal relationships in conducting previous demonstrations. This SBIR would be focused on maturing a company’s capability to support local decision makers in the planning and execution of local AAM demonstrations. These demonstrations would ideally be focused on “public-good” missions. The capability should include development and analysis of use case(s) or compelling missions, identification and forming the stakeholders needed to execute a demonstration into an effective team, the capability to develop and execute the local outreach necessary for a successful demonstration, knowledge of the local and federal regulations and decision makers critical for the successful execution of the demonstration, and the development and execution of a demonstration that achieves the desired goals whether they are a one-time demonstration or to enable a sustainable capability. Phase I would be to develop a generic plan that can be tailored for each demonstration customer and to compile case studies from previous AAM case studies that would provide lessons learned for future demonstrations and be available for incorporation into the generic plan. Phase I would also identify several localities seeking to conduct or already planning demonstrations. Phase II would be to support a certain number of these efforts in whichever stage they are currently in. Phase II would also include providing overviews to other localities interested in conducting demonstrations with the goal of beginning to build a sustainable customer base.

AAM System Planning Support: Planning for an urban, regional, or statewide passenger or large cargo carrying AAM system is a significantly complicated endeavor. It includes possessing the relevant subject matter expertise, the ability to conduct economic and demand analysis, system modeling and trade analysis, and to be able to provide decision makers either the tools to make those decisions or the material necessary to support the decision making process. An AAM system could be a system of urban vertiports or a statewide system leveraging existing general aviation airports supplemented by new vertiports. This planning capability is not expected to be a short-term endeavor but could potentially span multiple years from the development of a plan, through its initial construction and updating planning assumptions and analysis as the system matures. The purpose of this SBIR is to create and support the development of companies focused and able to provide long-term, local AAM planning support. A locally focused and long-term strategy would enable the building of long-term partnerships and relationships with local stakeholders including academic entities, business groups, and local and regional planning officials along with an awareness of and appreciation for local culture, customs, and values. Phase I of this SBIR would be to plan the structure needed, obtain the expertise, and identify the data sources needed to conduct AAM system planning for the locality identified in the proposal. Phase II would be to begin to support the locally needed long-term planning efforts.

Proposers seeking funding for aircraft design and individual aircraft operations should submit to vehicle technology subtopic in A1 and proposers seeking airspace design and operations funding should submit to A3 subtopics.

Expected TRL or TRL Range at completion of the Project: 1 to 6

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.X Other Software, Modeling, Simulation, and Information Processing

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Deliverables are further detailed in each scope.

Phase I Deliverables would include development of initial materials to support (1) meeting AAM educational and outreach needs, (2) support for planning demonstrations, and (3) AAM system planning. Phase I would also include identifying and contacting a regional or statewide customer base.

Phase II would be to provide services to these regional or statewide customers for education, demonstration planning, or AAM system planning as applicable.

State of the Art and Critical Gaps:
Current transportation planning is focused on either airport-based aviation or ground transportation. There are few resources for AAM planning and planning for AAM to be integrated into these modes of transportation. There is a dearth of small businesses that can bring deep local knowledge and the potential for long-term relationships to these communities. These 3 areas have been identified as near-term critical gaps as part of the partnership with 5 departments of transportation. The timing is also ideal to get these companies up and running as demonstrations are currently being planned and executed and the first electric vertical takeoff and landing (eVTOL) aircraft are expected to be certified in 2024.

Relevance / Science Traceability:
This subtopic is relevant to the Aeronautics Research Mission Directorate (ARMD) AAM Mission and the 8 projects supporting that mission.

References:

1. NASA's National Aeronautics Committee briefings: https://www.nasa.gov/aeroresearch/aero-nac-committee
2. George Price et al., "Urban Air Mobility Operational Concept (OpsCon) Passenger-Carrying Operations," NASA\CR—2020-5001587
3. https://www.nasa.gov/aeroresearch/one-word-change-expands-nasas-vision-for-future-airspace/
4. UAM UML-4 ConOps https://sti.nasa.gov/
5. FAA UAM ConOps 1.0 https://nari.arc.nasa.gov/sites/default/files/attachments/UAM_ConOps_v1.0.pdf
6. National Academies Report: https://www.nap.edu/catalog/25646/advancing-aerial-mobility-a-national-blueprint
7. Kenneth H. Goodrich and Colin R. Theodore, "Description of the NASA Urban Air Mobility Maturity Level (UML) Scale," AIAA SciTech 2021 https://arc.aiaa.org/doi/abs/10.2514/6.2021-1627

Scope Title: Reconfigurable Vertiport Surface Marking

Scope Description:

AAM is a concept for safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions. AAM includes many potential mission types (e.g., passenger transport, aerial work, and cargo transport) that may be accomplished with many different aircraft types (e.g., manned and unmanned; conventional, short, and/or vertical takeoff and landing; all electric and hybrid electric; etc.) and are envisioned to bring aviation into people's daily lives. Although passenger-carrying urban air mobility (UAM) is an AAM mission with much investment, other AAM missions, including but not limited to "thin haul"/regional air mobility, small package delivery, and medical transport, are also of interest. Responses to this subtopic are not limited to strictly any single AAM mission.

AAM at UAM maturity level-4 (UML-4) envisions multiple vehicle types utilizing multiple vertiports variously configured from one to multiple landing pads. It is also envisioned that these vehicle types will mature as more experience is gained to achieve safety and performance improvements. Additionally, the Federal Aviation Administration (FAA) is currently working on the design advisory circular for these vehicles, and while the planned 2022 engineering brief will meet early needs, definitive design guidance is likely several years away. These and many more factors will impact the markings on vertiport surfaces. While airports are well served by fixed pavement markings, future vertiports could achieve the needed degree of flexibility with reconfigurable Touchdown and Lift Off (TLOF) and Final Approach and Takeoff (FATO) areas markings. Reconfigurable surface markings could also serve to assist with the control of embarking and debarking passengers.

Expected TRL or TRL Range at completion of the Project: 1 to 3

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.X Other Manufacturing, Materials, and Structures

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:
Phase I of this Small Business Innovation Research (SBIR) would be to design a vertiport surface both meeting current surface performance criteria that also incorporates reconfigurable markings.

Phase II of this effort would be to manufacture and demonstrate this surface and begin the process to obtain FAA approval for utilization at future vertiports.

State of the Art and Critical Gaps:
Currently surface markings at airports and heliports are painted on the surface and not reconfigurable without significant effort. Vertiports capable of servicing passengers do not currently exist in the U.S. as design criteria does not exist and no electric vertical takeoff and landing (eVTOL) have been certified.

Relevance / Science Traceability:
With the issuance of the FAA's vertiport design advisory circular not expected until 2025, many entities are hesitant to invest significant resources in infrastructure that has the potential to not meet future standards, requirements, or regulations. The ability to have a vertiport surface that is reconfigurable would reduce the risk for vertiport surfaces to not meet future standards, requirements, or regulations; increase safety; allow vertiport configurations that are specific to a vehicle type; and reduce the cost associated with reconfiguring markings to meet future updated standards, requirements, or regulations.

References:

1. FAA Airport Technology Research & Development Branch Home Page: https://www.airporttech.tc.faa.gov/Airport-R-D

2. State of the art: Asphalt for airport pavement surfacing: https://www.sciencedirect.com/science/article/pii/S1996681417300068
3. 150/5390-2D - Draft AC 150/5390-2D, Heliport Design: https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/1038739
4. Standards for Airport Markings: https://www.faa.gov/documentLibrary/media/Advisory_Circular/150-5340-1M-Chg-1-Airport-Markings.pdf

Scope Title: Low-Altitude Meteorological Information Supplemental Data Service

Scope Description:

Currently low-level AAM operations operate either under visual line of sight or under a waiver for beyond visual line of sight (BVLOS). Frequently, if local, approved weather stations, e.g., at an airport located a distance from the operations, reports instrument meteorological conditions (IMC), the entire area is assumed to be under IMC for BVLOS flights. Often, the planned route or area of AAM operations is under visual flight rules (VFR) conditions even though the weather station is reporting IMC or critical weather conditions. The use of data from not currently aviation-approved sensors to identify current local conditions that can be correlated to the data from the selected weather sensor could determine conditions when the certified weather sensor is reporting IMC and the intended area or route of flight is actually under VFR conditions. For example, the weather at Monterey Bay Regional Airport in California is 0 vertical feet and 0 mi horizontally with no wind and an operator wishes to fly a cargo delivery from Carmel Valley where they can see at least 1,000 ft and 3 mi and their weather station says winds are 5 to 7 kn to a customer in Big Sur, where the customer verifies that the weather is also 1,000 ft and 3 mi with similar winds. The weather between the Valley and Big Sur is not serviced by an approved aviation weather station, but several traffic cameras along the proposed route show the tops of local buildings, images of buildings 3 mi in the distance, and the local vegetation relatively motionless. The operator could utilize this information to determine if the weather-based risk to the flight is acceptable and within the limits of their operating waiver and perform the mission. In a second similar case except where the winds at the regional airport were 15 kn and the traffic cameras show local vegetation moving significantly, the operator could then determine that the winds along the route could exceed the operating limits of the aircraft and determine that the risk is too high and not perform the mission. This effort would determine that there is not a high degree of correlation of visibility between the airport and the local surrounding areas but that there was a high degree of correlation between the winds at the airport and those in the surrounding area.

Another potential scenario is around winds aloft. It could be feasible to deploy enough wind lidars to determine with a high degree of accuracy the winds aloft all along a specific route. An effort under this Small Business Innovation Research (SBIR) scope would be to correlate winds speeds aloft with ground windspeeds. This would allow for the deployment of expensive wind lidars and other sensing equipment during initial installation of weather sensing networks to be gradually replaced with less expensive sensors that could utilize this information to provide aloft wind speed information that could be validated at specific points by airborne traffic instead of continuing to maintain an expensive sensing network. It would also identify situations where correlations start to break down or are not possible, for example, around a thunderstorm.

Given the highly localized nature of this effort, it is anticipated that to be effectively commercialized, the location for the research would need to be in conjunction with either current small unmanned aerial system (sUAS) operations or a passenger/large cargo carrying AAM demonstration/planned early operation that would have a high likelihood of potential customers for the capability/data.

Expected TRL or TRL Range at completion of the Project: 1 to 3

Primary Technology Taxonomy:
Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
Level 2: TX 11.4 Information Processing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software
- Hardware

Desired Deliverables Description:
Phase I will deliver a plan to identify selected reference stations (weather or other sensors, e.g., camera) with accessible access to past and present data, potential low-level routes or areas either being used or planned for early AAM operations (sUAS or vehicles sized to carry passengers), and obtain past reports or plan to develop a collection of adverse weather conditions that can be correlated to topography or pilot reports in the vicinity of the reference stations, low-level routes, and areas. The plan should also outline the methodology to be more fully developed during Phase II and identify opportunities to conduct Phase II investigations in multiple localities.

Phase II would be to collect the data identified in Phase I, refine and execute the methodology outlined in Phase I, and implement that methodology to evaluate whether the conditions along the routes/within the areas actually satisfy VFR or other conditions when the reference stations are reporting IMC or other conditions.

State of the Art and Critical Gaps:
Currently there are a limited number of sensors beyond airports that are able to provide actual weather conditions to aircraft flying in the areas envisioned by AAM operations. Installing infrastructure of equal capabilities across the entire U.S. would be prohibitively expensive. This supplemental service would serve to leverage the existing sensors in combination with data correlated from past observations to be able to predict specified routes or areas are accessible to low-level flight when heights of cloud bases at selected reference stations reach specified values. For the winds aloft case, they are currently measured by balloons or onboard aircraft sensors. This results in few, specific point measurements versus a broader data set that would support denser operations.

Relevance / Science Traceability:
Current sUAS operations are largely using risk-based methodologies to determine whether their vehicles can safely fly in weather conditions provided by a limited number of sensors. This effort would provide a methodology that would provide additional data to inform these risk-based decisions.

References:

1. NASA UAM ConOps: https://sti.nasa.gov/

Scope Title: Multipurpose AAM Sensor Networks

Scope Description:
AAM is a concept for safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions. AAM includes many potential mission types (e.g., passenger transport, aerial work, and cargo transport) that may be accomplished with many different aircraft types (e.g., manned and unmanned; conventional, short, and/or vertical takeoff and landing; all electric and hybrid electric; etc.) and are envisioned to bring aviation into people’s daily lives. Although passenger-carrying urban air mobility (UAM) is an AAM mission with much investment, other AAM missions, including but not limited to “thin haul”/regional

air mobility, small package delivery, and medical transport, are also of interest. Responses to this subtopic are not limited to strictly any single AAM mission.

At UAM maturity level-4 (UML-4), it is envisioned there will be multiple sensor types networked to perform the functions necessary for safe and efficient movement of passengers and cargo. These networks include sensors for navigation, surveillance, and weather. Types of sensors will include radars, lidars, anemometers, thermometers, and the novel use of sensors such as traffic cameras. Independent sensors could be purchased, installed, and networked to satisfy each need; however, this would be inefficient and expensive. Localities are also investing funds in installing significant networks for both citizen internet connectivity and other efforts such as connected vehicles. This effort is to identify the opportunities and drawbacks associated with multipurpose usage of sensors and networks.

Expected TRL or TRL Range at completion of the Project: 1 to 3

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:
Effort under Phase I of this Small Business Innovation Research (SBIR) would be to collect or catalog performance requirements and capabilities for navigation, surveillance, weather, and other sensors that could potentially perform multiple functions. The effort would also catalog the existing or planned networks supporting these sensors. This would include the use of radars for both aircraft surveillance and precipitation or lidars to determine navigational performance or wind turbulence. Exploration of novel sensors would include the identification of sensors supporting other uses that could benefit AAM operations such as traffic cameras for determining visibility and sensors supporting other forms of transportation such as Advanced Road Weather Information System (ARWIS) to provide temperature and potential surface icing conditions. Phase I would also identify sensors existing or being planned for near-term installation that could be leveraged for future demonstrations.

Phase II of this effort would be to leverage existing AAM activities to investigate the potential incorporation of additional AAM functionality while utilizing current or planned sensors. Potential activities could include the Ohio Department of Transportation (DOT) Route 33 Active Traffic Management (ATM) efforts, Minnesota’s extensive ARWIS system, or North Central Texas Collaborative Adaptive Sensing of Atmosphere (CASA), or it’s Arlington Entertainment district demonstration. Efforts in Phase II would also identify potential additional benefits achievable through these sensors such as counter drone capability or weather warning alerting to the local community.

State of the Art and Critical Gaps:
Current state of the art is to identify and utilize either customized or purpose-built sensors targeted to meet the requirements for the system they are supporting. While this results in high performance capability, these networks are both expensive to install and maintain and difficult to upgrade with new and innovative technologies and capabilities. This SBIR would be a start at closing the gap between attempting to fund expensive single purpose systems and installing affordable capable systems with shorter return on investments and more amenable to upgrading.

Relevance / Science Traceability:

Information collected during this phase should also be targeted to inform the ATM-X AAM X series simulations and potential automated vertiport functions being investigated by the High Density Vertiport subproject within the AAM Project.

References:

1. Using Connected Vehicle Technologies to Solve Real-World Operational Problems: https://www.its.dot.gov/pilots/

A2.04 AERONAUTICAL INFORMATION SYSTEM SECURITY (AISS): Aircraft Systems (SBIR)

Lead Center: GRC
Participating Center(s): N/A

Scope Title: Onboard Noninvasive Intrusion Detection Systems

Scope Description:
In order to accommodate the anticipated diversity and complexity of operations in the future National Airspace System (NAS), the system must be more digitally connected, but by being connected this provides more pathways for hackers into the NAS and its systems, increasing the likelihood that an aircraft will be hacked. With new entrants, such as Unmanned Aircraft Systems (UAS) and Advanced Air Mobility (AAM), they will rely on third party services to operate. There is a need to detect safety events and safety threats caused by hackers to increase the ability of the systemwide safety assurance to perform its functions. The increased assurance will play a critical role in how quickly new operations and new vehicles can be safely integrated with NAS operations. NASA is developing ground and vehicle based In-Time System-Wide Safety Assurance (ISSA) capabilities to monitor, assess and mitigate safety threats, and this SBIR will address the detection of cybersecurity threats that will cause safety threats, to both commercial and emerging operations. The eventual goal is for these capabilities to be integrated into an In-Time Aviation Safety Management System (IASMS) capable of system-level safety assessment.

This subtopic seeks technologies to enhance cybersecurity monitoring and assessment capabilities for air-vehicle-based systems. This may include cyber related ISSA tools or techniques that fit within the architecture being developed by NASA or it may include a separate cybersecurity device that performs monitor-assess functions whose outputs may be integrated with a larger IASMS at some future point. Proposal areas include, design architectures, and development and/or demonstration in the following areas, with an emphasis on onboard flight cyber safety:

- Onboard system monitoring and assessing with reporting both locally and to off-board operations centers.
- Interfacing to the larger network systems monitoring and assessing with reporting, both locally and to operations centers.
- Integration of individual monitor-assessing instances into the greater system-of-system approach, either standalone or as a capability of safety ISSA architectures.

From a functionality point of view, each instance of the monitor-predict entity, a combination of entities, or the systemwide ISSA may perform one or more of these functions:

- Monitor: detect anomalies or deviations from normal operations.
- Assess: localization; determine attack target, provide analysis to forecast the probability of events.
- Report: onboard, off board, and logging.
- Mitigate: when mitigation is possible, mitigate incidents without loss of operational and prioritize corrective actions for onboard operators/systems.

Given the developing Advanced Air Mobility (AAM) and traditional aviation systems, several possible analytical approaches may be possible. These include:

- Digital Twin: analytical combinations of on onboard and off-board models.

- Attestation: provable by observation methodologies.
- Traffic monitoring: monitoring of aviation bus data, network data, or other data flows.
- MDAO: multidisciplinary design analysis optimization.
- Artificial intelligence/machine learning: i.e., “teach” a model to adapt itself to defenses as they engage.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Hardware
- Software
- Analysis
- Prototype
- Research

Desired Deliverables Description:

Phase I:

- Analysis and architectures for onboard cyber anomaly monitoring system, to include aviation buses and other data flows.
- Analysis and architectures for predictive analysis of cyber anomalies.
- Reporting capabilities to operations centers.

Phase II:

- Analysis and architectures for systemwide cyber anomaly monitoring including node and aggregation methods.
- Mitigation: analysis and design of cyber-resilience methodologies that include mitigation incidents without loss of mission success.
- Prioritize corrective actions for operators/systems.
- Propose a demonstration system implementation including hardware, software, testing, and validation.

State of the Art and Critical Gaps:

There are clear limitations to near term adoption of these new cyber technologies into the National Airspace System (NAS) or the AAM equivalent. These include:

- Current aviation communication technologies, certified for use in the NAS, are severely limited in bandwidth and constrained to specific functions. This makes concepts that may move large amounts of data between air vehicles and the ground difficult to implement.
- In-time data prediction can be computer processing unit (CPU) intensive. The onboard capabilities of Unmanned Aircraft Systems (UAS) and AAM-type vehicles may not provide significant onboard processing capabilities.
- Data needed for the prediction of aviation cyber events is not well understood or data is difficult to obtain or synthesize.
- Data needed for aviation cybersecurity machine learning methodologies is also difficult to obtain and validate. Attempts to use information technology (IT) ground-based systems as surrogates for aviation systems may not yield reliable comparisons.

Relevance / Science Traceability:

As our world becomes more digitally connected, there are increasing opportunities for cyber attacks across all domains. Aviation is no exception.

Communication links and maintenance loads are susceptible to viruses and other attacks. Most communication systems in the aircraft are not protected via authentication or by encryption and with newer systems that rely on commercial standards like Ethernet and Internet Protocols (IP) vulnerability to cyber threats increases. It is possible to send data to an aircraft via the communications link and as long as the messages are formatted properly they will be acted up by the onboard systems, potentially causing Denial of Service attack or affecting other systems by disrupting processes. This SBIR focuses on air vehicle cybersecurity and seeks proposals for observation of nominal system states, assessment and reporting of off-nominal traffic, and mitigation of off-nominal operations.

References:

1. Eurocae / RTCA Aeronautical Information Systems Security (AISS), Airworthiness Security Methods and Considerations, Information Security Guidance for Continuing Airworthiness, Process Standard for Security Certification and Declaration of ATM ANS Ground Systems and Guidance on Security Event Management.
2. Ellis, K., Koelling, J. Davies, M, Krois, P. (2020) In-time System-wide Safety Assurance (ISSA) Concept of Operations and Design Considerations for Urban Air Mobility (UAM), NASA/TM—2020–5003981

Focus Area 20 Airspace Operations and Safety

This focus area includes technologies addressing the Airspace Operations and Safety Program (AOSP), which supports NASA's ARMD Strategic Thrusts 1, 5, and 6. AOSP performs research to develop revolutionary air traffic management and operational safety concepts for transformation of the National Airspace System (NAS). These technologies benefit the public by increasing capacity, decreasing fuel consumption, and reducing the total cost of air transportation. The Airspace Operations and Safety SBIR Topic is focused on research and technology development for enabling a modernized air transportation system that will achieve much greater capacity and operational efficiency while maintaining or improving safety and other performance measures. This will include the integration of new types of vehicles such as unmanned vehicles, advanced subsonic aircraft, supersonic or commercial space vehicles; new types of business models or operations such as urban air mobility and integrated aerial wildfire response; and new architectures or services for enabling these operations within the NAS.

A3.01 Advanced Air Traffic Management System Concepts (SBIR)

Lead Center: ARC

Participating Center(s): LaRC

Scope Title: Advanced Air Traffic Management (ATM) System Concepts

Scope Description:

This subtopic addresses contributions towards ATM systems and concepts with potential application in the near-future (2025 to 2030) National Airspace System (NAS). The subtopic seeks proposals that can apply novel and innovative technologies and concepts towards addressing established ATM challenges of improving efficiency, capacity, and throughput while minimizing negative environmental impact, maintaining or improving safety, and/or accelerating the implementation of NASA technologies in the current and future NAS.

Given the recent coronavirus pandemic and the dramatic impact to the airlines and U.S. aviation industry as a whole, this solicitation also seeks proposals that can apply novel and innovative concepts, technologies, and capabilities towards enabling the U.S. air transportation system to recover from the recent negative impacts of reduced traffic demand.

The NASA technologies that are being researched and developed for the future NAS include, but are not limited to: Integrated Arrival, Departure, and Surface (IADS) capabilities, routing and rerouting around weather from ground-based and cockpit-based systems, tools enabling trajectory-based operations (TBO), and capabilities that can be integrated with a fully realized Unmanned Aircraft Systems Traffic Management (UTM) system for a wide range of commercial and public use.

Technologies, concepts, models, algorithms, architectures, and tools are sought in this solicitation to bridge the gap from NASA's research and development (R&D) to operational implementation, and should address such nearer term ATM challenges as:

- Safe, end-to-end TBO.
- Enabling and integrating existing independent systems and domains, and increasingly diverse and unconventional operations (gradually enabling the future integration of large unmanned vehicles, unconventional commercial airline business models, space traffic management, and subsonic and supersonic vehicles).
- Applying elements of the service-based architecture concept being pioneered in the UTM domain.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:
Level 1: TX 16 Air Traffic Management and Range Tracking Systems
Level 2: TX 16.3 Traffic Management Concepts

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:
Technologies that can advance safe and efficient growth in global operations (Aeronautics Research Mission Directorate (ARMD) Thrust 1 Goal) that can be incorporated into existing and future NASA concepts.

Phase I deliverables may take the form of a prototype/proof-of-concept decision support tool, automation and/or service, a proof-of-concept demonstration of the underlying architecture, and/or validation of the approach taken, which shows focus on a particular aspect or use case of the R&D challenge being investigated.

Phase II deliverables would presumably take the form of higher TRL tools/decision support services that convincingly demonstrate a solution to the proposed R&D challenge.

State of the Art and Critical Gaps:
State of the Art: NASA has been researching advanced air transportation concepts and technologies to improve commercial operations in the NAS.

Critical Gaps: Significant challenges remain in integrating air transportation technologies across different domains and operators (e.g., airport surface and terminal area; airport authority and air navigation service providers; etc.), providing comprehensive strategic scheduling and traffic management technologies, enabling concepts that will allow for increased demand and complexity of operations, and enabling recovery from the global-pandemic-induced air transportation system impacts.

Relevance / Science Traceability:
Airspace Operations and Safety Program (AOSP) within ARMD.

Successful technologies in this subtopic have helped to advance the air traffic management/airspace operations objectives of the Program and enable successful technology transfer to external stakeholders (including the Federal Aviation Administration and the air transportation industry).

References:

1. Airspace Operations and Safety Program (AOSP): https://www.nasa.gov/aeroresearch/programs/aosp

A3.02 Increasing Autonomy in the National Airspace System (NAS) (SBIR)

Lead Center: ARC

Participating Center(s): LaRC

Scope Title: Human-Autonomy Teaming in the National Airspace System (NAS)

Scope Description:

In current airspace operations, human operators occupy extensive decision-making capabilities and perform the most significant roles in the National Airspace System (NAS). As more autonomous system capabilities are introduced in air transportation, a critical research question for future airspace operations is the appropriate allocation of tasks and functions for the human operators and future autonomous systems, as they seamlessly team together to achieve common goals.

This collaboration between the human-operator and the autonomous technology, also known as “human-autonomy teaming,” is the primary focus of this subtopic.

NASA’s future concepts of air transportation (2030 and beyond) are anticipated to increasingly rely on autonomy, artificial intelligence, and machine learning, to maintain operational efficiency and safety, dynamically accommodating changes to environmental and operational conditions. The future concepts will significantly expand the capabilities of airspace operations and vehicle management to ensure safe, secure, and equitable operations, assuming seamless, integrated, flexible, and robust systems, resilient and resistant to cyber-attack. The future concepts include traditional and nontraditional vehicle types and operations, along with diverse airspace domains and mission types, and a service-based architecture to provide user services, as appropriate. Examples of such service-based systems include those demonstrated within NASA’s Unmanned Aircraft Systems Traffic Management (UTM) and the Air Traffic Management – eXploration (ATM-X) Urban Air Mobility (UAM) Projects.

This subtopic seeks proposals that will apply novel and innovative solutions to technologies, methods, and approaches to developing tools and/or technologies that will enable successful human-autonomy teaming in the future NAS (2030 and beyond).

Proposals that do not address or consider the human operator’s interaction with future, autonomous, NAS technologies will be declined.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:

Level 1: TX 16 Air Traffic Management and Range Tracking Systems
Level 2: TX 16.3 Traffic Management Concepts

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Technologies that can advance safe and efficient growth in global operations (Aeronautics Research Mission Directorate (ARMD) Thrust 1 Goal) as well as developing autonomy applications for aviation (as under ARMD Thrust 6).

Phase I deliverables may take the form of a prototype/proof-of-concept decision support tool, automation and/or service, a proof-of-concept demonstration of the underlying architecture, and/or validation of the approach taken, which shows focus on a particular aspect or use case of the research and development (R&D) challenge being investigated. Phase II deliverables would presumably take the form of higher TRL tools/decision support services that convincingly demonstrate a solution to the proposed R&D challenge.

State of the Art and Critical Gaps:
State of the Art: NASA has been researching advanced air transportation concepts and technologies to improve commercial operations in the NAS. Autonomy is the focus of increased ARMD interest as evidenced in Thrust 6, Assured Autonomy for Aviation Transformation. Airspace Operations and Safety Program (AOSP) research is increasingly applying autonomous technologies and capabilities towards air transportation challenges. These technologies and capabilities may address limited solutions to targeted problems.

Critical Gaps: The growth of data sciences and autonomy/artificial intelligence technologies continue to have great potential to benefit the development of a more autonomous air transportation system. This is needed to accommodate the increasing demand and diversity of air transportation missions and operations. The interpretation and use of data-science-based information by human operators and decision makers, continues to be of interest.

This subtopic is focused on the human-autonomy teaming of the airspace operations in the future NAS. Proposals that do not address the human operator interaction with future NAS technologies will be declined.

Relevance / Science Traceability:
Relevance to AOSP.

Successful technologies in this subtopic have helped to advance the air traffic management/airspace operations objectives of the AOSP Program. The technologies also introduce new autonomy/artificial intelligence/data science methods and approaches to air transportation problems for current and near-future application, and show where such approaches are/are not appropriate to advance airspace operations.

References:

1. Airspace Operations and Safety Program (AOSP): https://www.nasa.gov/aeroresearch/programs/aosp

A3.03 Future Aviation Systems Safety (SBIR)

Lead Center: ARC
Participating Center(s): LaRC

Scope Title: Future Aviation Systems Safety

Scope Description:
Public benefits derived from continued growth in the transport of passengers and cargo are dependent on the improvement of the intrinsic safety attributes of the Nation’s and the world’s current and future air transportation system. Recent developments to address increasing demand for access to the airspace include: increased use of automation and autonomy to enhance system capabilities; airspace systems with tightly coupled air and ground functionality; cloud computing-based technologies used to perform functions or services; other widely distributed functions across ground, air, and space environments; increasingly integrated aircraft systems; and novel vehicle capabilities for both traditional and advanced air mobility (AAM)

operations such as Unmanned Aircraft Systems (UAS) and Urban Air Mobility (UAM). These revolutionary changes are leading to greater system complexity, and current methods of ensuring that airspace and vehicle designs meet desired safety levels will likely not scale to these levels of complexity (Aeronautics R&D Plan, p. 30). The Airspace Operations and Safety Program (AOSP) is addressing this challenge with a major area of focus on In-Time System-Wide Safety Assurance (ISSA). Understanding and predicting systemwide safety concerns of the airspace system and the vehicles flying in it, as envisioned in future aviation systems, is paramount. Thus, a proactive approach to managing system safety requires that once a new system, technology, procedure, or training is introduced, that operators have: (1) the ability to monitor the system continuously and to extract and fuse information from diverse data sources to identify emergent anomalous behaviors through health monitoring of systemwide functions and (2) the ability to reliably predict probabilities of the occurrence of hazardous events and of their safety risks. Specifically, AOSP's System-Wide Safety (SWS) Project is developing an In-Time Aviation Safety Management System (IASMS), a scalable and distributed system approach to address aviation safety needs. Based on ISSA building blocks, IASMS services, functions, and capabilities (SFCs) are architecturally structured to “Monitor—Assess—Mitigate” operational safety risks. For definition, services are systems that produce safety-relevant information, functions produce safety-relevant outputs or data needed to compute safety-relevant metrics, and capabilities provide safety-relevant benefits that may leverage services and functions. IASMS SFCs are envisioned to include increasingly automated and autonomous functionality to adapt and scale to the increasing complexity of aviation operations, necessitating new approaches to assure autonomous functionality. Therefore, proposals focused on assurance of autonomy for operational systems will also be considered for award. Additionally, due to the increasingly digital transformation of the airspace system and nature of the IASMS, one research area of high interest is methods for monitoring, assessing, and mitigating cybersecurity vulnerabilities and attacks. Innovative approaches and methods are sought that monitor/assess/mitigate vulnerabilities before they can be exploited by malicious actors. Proposed innovations are sought that can be easily incorporated into the IASMS. Proposals that lack a technology/function that can be integrated into the concept of an IASMS will be declined.

Specifically, this subtopic seeks the following types of proposals, whose technologies can be integrated into IASMS:

- Proposals to address the safety-critical risks identified in beyond visual-line-of-sight (BVLOS) operations in small and large UAS, including but not limited to risks such as:
    - Flight outside of approved airspace.
    - Unsafe proximity to people/property.
    - Critical system failure (including loss of command and control (C2) link, loss or degraded Global Positioning System (GPS), loss of power, and engine failure).
    - Loss-of-control (i.e., outside the envelope or flight control system failure).
    - Any potential cybersecurity or cyber-physical attack affecting any or all operations within the UAS airspace system.
- Proposals supporting the research and development of ISSA objectives:
    - To detect and identify systemwide safety anomalies, precursors, and margins.
    - To develop the safety-data-focused architecture, data exchange model, and data collection mechanisms.
    - To enable simulations to investigate flight risk in attitude and energy aircraft state awareness.
- Proposals supporting safety prognostic decision support tools, automation, techniques, strategies, and protocols:
    - To support real-time safety assurance (including in-time monitoring of safety requirements).
    - That consider operational context, as well as operator state, traits, and intent.
    - For integrated prevention, mitigation, and recovery plans with information uncertainty and system dynamics in a UAS and trajectory-based operations (TBO) environment.
    - To enable transition from a dedicated pilot in command or operator for each aircraft (as required per current regulations) to single-pilot operations.

    - To enable efficient management of multiple unmanned and AAM aircraft in civil operations.
    - To assure safety of air traffic applications through verification and validation (V&V) tools and techniques used during certification and throughout the product lifecycle.
- Proposals supporting assurance of highly automated and increasingly autonomous systems that support safety-critical functions. Specific focus includes:
    - Identification and development of new technologies that enable increasingly autonomous air safety services. Each new technology should be accompanied by examples of the services it enables.
    - Technologies that overcome the limitations of current V&V capabilities with respect to new increasingly autonomous systems. For example, new testing techniques sufficient for deploying machine learning (ML)-enabled systems.
    - Determination of where current certification standards (such as DO-178C) fail to address assurance needs for these technologies or fail to consider V&V results associated with the new technologies.
    - Development of use cases demonstrating novel certification approaches, such as Overarching Properties or safety cases, that enable the certification of increasingly autonomous systems.
    - Development of use cases demonstrating the assurance of cyber-physical-human systems that accommodate shifting roles and responsibilities between humans and automation.
- Cybersecurity resiliency requiring availability and integrity of critical functions including:
    - Rapid detection of incidents to enable remediation.
    - Automatic remediation actions to restore sufficient network or application services to support mission essential functions.
    - Information resilience for shared airspace status.
    - Reliable delivery and authentication of important messages.
    - Security management systems, security management frameworks, or information security management systems.
    - Resilient voice, data, and precision navigation and timing.
- Proposals that develop, apply, and assure IASMS services, functions, and/or capabilities to emergency response missions using aerospace vehicle operations. Operations may include but are not limited to: wildfire fighting, hurricane disaster relief and recovery, search and rescue, medical courier, and security operations.
    - SFCs should address one or more hazards highlighted in previous sections or identified through hazard analysis. Proposers are encouraged to leverage prior NASA work in this area.

Expected TRL or TRL Range at completion of the Project: 1 to 3

Primary Technology Taxonomy:
Level 1: TX 16 Air Traffic Management and Range Tracking Systems
Level 2: TX 16.1 Safe All Vehicle Access

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:
Technologies that can advance the goals of safe air transportation operations that can be incorporated into existing and future NASA concepts.

Desired deliverables for Phase I include development of multiple concepts/approaches, tradeoffs analyses, and proof-of-concept demonstrations.

Desired deliverables for Phase II include development of functional prototypes, integration of prototypes into existing and future NASA concepts, and demonstration of the prototype in a realistic environment.

State of the Art and Critical Gaps:
State of the art: Recent developments to address increasing air transportation demand are leading to greater system complexity, including airspace systems with tightly coupled air and ground functions as well as widely distributed and integrated aircraft systems. Current methods of ensuring that designs meet desired safety levels will likely not scale to these levels of complexity (Aeronautics R&D Plan, p. 30). AOSP is addressing this challenge with a major area of focus on ISSA.

Critical gaps: A proactive approach to managing system safety requires: (1) the ability to monitor the system continuously and to extract and fuse information from diverse data sources to identify emergent anomalous behaviors after new technologies, procedures, and training are introduced and (2) the ability to reliably predict probabilities of the occurrence of hazardous events and of their safety risks. Also, with the addition of UAM/AAM concepts, and increasing development of UAS Traffic Management (UTM), the safety research needs to expand to include these various missions and vehicles.

Relevance / Science Traceability:
Successful technologies in this subtopic will advance the safety of the air transportation system. The AOSP safety effort focuses on proactively managing safety through continuous monitoring and extracting relevant information from diverse data sources and identifying anomalous behaviors to help predict hazardous events and evaluate safety risk. This subtopic contributes technologies towards those objectives.

References:

1. Airspace Operations and Safety Program (AOSP): https://www.nasa.gov/aeroresearch/programs/aosp
2. National Aeronautics Research and Development Plan: https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/aero-rdplan-2010.pdf

A3.04 Nontraditional Airspace Operations and Aerial Wildfire Response (SBIR)

Lead Center: ARC
Participating Center(s): LaRC

Scope Title: Nontraditional Airspace Operations

Scope Description:
NASA is exploring airspace operations incorporating unmanned vehicles and novel operations occurring in all airspaces (controlled and uncontrolled), with a goal to safely and efficiently integrate with existing operations and mission types. NASA's research to enable unmanned vehicles to be safely and fully integrated into existing airspace structures (or lack thereof) has already demonstrated the potential benefits and capabilities of a service-based architecture (such as that developed for the Unmanned Aircraft Systems Traffic Management (UTM) Research and Development (R&D) evaluations), and has led to new procedures, equipage and operating requirements, and policy recommendations, to enable widespread, harmonized, and equitable execution of diverse unmanned missions.

This scope is focused on Urban Air Mobility (UAM)/Advanced Air Mobility (AAM) airspace operations only and is not accepting proposals specific to other nontraditional operations. In addition, proposals that focus only on cyber-resiliency solutions without proposing specific UAM/AAM services, will be declined.

This subtopic seeks proposals to continue to adapt the UTM concept elements for application to UAM/AAM including:

- Service-based architecture designs that enable dense and/or increasingly complex UAM operations.
- Dynamic route planning that considers changing environmental conditions, vehicle performance and endurance, and airspace congestion and traffic avoidance.
- Dynamic scheduling for on-demand access to constrained resources and interaction between vehicles with starkly different performance and control characteristics.
- Integration of emergent users with legacy users, large commercial transport, including pass-through to and from ultrahigh altitudes and interactions around major airports.
- Operational concepts for fleet and network management, market need and growth potential for future operations, and airspace integration.
- Identification of potential certification approaches for new vehicles operations (such as electric vertical takeoff and landing).

Future service-based architectures also require resiliency to cyberattacks to ensure safe and robust operations that maintain expected levels of safety, as well as accommodating changes to environmental and operational conditions. Therefore, proposals should incorporate cyber-resiliency methods, tools, or capabilities, or address cyber-resiliency as part of the proposed effort, but proposals focused exclusively on cybersecurity will be declined.

Expected TRL or TRL Range at completion of the Project: 1 to 4

Primary Technology Taxonomy:
Level 1: TX 16 Air Traffic Management and Range Tracking Systems
Level 2: TX 16.3 Traffic Management Concepts

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:
Technologies that can advance safe and efficient growth in global operations (Aeronautics Research Mission Directorate (ARMD) Thrust 1 Goal) as well as developing autonomy applications for aviation (as under ARMD Thrust 6), that are specifically applicable to UAM operations, and address post-pandemic recovery, as appropriate.

Phase I deliverables may take the form of a prototype/proof-of-concept decision support tool, automation and/or service, a proof-of-concept demonstration of the underlying architecture, and/or validation of the approach taken, which shows focus on a particular aspect or use case of the R&D challenge being investigated.

Phase II deliverables would presumably take the form of higher TRL tools/decision support services that convincingly demonstrate a solution to the proposed R&D challenge.

State of the Art and Critical Gaps:
Current state of the art - Nontraditional airspace operations: NASA has been researching advanced air transportation concepts and technologies to improve commercial operations in the National Airspace System and has been applying this expertise, as well as a service-based architecture and concepts pioneered for UTM, towards UAM/AAM.

Critical gaps - Nontraditional airspace operations: Significant challenges remain to fully develop the UAM/AAM airspace concept of operations, including integrating air transportation technologies across different domains and operators; providing comprehensive, strategic scheduling and traffic management technologies; and enabling concepts that will allow for scaling demand and complexity of operations. This subtopic is focused on the Airspace Operations of the UAM/AAM concept only. Proposals must have clear application to UAM/AAM airspace operations. Proposals that focus on UAM/AAM vehicle capabilities, or onboard vehicle technologies or systems, will be declined. Proposals that are specific to other nontraditional operations (such as, but not limited to, space traffic management, automated air cargo, UTM, and ultrahigh altitude), without clear application to UAM/AAM, will be declined.

Relevance / Science Traceability:
Airspace Operations and Safety Program (AOSP).

Air Traffic Management-eXploration (ATM-X) Project.

Successful technologies in this subtopic will help NASA pioneer UAM concepts and technologies. The technologies also incorporate new autonomy/artificial intelligence/data science methods and approaches to air transportation problems for current and near-future application.

References:

1. Airspace Operations and Safety Program (AOSP): https://www.nasa.gov/aeroresearch/programs/aosp
2. NASA Ames Aviation Systems Division publications: https://aviationsystems.arc.nasa.gov/publications/index.shtml
3. NASA Ames Aviation Systems Division: https://aviationsystems.arc.nasa.gov/index.shtml
4. ARMD Strategic Implementation Plan: https://www.nasa.gov/aeroresearch/strategy

Scope Title: Aviation Operations for Wildfire Response

Scope Description:
In the United States, wildfires are becoming increasingly severe and costly in terms of acreage burned, property damage, and most importantly, lives lost. Wildfire frequency and intensity is escalating, inducing budgetary, personnel, and equipment challenges. Furthermore, California and other western states have been facing persistent drought conditions and much hotter temperatures, which are fueling wildfire intensity and duration. These alarming trends have made it urgent to recognize how wildfires could be better predicted, mitigated, and managed.

NASA has a history of contributions to wildfire and other disaster management including remote sensing, instrumentation, mapping, data fusion, and prediction. More recently, the NASA Aeronautics Research Mission Directorate (ARMD) has been investigating capabilities to help manage wildfire suppression and mitigation efforts through technologies for coordination of airspace operations for wildfire management.

NASA ARMD has recently made significant contribution to enable widespread use of small unmanned aircraft systems (sUAS) by developing air traffic management capabilities for low-altitude unmanned vehicle operations, called UAS Traffic Management (UTM). This work is being expanded to safely and efficiently integrate larger Urban Air Mobility (UAM) vehicles and operations with existing operations and mission types. NASA recognizes the value these capabilities could provide when applied to the aerial wildfire management domain.

Current applications of aviation to wildfire management include deployment of smokejumpers to a fire, transport of firefighters, equipment and supplies, fire retardant or water drop, reconnaissance of fire locations and fire behavior, and supervision of air tactical operations.

Current challenges of aerial wildfire management include: existing airspace management techniques are manual and cannot accommodate the demand for new types of aircraft (e.g., unmanned aircraft); aerial firefighting is limited to acceptable visual conditions (no night operations); monitoring and remote sensing missions are intermittent, flown outside of active fire-fighting or available periodically from satellite assets; and there is a lack of reliable, resilient, and secure data communications for quick information dissemination to support effective decision making.

NASA is seeking technologies to:

- Provide an extension to the UTM network considering the unique needs and characteristics of wildfire disaster situations and the response to combat them.
- Provide capabilities that address UAS integration to aerial wildfire management but also have the potential to represent a dynamic airspace for coordination of multiple manned and unmanned vehicles.
- Increase the capacity of available communications, reduce the latency of data transfer, and provide a persistent network for the use of UAS and other aviation assets by emergency responders.
- Provide airspace coordination and resource tracking for a common operating picture for situational awareness.
- Ensure highest safety and efficiency of operations.

Expected TRL or TRL Range at completion of the Project: 1 to 5

Primary Technology Taxonomy:
Level 1: TX 16 Air Traffic Management and Range Tracking Systems
Level 2: TX 16.3 Traffic Management Concepts

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:
Phase I deliverables may include prototype/proof-of-concept decision support tool, automation and/or service, a proof-of-concept demonstration of the underlying architecture, and/or validation of the approach taken, which shows focus on a particular aspect or use case of the research and development challenge being investigated.

Phase II deliverables would presumably take the form of higher TRL tools/decision support services that convincingly demonstrate a solution to the proposed research and development challenge.

State of the Art and Critical Gaps:
The current state of the art for coordination of aerial firefighting is a manual process that must be coordinated across multiple entities, often bringing multiple aerial assets to wildfire fighting environment. Advanced tools and techniques are required to address the following gaps:

- Existing airspace management process very manual and slow.
- Awareness of aircraft operations conducted by visual monitoring and radio communication.
- Unmanned systems are not easily integrated into aerial fire suppression operations.
- Operations are limited by visibility and no operations are conducted at night when fires often die back.
- Surveillance images are captured and disseminated only every 4 hours.
- Intermittent communication can delay effective response.
- Conditions can rapidly change requiring timely information for effective decision making.

- Decision makers for emergency response are overloaded with data.
- Information requirements differ for various roles within the disaster response.

Tools and data are often spread across numerous applications.

Relevance / Science Traceability:
Due to climate change, wildfires are becoming increasingly more frequent and severe. Fire seasons are longer, lasting 6 to 8 months and in some cases are year-round. The 2020 fire season was the worst in recorded history, burning over 4 million acres of land, destroying more than 8,500 structures, and killing more than 30 people. The economic impact of these fires is in the hundreds of billions of dollars and results in lasting societal impact. The annual cost of fire suppression has soared from roughly $425 million per year in 1999 to $1.6 billion in 2019.

Recently, President Biden and Vice President Harris met with Governors from western states, Cabinet officials, and private sector partners to discuss specific actions the public and private sector are each taking to strengthen prevention, preparedness, mitigation, and response efforts to protect communities across our country from wildfires and their devastating impacts. The President directed a number of actions, in close coordination with State and local governments and the private sector, to ensure the Federal Government can most effectively protect public safety and deliver assistance to our people in times of urgent need.

References:

1. Airspace Operations and Safety Program (AOSP): https://www.nasa.gov/aeroresearch/programs/aosp
2. NASA Ames Aviation Systems Division publications: https://aviationsystems.arc.nasa.gov/publications/index.shtml
3. NASA Ames Aviation Systems Division: https://aviationsystems.arc.nasa.gov/index.shtml
4. ARMD Strategic Implementation Plan: https://www.nasa.gov/aeroresearch/strategy

Focus Area 21 Small Spacecraft Technologies

NASA is pursuing rapid identification, development, and testing of capabilities that exploit small spacecraft platforms and responsive launch capabilities to increase the pace of space exploration, scientific discovery, and the expansion of space commerce in a sustainable manner. These emerging capabilities have the potential to enable new mission architectures, enhance conventional missions, and promote development and deployment on faster timelines. This will, in turn, allow NASA and other space mission operators to achieve their objectives at significantly lower programmatic risk and cost than traditional approaches.

Small spacecraft are typically defined as those weighing 180 kg or less and are often designed for shared launch using standardized form factors and interfaces and containerized deployment (e.g. CubeSats). Small spacecraft and responsive launch capabilities are proving to be disruptive innovations for exploration, discovery, and commercial applications. NASA seeks technical innovations that enable small spacecraft to rival the capabilities of their larger, more expensive counterparts, while also striving to make them cheaper and quicker to build, and easier to launch and operate. In addition, NASA seeks innovations to help address the looming concern of space debris growth in Low Earth Orbit (LEO) following the expected launch of constellations consisting of thousands of satellites, whilst also further expanding the reach of small spacecraft beyond LEO. Greatly improved capabilities are needed for lunar exploration missions, lunar communications and navigation infrastructure, and exploration at Mars and other deep space destinations. Technology and capability investment will be needed to meet these upcoming mission needs while keeping overall costs low, mission cadence high, and retaining the agile aerospace approach that has fueled what has been termed the “smallsat revolution”.

Specific improvements required are long-range high-bandwidth optical and RF communications; novel navigation devices and navigation references for use well beyond Earth; improved power management; and robust tolerance of the harsher thermal and radiation environment of deep space. Propulsion technologies with improved performance are sought for Trans Lunar Injection (TLI), lunar orbit insertion and maintenance, return-to-Earth and Earth entry and descent mechanisms. Transfer stages that host small spacecraft and can provide support services to the deployed spacecraft are also desired. Innovations are wanted to increase the speed, economy, and reliability of production; modular designs will facilitate reliable assembly and test of singly- or batch-produced small spacecraft, with specifically sought-after technologies including wirelessly interconnected sensors and modules. De-orbit or rapid disposal devices for single spacecraft, and autonomous space traffic management technologies for small spacecraft swarms and constellations are also needed. These include affordable powerful computing hardware and intelligent software tools and infrastructure for autonomous operation of spacecraft or for cooperation of spacecraft groups, minimizing human-in-the-loop bottlenecks, that are applicable to both the space debris management environment, as well as deep space missions.

NASA’s Small Spacecraft Technology Program will consider promising SBIR technologies for spaceflight demonstration missions and seeks partnerships to accelerate spaceflight testing and commercial infusion.

The following references discuss some of NASA's small spacecraft technology activities:

- Small Spacecraft Technology (SST) program: https://www.nasa.gov/directorates/spacetech/small_spacecraft/index.html
- Small Satellite Missions: www.nasa.gov/smallsats
- Small Spacecraft Virtual Institute: https://www.nasa.gov/smallsat-institute

Another useful reference is the Small Spacecraft Technology State of the Art Report at:

- https://www.nasa.gov/sites/default/files/atoms/files/soa_2021.pdf

Z8.02 Communications and Navigation for Distributed Small Spacecraft Beyond Low Earth Orbit (LEO) (SBIR)

Lead Center: GRC
Participating Center(s): ARC, GSFC, JPL

Scope Title: End-to-End Deep Space Communications

Scope Description:
Develop enabling communications technologies for small spacecraft beyond Low Earth Orbit (LEO). These technologies will be required by spacecraft to conduct NASA lunar and deep space distributed spacecraft science missions. Innovations in communications technologies for distributed small spacecraft are essential to fulfill the science missions envisioned within the decadal surveys and contribute to the success of human exploration missions. To construct the lunar communications architecture [Ref. 11], it is appropriate to consider a hybrid approach of large and small satellite assets. Primary applications include lunar surface-to-surface data relay, data relay to Earth, and navigational aids to surface and orbiting users. Distributing these capabilities across multiple small satellites may be necessary because of limited size, weight, and power (SWaP), but also to enhance coverage.

Technologies for specific lunar architectures are especially needed. For example, landers near the lunar South Pole may not have—and landers on the far side of the Moon will not have—direct line-of-sight to Earth-based ground stations and will need to send data through a relay satellite (or Gateway) to return data to Earth. Small surface systems (including rovers or astronauts on extravehicular activities (EVAs)) on the Moon will likely not have the necessary system resources to close a direct link to Earth. Human surface operations may require surface-to-surface over-the-horizon communications through an orbital relay. Deployment of sufficient traditional communications assets to maintain persistent global coverage of the lunar surface may be prohibitively expensive. Analogous to emerging LEO communications constellations, small spacecraft can operate as local relays in cislunar space.

Considerations for technology and capability extension to the Martian domain and other deep space applications are also solicited.

Interspacecraft networking is inherent to distributed mission and interoperable communications relay architectures. Enabling networking capabilities in small spacecraft requires low SWaP, low-cost hardware for radio-frequency (RF) and optical crosslinks. While network protocols developed for interoperable communications relays may be interchangeable with those for distributed missions, relay networks may not be scalable to very large-scale sensor webs of small spacecraft. As such, addressing interspacecraft networking gaps may require investment in both hardware crosslinks and networking protocols that scale to hundreds of nodes, and requires robustness for loss of nodes or as new nodes enter the network. Network management technologies may be needed due to the increased operational complexity.

An end-to-end system needs to be considered for the application of small satellites for deep space missions as described in preceding paragraphs. Therefore, enabling technologies also include non-NASA ground services that keep the operations cost commensurate with the lower costs of the small satellites themselves. Automation of the ground services as well as the small satellite constellations are needed.

Communications solutions can operate in optical or various RF bands; however, considerations must be given to bandwidth, public and Government licensing, network and data security, and compatibility with referenced candidate architectures.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.X Other Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I: Identify and explore options for the deep space small-satellite missions, including ground services. Conduct trade analysis and simulations, define operating concepts, and provide justification for proposed multiple access techniques, frequency bands of operation, command and data handling, and networking solutions. Also identify, evaluate, and develop design for integrated communications payload(s) and one or more constituent technologies that enable distributed spacecraft operations in the relevant space environment beyond LEO. Integrated communications system solutions and constituent component deliverables should offer potential advantages over the state of the art, demonstrate technical feasibility, and show a path toward a hardware/software infusion into practice. Bench-level or laboratory-environment-level demonstrations or simulations are desirable. The Phase I proposal should outline a path that shows how the technology can be developed into space-qualifiable and commercially available small-spacecraft communications payloads through Phase II efforts and beyond.

Phase II: Demonstration of communication technology via prototype or high-fidelity emulation. The relevant deep space environment parameters should be simulated as much as possible.

State of the Art and Critical Gaps:
Small-spacecraft missions beyond Earth require compact, low-power, high-bandwidth radios for use on the Moon, Mars, the rest of the inner planets, around asteroids or other small bodies, and at other deep space destinations. The current state of the art is the Iris radio (0.5U, 1.2 kg, and 35 W) [Ref. 12] that has been

operationally used at Mars, and there is no known affordable, readily available competitor. Future missions require systems that are lower SWaP-C, can operate in multiple bands (S, X, Ka-band, and optical), and can reach uplink and downlink speeds in excess of 20 Mbps. Spectral, modulation, information layer, and protocol compatibility with current technologies (Space Communications and Navigation (SCaN)); licensing and spectrum approval; and planned Government or commercial deep space communication architecture must all be considered.

Communications among spacecraft in a distributed spacecraft mission (DSM) configuration and between the DSM configuration and the Earth become more challenging beyond LEO distances. Collaborative configurations of widely distributed (tens to hundreds of kilometers apart) small spacecraft (180 kg or less) will operate far into the near-Earth region of space and beyond into deep space, further stressing the already limited communications capabilities of small spacecraft. Alternative operational approaches with associated enabling hardware and/or software will be needed with the following:

- Uplinks (Earth-to-space) and downlinks (space-to-Earth): Alternatives for coordinated command and control of the DSM configuration and individual small spacecraft from Earth as well as return of science and telemetry data to Earth. Each spacecraft cannot rely on its own dedicated Earth link, consuming valuable ground infrastructure and operators.
- Integrated communications payload: Hardware and software designs for the common and unique capabilities of each small spacecraft in the DSM configuration. Spacecraft communication SWaP-C should be reduced by at least 25% from a non-DSM spacecraft.
- Small-spacecraft antennas: Development of antennas optimized for either intersatellite or uplink/downlink communications are sought across a broad range of technologies including but not limited to deployable parabolic or planar arrays, active electronically steered arrays, novel antenna steering/positioning subsystems, and others suitable for use in high data rate transmission among small spacecraft over large distances. SWaP-C should be reduced from state of the art, such as the recent 6U CubeSat MarCO mission, which used a 0.2 m^2 X-band reflectarray to achieve 29 dBic gain and 42% efficiency [Refs. 13, 14]. Operations compatible with NASA’s space communications infrastructure [Ref. 9] and Government-exclusive or Government/non-Government-shared frequency spectrum allocations is required [Refs. 6, 7, 8].
- Small-spacecraft RF solid-state power amplifiers and RF front ends with smart electronics that increase operational efficiencies.
- Compatibility and interoperability with lunar communications and navigation architecture plans [Refs. 1, 2, 3]. Application of the emerging lunar standards includes frequency allocations per link functionality, modulation, coding, and networking protocol standards. Ka-band frequencies and above are highly desired.
- Optical end-to-end considerations for Earth links. If a DSM design relies on an optical link to Earth, the needed ground infrastructure should be considered.

Relevance / Science Traceability:

Several missions are being planned to conduct investigations/observations in the cislunar region and beyond. For example: Commercial Lunar Payload Services (CLPS); Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE); human exploration (Artemis) landing site and resource surveys; and communications and navigation infrastructure, including LunaNet, Mars communications relay, etc. Commercial and NASA small spacecraft, lunar surface assets, and manned vehicles in cislunar space and beyond will multiply within the decade. All these missions will depend on small-spacecraft communications relays, time reference transmissions, and navigation capabilities.

References:

1. International Communication System Interoperability Standard (ICSIS): https://www.internationaldeepspacestandards.com
2. Interagency Operations Advisory Group (IOAG): https://www.ioag.org/

3. Space Communication Architecture Working Group (SCAWG) (2006) NASA Space Communication and Navigation Architecture Recommendations for 2005-2030: https://www.nas.nasa.gov/assets/pdf/techreports/2006/nas-06-014.pdf
4. NASA Delay/Disruption Tolerant Networking (DTN): http://www.nasa.gov/content/dtn
5. "Delay-tolerant networking: an approach to interplanetary internet." IEEE Communications Magazine 41, no. 6 (2003): 128-136.
6. National Telecommunications and Information Administration Frequency Allocation Chart: https://www.ntia.doc.gov/files/ntia/publications/january_2016_spectrum_wall_chart.pdf
7. National Telecommunications and Information Administration Tables of Frequency Allocations: https://www.ntia.doc.gov/legacy/osmhome/alloctbl/alloctbl.html
8. NASA Spectrum Policy and Guidance for Small Satellite Missions: http://www.nasa.gov/directorates/heo/scan/spectrum/policy_and_guidance.html
9. NASA Space Communications and Navigation networks: https://www.nasa.gov/directorates/heo/scan/services/networks/index.html
10. NASA Optical Communications: https://www.nasa.gov/directorates/heo/scan/opticalcommunications/overview
11. LunaNet: A Flexible and Extensible Lunar Exploration communications and Navigation Infrastructure: https://esc.gsfc.nasa.gov/news/_LunaNetConcept
12. IRIS Radio: https://www.jpl.nasa.gov/cubesat/missions/iris.php
13. N. Chahat et al.: "Advanced CubeSat Antennas for Deep Space and Earth Science Missions: A review." IEEE Antennas and Propagation Magazine, vol. 61, no. 5, pp. 37-46, Oct. 2019, doi: 10.1109/MAP.2019.2932608.
14. Mars Cube On (MarCO) mission overview: https://www.jpl.nasa.gov/cubesat/missions/marco.php
15. NASA/TP-2018-220027, State of the Art Small Spacecraft Technology Report: https://www.nasa.gov/smallsat-institute/sst-soa

Scope Title: Relative and Absolute Deep Space Navigation

Scope Description:
Develop enabling technologies for beyond Low Earth Orbit (LEO) relative and/or absolute position knowledge. This situational awareness allows for autonomous control of small spacecraft as well as determining and maintaining position within a swarm or constellation of small spacecraft. In addition, timing distribution solutions for the SmallSats are important. Earth-independent and Global Positioning System- (GPS-) independent navigation and timing are enabling capabilities required by spacecraft to conduct NASA lunar and deep space distributed spacecraft science missions. Innovations in navigation technologies for distributed small spacecraft are essential to fulfill the science missions envisioned within the decadal surveys and contribute to the success of human exploration missions.

Multiple small spacecraft operating in coordinated orbital geometries or performing relative station-keeping can further expand human knowledge deeper into the universe by performing coordinated occultation, acting as virtual telescopes, and forming distributed apertures that would be prohibitively complex and expensive to launch into space as monolithic structures. Small-spacecraft formation flight can also enable swarm gravimetry, synchronized observation of transient phenomena, and proximity operations for inspection of other assets. Realizing these capabilities on affordable small spacecraft requires sensors and maneuvering systems that are low in mass, volume, power consumption, and cost.

Further expansion of small spacecraft use into deep space requires highly accurate position knowledge and precision timing that does not depend on GPS or other Earth-centric aids. Exploration mission operations that involve multiple-element distributed-mission architectures may involve 30 to 100 spacecraft, and the general expansion of the number of cislunar and deep space missions will stress or exceed current capacity of the Deep Space Network (DSN). Access to DSN ranging may not be available for multiple concurrent missions, may be blocked by terrain for surface operations, or may be limited by the radio capabilities of smaller missions. In concert with other available signals of opportunity and landed beacons, small spacecraft can provide relative ranging or triangulation to aid lunar navigation. Knowledge at the spacecraft of relative (between-spacecraft) situational awareness is needed for real-time station-keeping/relative position control where required rapid reaction speeds preclude human-in-the-loop operation.

Future small-spacecraft missions will need to autonomously determine and transmit relative and absolute position as well as keep and exchange precise timing. These capabilities are required for small spacecraft to act as infrastructure for other missions and for distributed missions composed of small spacecraft beyond Earth. Navigation technologies and techniques may include inertial navigation combined with enhanced visual navigation capabilities (e.g., dual use of star-tracking instruments for relative navigation using surface features or other nearby spacecraft), x-ray emissions (from pulsars), and laser range finding to other spacecraft or surface landmarks. For use with small spacecraft, these systems must be compatible with the inherent size, weight, power, and cost (SWaP-C) constraints of the platforms.

Precise timekeeping and timing exchange is not only required for navigation but is fundamental to science data collection. Internetworked small spacecraft can help synchronize timing across multiple mission assets using an external timing source. Recently improved chip-scale atomic clocks that can be carried by the small spacecraft themselves can augment this capability to reduce the accumulation of errors over time or serve as the primary clock when other larger but more accurate reference sources are not available or feasible. The vast majority of current commercial interests and Government missions operate in near-Earth orbits. To date, both NASA and the commercial spaceflight industry have enjoyed strong investment in near-Earth situational awareness made possible by tracking and identification capabilities provided by the Department of Defense. As the number of cislunar missions grows and NASA encourages the development of the lunar service economy, similar investments in situational awareness capabilities in these new orbital regimes will be needed to help support NASA and commercial operations.

Primary applications include navigational aids to lunar surface and orbiting users. Distributing these capabilities across multiple SmallSats may be necessary because of limited SWaP, but also to enhance coverage. Technologies for specific lunar architecture are especially needed, but considerations of extension to the Martian domain are also solicited. Navigation solutions for deep space distributed spacecraft missions (DSMs) may be addressed via hardware or software solutions or a combination thereof.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
Level 2: TX 17.2 Navigation Technologies

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software
- Hardware

Desired Deliverables Description:
Phase I: Identify and explore options for the deep space navigation technology, conduct trade analysis and simulations, define operating concepts, and provide justification for proposed techniques, frequency bands of operation, command and data handling, and networking solutions. Also identify, evaluate, and develop design for integrated navigation payload(s) and one or more constituent technologies that enable distributed spacecraft operations in the relevant space environment beyond LEO. Integrated navigation system solutions and constituent component deliverables should offer potential advantages over the state of the art, demonstrate technical feasibility, and show a path toward a hardware/software infusion into practice. Bench-level or laboratory-environment-level demonstrations or simulations are desirable. The Phase I proposal should outline a path that shows how the technology can be developed into space-qualifiable and commercially available small-spacecraft communications payloads through Phase II efforts and beyond.

Phase II: Demonstration of navigation technology via prototype or high-fidelity emulation. The relevant deep space environment parameters should be simulated as much as possible.

State of the Art and Critical Gaps:
Science measurements of distributed satellite missions (DSMs) are based on temporal and spatially distributed measurements where position knowledge and control are fundamental to the science interpretation. Current space navigation technologies are not adequate when relative or absolute position knowledge of multiple spacecraft is involved. State of the art (SOA) for attitude is the Jet Propulsion Laboratory's ASTERIA (Arcsecond Space Telescope Enabling Research in Astrophysics) 6U CubeSat demonstrated pointing stability of 0.5 arcsec (0.1 microdeg) rms over 20 min using guide stars. For position knowledge, missions still primarily use ranging transponders relying on a two-way Earth link. Examples of SOA for this ranging are the Iris transponder and the Small Deep Space Transponder (SDST) [Ref. 13].

Global navigation satellite services like the United States' Global Positioning System (GPS) provide very limited services beyond geostationary Earth orbit distances, and no practical services in deep space. Autonomous navigation capabilities are fundamental to DSMs to ensure known topography of the configuration at the time of data acquisition. Control of the distributed configuration requires robust absolute and relative position knowledge of each spacecraft within the configuration and the ability to control spacecraft position and movement according to mission needs. Critical areas for advancement are:

- Long-term, high-accuracy attitude determination: In particular, low-SWaP absolute attitude determination using star trackers, etc., to achieve sub-arcsec accuracy.
- Optical navigation: Solutions are sought for visual-based systems that leverage advances in optical sensors (e.g., cameras, star trackers) to observe and track a target spacecraft and perform pose and relative position estimation. Opportunities for innovation include methods that do not require the execution of satellite maneuvers and/or the design of external satellite features that enhance observability. Innovations may be appropriate for only certain regimes, such as near, medium, or far range; however, this context should be described. Solutions for various lunar and deep space mission operations concepts are of interest.
- Other novel navigation methods: Stellar navigation aids, such as navigation via quasars, x-rays, and pulsars, may provide enabling capabilities in deep space. Surface-based navigation aids, such as systems detecting radio beacons or landmarks, are invited. Emerging quantum-based technologies are of high interest.
- Methods for autonomous position control are also of interest. Technologies that accomplish autonomous relative orbit control among the spacecraft are invited. Control may be accomplished as part of an integrated system that includes one or more of the measurement techniques described above. Of particular interest are autonomous control solutions that do not require operator commanding for individual spacecraft. That is, control solutions should accept as input swarm-level constraints and parameters and provide control for individual spacecraft. Opportunities for innovation include the application of optimization techniques that are feasible for small-satellite platforms and do not assume particular orbit eccentricities. State of the art in this area is the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE), the first spacecraft to attempt to navigate to and maintain a near-rectilinear halo orbit around the Moon as a precursor for Gateway [Ref. 11]. NASA is also partnering with universities for use of surface-feature-based navigation and timing [Ref. 12].

NOTE: Small-spacecraft propulsion technologies are not included in this subtopic.

Relevance / Science Traceability:
Space communications and position knowledge and control are enabling capabilities required by spacecraft to conduct all NASA missions. The concept of distributed spacecraft missions (DSMs) involves the use of multiple spacecraft to achieve one or more science mission goals.

Several missions are being planned to conduct investigations/observations in the cislunar region and beyond. For example, CLPS; human exploration (Artemis) landing site and resource surveys; and communication and navigation infrastructure, including LunaNet, Mars communications relay, etc. All of these missions will benefit from improved communications and navigation capabilities.

References:

1. International Communication System Interoperability Standard (ICSIS): https://www.internationaldeepspacestandards.com
2. Interagency Operations Advisory Group (IOAG): https://www.ioag.org/
3. Space Communication Architecture Working Group (SCAWG) (2006) NASA Space Communication and Navigation Architecture Recommendations for 2005-2030: https://www.nas.nasa.gov/assets/pdf/techreports/2006/nas-06-014.pdf
4. NASA Delay/Disruption Tolerant Networking (DTN): http://www.nasa.gov/content/dtn
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7. National Telecommunications and Information Administration Tables of Frequency Allocations: https://www.ntia.doc.gov/legacy/osmhome/alloctbl/alloctbl.html
8. NASA Spectrum Policy and Guidance for Small Satellite Missions: http://www.nasa.gov/directorates/heo/scan/spectrum/policy_and_guidance.html
9. NASA Space Communications and Navigation Networks: https://www.nasa.gov/directorates/heo/scan/services/networks/index.html
10. NASA Optical Communications: https://www.nasa.gov/directorates/heo/scan/opticalcommunications/overview
11. Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE): https://www.nasa.gov/press-release/nasa-funds-cubesat-pathfinder-mission-to-unique-lunar-orbit
12. On-Orbit Demonstration of Surface Feature-Based Navigation and Timing: https://www.nasa.gov/feature/ames/nasa-selects-universities-for-collaborative-development
13. NASA/TP-2018-220027, State of the Art Small Spacecraft Technology Report: https://www.nasa.gov/smallsat-institute/sst-soa

Z8.09 Small Spacecraft Transfer Stage Development (SBIR)

Lead Center: MSFC
Participating Center(s): AFRC, GRC, JSC

Scope Title: Small Spacecraft Transfer Stage Development

Scope Description:

NASA and industry represent prospective customers for sending small-spacecraft payloads in the near term to the cislunar environment, with longer term potential for farther destinations such as near-Earth objects, Mars, or Venus. The lunar destinations in this case include the lunar surface, with specific interest in the South Pole, low lunar and frozen lunar orbits, and cislunar space, including Earth-Moon LaGrange points (e.g., E-M L3) and the lunar near-rectilinear halo orbit (NRHO) intended for Gateway. In future missions, NASA may transport small spacecraft to Venus for scientific discovery, to Mars to serve as precursors and infrastructure for human (and scientific) exploration, and on small-spacecraft missions to near-Earth objects for science measurements needed to understand prospective threats to Earth and perhaps even for resource extraction and return to Earth. The ultimate goal is to exploit the advantages of low-cost and rapidly produced CubeSats and small spacecraft, defined as total mass less than 180 kg fueled, by enabling them to reach these locations. Due to the current limits of SmallSat propulsion capabilities and the constraints of rideshare opportunities, NASA has an interest in the development of a low-cost transfer stage to guide and propel small spacecraft on trajectories to the vicinity of the Moon and enable their insertion into the above-referenced orbits. In addition, NASA has interest in the transfer stage being able to provide support services to the spacecraft post-deployment, such as communications relay or positioning, navigation, and timing (PNT) services. Advancement and extension of these capabilities will be needed for future planetary exploration.

Transfer stage designs shall be compatible with U.S. small launch vehicles that are currently flying or will be launching imminently. Proposals shall identify one or more relevant small launch vehicles, describe how their designs fit within the constraints of those vehicles, and define the transfer capability of the proposed system (i.e., from Low Earth Orbit (LEO), geosynchronous transfer orbit (GTO), etc., to low lunar orbit (LLO), NRHO, E-M L3, etc.). Establishment of a partnership or cooperative agreement with a launch vehicle provider is strongly encouraged. Transfer stage designs shall contain all requisite systems for navigation, propulsion, and communication to complete the mission. Novel propulsion chemistries and methods may be considered, including electric propulsion, as long as the design closes within the reference mission constraints. Transfer stages shall also include method(s) to deploy one or more SmallSat payloads into the target trajectory or orbit. Innovations such as novel dual-mode propulsion systems that enable new science missions or offer improvements to the efficiency, accuracy, and safety of lunar missions are of interest. Concepts that enable small cargo delivery and inspections to support on-orbit servicing, assembly, and manufacturing platforms are also desired. Additionally, technologies with dual-use potential (such as hypersonic or suborbital demonstrations) are applicable to this subtopic. The ability of the transfer stage to provide support services, such as Communications Relay or PNT, after spacecraft deployment is highly desirable.

This subtopic is targeting transfer stages for launch vehicles that have a capability range similar to that sought by the NASA Venture Class Launch Services. Rideshare applications that involve medium- or heavy-lift launch vehicles (e.g., Falcon 9, Atlas V) or deployment via the International Space Station (ISS) airlock are not part of this topic.

Lunar design reference mission:

- Launch on a small launch vehicle (ground or air launch).
- Payload (deployable spacecraft) mass: at least 25 kg.
- Provide sufficient delta-v and guidance to enter into trans-lunar injection (TLI) orbit after separation from small launch vehicle. An example mission is the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE)/NRHO Pathfinder 12U (25 kg) CubeSat, which requires a TLI orbit with a C_3 (characteristic energy) of -0.6 km^2/s^2.
- (Alternative) Provide sufficient delta-v and guidance to place a 25- to 50-kg spacecraft directly into lunar NRHO or E-M L3 orbit.
- Deploy spacecraft from transfer stage.
- Perform transfer stage safing and disposal operations.

Stretch goals are:

1. Extensibility of the design for planetary design reference missions: Similar to the above, for Venus, Mars, or near-Earth object destinations.
2. Ability to provide postdeployment spacecraft support services such as Communications Relay and/or PNT. Proposer to outline the performance and duration these support services can achieve for applicable orbital environments.
3. Enable small-cargo delivery and inspections to support on-orbit servicing, assembly, and manufacturing platforms.

Expected TRL or TRL Range at completion of the Project: 4 to 6

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.1 Chemical Space Propulsion

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software
- Analysis

Desired Deliverables Description:
A Phase I effort should provide evidence of the feasibility of key elements of cost, assembly, integration, and operations through fabrication and testing demonstrations. A flight concept should reach sufficient maturity to be able to clearly define mission environments and performance requirements. A prototype system design should reach sufficient maturity to define test objectives and map key performance parameters (mass, power, cost, etc.) from the prototype to the flight design. Hardware development during the Phase I effort should provide confidence in the design maturity and execution of the Phase II effort. Lastly, the Phase I effort should identify potential opportunities for mission infusion and initiate partnerships or cooperative agreements necessary for mission execution.

The Phase II deliverable should provide significant evidence of the progress toward mission infusion (PMI) as outlined in the 2020 NASA Small Spacecraft Technology: State of the Art report. Phase II objectives should meet the intent of the In-Development or Engineering-to-Flight classifications, including demonstrations in a relevant environment or execution of a qualification program. Efforts leading to Phase II delivery of an integrated system that could either be ground- or flight-tested as part of a post-Phase II effort are of particular interest.

State of the Art and Critical Gaps:
Many CubeSat/SmallSat propulsion units are designed for low delta-v maneuvers such as orbit maintenance, station-keeping, or reaction control. Larger delta-v systems are employed for larger satellites and science/exploration missions but are often costly and integrated as part of the satellite design. Systems typically range from cold-gas to bipropellant storables with electric systems also viable for very small systems. Rocket Lab has recently introduced an upgraded version of their monopropellant kick stage, which includes a bipropellant engine, advanced attitude control, and power subsystems. This system will be used for the first time for NASA's Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission and is suggested to have capability for orbits beyond the lunar environment. At the component level, suppliers of state-of-the-art (SOA) thrusters include Aerojet Rocketdyne, Moog Inc, and Bradford Space, among others, while companies like Blue Canyon Technologies offer spacecraft bus solutions absent dedicated propulsion elements. Advanced manufacturing, electric pumps, and actuators, nontoxic or nontraditional propellants, and electrospray thrusters all offer potential improvements in the flight capabilities of small propulsion systems. System concepts that enable improved spacecraft performance and control, such as dual-mode systems, provide potential advancements to the current SOA, especially those that enable new science missions and those that offer potential improvements to the efficiency, accuracy, and safety of future lunar manned missions. While many of these component technologies are reasonably mature, progress has been limited in the development and qualification of an integrated system as a rapid, low-cost solution for translunar or cislunar missions.

Deployment of small spacecraft beyond geosynchronous orbits typically exacerbates their limitations with respect to communications and navigation, by virtue of longer communication distances and limited ability to use Global Navigation Satellite System (GNSS) PNT services. This typically requires the spacecraft to throttle their communications and rely on more cumbersome ranging transponders with Earth for position knowledge, adversely affecting spacecraft designs and operations. Equipping transfer stages with such support services potentially allows for a less constraining environment for small spacecraft deployed in deep space. With respect to the current SOA, the Air Force Research Laboratory's EAGLE mission (Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) Augmented Geostationary Laboratory Experiment), launched into a near geosynchronous orbit, is an example of a host vehicle able to deploy smaller spacecraft as well as providing support services to hosted payload only.

Relevance / Science Traceability:
This subtopic extends the capabilities of the Flight Opportunities program and the Launch Services Program by seeding potential providers to establish lunar/cislunar transfer capabilities. The Small Spacecraft Technology (SST) program also seeks demonstrations of technical developments and capabilities of small spacecraft to serve as precursor missions (such as landing site investigation or in situ resource utilization (ISRU) prospecting) for human exploration, and as communications and navigation infrastructure for follow-on cislunar missions. SST CAPSTONE is an example mission.

Many technologies appropriate for this topic area are also relevant to NASA's lunar exploration goals. Small stages developed in this topic area would also be potential flight testbeds for cryogenic management systems, wireless avionics, or advance guidance systems and sensors. Sound rocket capabilities are being improved with options financed through this topic.

Small launch vehicles provide direct access for a small spacecraft to the destination or orbit of interest at a time of the small-spacecraft mission’s choosing. In support of exploration, science, and technology demonstration missions, further expansion of these vehicles' reach beyond LEO is needed. To expand the risk-tolerant small-spacecraft approach to deep space missions, frequent and low-cost access to destinations of interest beyond Earth is required. Provision of support services by the transfer stage to the spacecraft post-deployment could enable more ambitious small-spacecraft missions.

In the longer term, technical capabilities of small spacecraft at Venus, Mars, or NEO destinations will be demonstrated by SST, and ultimately new kinds of transfer vehicles derived from these capabilities may be needed to propel them there.

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Z8.10 Modular Systems for Cost-Effective Spacecraft Missions (SBIR)

Lead Center: ARC
Participating Center(s): GRC, JPL, LaRC, MSFC

Scope Title: Wireless Avionics Architectures and Wireless Sensing and Integrated Avionics

Scope Description:
This subtopic scope solicits proposals to develop enabling concepts, components, and subsystems based on innovative avionics architectures for spacecraft. Of interest are wireless systems that demonstrate reliable data transfer across avionics components, subsystems, and interfaces to simplify system integration, reconfiguration, and testing. These can range from developmental and flight instrumentation systems used for qualification and diagnostics on large spacecraft to fully wireless avionics for small spacecraft. Solutions that enable new avionic architectures and provide capabilities that expand mission performance while decreasing the size, weight, and power consumption (SWaP) and cost of the resulting spacecraft are highly desirable. The goal of this effort is to mature wireless avionics technology that facilitates the reuse of components, subsystems, and software across multiple spacecraft and missions while reducing production and operating costs. Initial development and demonstration is anticipated to be performed using small spacecraft, but applicability to large spacecraft, lunar outposts, human-rated landers, and robotic elements is highly desirable.

Modularity is defined as utilizing a set of standardized parts or independent units to form a full avionics system, and flexibility allows adapting modular components across different configurations, missions, and design stages. For example, wireless subnets improve modularity by eliminating the physical data connections from each component, simplifying physical integration. The scope is intended to range from simple wireless sensors to complete avionics systems, including software incorporating functions compatible with common spacecraft components. This means being able to integrate a given component or entire subsystem into flight hardware and software using object-oriented frameworks, allowing components or functions to be added to a new or existing spacecraft design without requiring significant changes to the other nonrelated components or subsystems.

This subtopic also solicits proposals to develop techniques, components, and systems that reduce or eliminate the dependency on wires, connectors, and penetrations for sensing and for the transmission of data and power across avionics subsystems, interfaces, and structures. Of interest are techniques that enable new applications through innovative methods such as the use of flexible materials and additive manufacturing. For example, the use of additive manufacturing and 3D printing to embed avionics components such as antennas, sensors, transmission lines, and interface functions into a spacecraft structure during the design and manufacturing process can increase efficiency while maintaining structural integrity. Similarly, the use of thin and flexible materials to construct passive wireless sensors enables sensing systems for structures such as parachutes and inflatable spacecraft without breaching the pressure interface. Systems that are applicable to small spacecraft (typically 6U/12U/24U CubeSats, including ESPA-class (Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter class)) but scalable to large vehicles can result in a significant reduction of risk for more complex and longer duration missions. Near-term missions include cislunar, lunar orbiting, lunar landed, and exploration precursor missions; Low Earth Orbit (LEO) “swarms” for Earth science and heliophysics; and disaggregated cooperative ensembles and sustained infrastructure for human exploration. New applications might include manned spacecraft inspection, repair, communications support, and related areas. Technology that supports onboard servicing, assembly, and manufacturing is specifically solicited. Proposals that provide reliable performance in extreme environments and that show a path to a flight demonstration are preferable.

The subtopic solicits developments in wireless avionics and wireless sensing for small spacecraft and may include technologies that:

1. Improve the reliability and applicability of wireless avionics for spacecraft with significant improvements in subsystem size, mass, and volume, particularly if the technology can simplify the spacecraft fabrication, test, and integration process.
2. Allow innovative architectures for wireless avionics featuring plug-and-play software supporting modular subsystems that can be easily incorporated into specific small-satellite missions.

3. Improve fault detection aboard spacecraft using wireless sensor systems to augment current wired sensors and which include the capability of adding sensors to address developmental and flight instrumentation use.
4. Use innovative techniques for embedding sensors and other avionics components into a spacecraft to reduce or eliminate large and heavy cables and connectors, or that enable data transfer inside and across rotating mechanisms and pressure interfaces or into remote locations where it is difficult or unfeasible to run cables or where cables are at risk of failure.
5. Use additive manufacturing of wireless components such as antennas, sensors, and processing elements to create new components that may be smaller and lighter than current products. These new components could be embedded into materials and structures that enable in situ structural health management, contributing to the development of smart structures and materials.
6. Include sensors and actuators that can be distributed among cooperative spacecraft to enable automated inspection of space assets or resource detection at the surface of the Moon, Mars, or other celestial bodies.
7. Development of wireless network and component technology that can enable time-critical control loops across spatially distributed elements can produce new avionics capability.

Key performance parameters (KPPs) would include improvements of at least a factor of 2 over existing technology in size, mass, and power consumption for sensors and associated components for a wireless instrumentation system. Improvements of sensor network throughput greater than five times the current 2-Mbps performance is desired, along with reduction of latency and incorporation of timing and position information.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.2 Avionics Systems and Subsystems

Desired Deliverables of Phase I and Phase II:

- Hardware
- Prototype
- Software
- Research
- Analysis

Desired Deliverables Description:
Possible deliverables include benchtop hardware systems that demonstrate reliable wireless interconnectivity of two or more modules with a host flight central processing unit (CPU), or payload/developmental flight instrumentation (DFI) processor, inside a CubeSat or small-satellite form-factor bus. This system need not be flight ready, but it should be in a path to a flight demonstration that would serve as technology maturation and risk reduction activity for larger NASA missions such as Gateway and other Artemis projects.

Specific Phase I deliverables include:

- Methods of improving reliability of wireless avionics technology.
- Redundancy methods to broaden mission applicability.
- Improvements in tolerance to extreme environments, including radiation.
- Novel avionics architecture definition and demonstration.
- Software support for redundant modular avionics.
- Plug-and-play methods for handling dynamic changes to avionics configuration.
- Fault detection and recovery for wireless avionics.
- Improvements in spacecraft production.
- Improvements in spacecraft integration and test.

- Technologies that use additive manufacturing technology for embedded avionics systems that reduce cables, connectors, and penetrations and show a path to a full solution.
- Sensors and sensor systems based on current technology needs to develop point solutions that are applicable to NASA missions in near- to mid-range timeframes.

Phase II deliverables should build upon the work completed in Phase I to demonstrate the new technology at a higher Technology Readiness Level (TRL) with alignment to NASA mission needs:

- Demonstration showing the key innovations of the developed technology.
- Demonstration of specific new mission capabilities.
- Delivery of prototype hardware for NASA evaluation.

State of the Art and Critical Gaps:
Development of small-satellites missions benefits from a growing number of users worldwide. This means there may be a large pool of commercial off-the-shelf components available for a specific mission (depending on the type and class of mission). A variety of command and data handling (C&DH) developments for CubeSats have resulted from in-house development, from new companies that specialize in CubeSat avionics, and from established companies who provide spacecraft avionics for the space industry in general. Presently there are a number of commercial vendors who offer highly integrated systems that contain the onboard computer, memory, electrical power system (EPS), and the ability to support a variety of input and output (I/O) for the CubeSat class of small spacecraft.

Wireless networks have been incorporated as crew support aboard the International Space Station (ISS). Wireless sensor networks have been flown as demonstrations. Dynamic self-configuring wireless networks have been evaluated in the laboratory. The American Institute of Aeronautics and Astronautics (AIAA) has defined the Space Plug-and-Play Architecture (SPA) standard, and flight demonstrations are planned.

The maturation of additive manufacturing and 3D printing technology are making embedded wireless sensors and avionics a possibility. Embedding transmission lines, antennas, connectors, and sensors onto a spacecraft structure turns that structure into a multifunctional system that reduces or eliminates bulky cables and connectors. Embedded passive wireless sensors can greatly increase sensing and telemetry capabilities, including providing low-cost techniques for vehicle health management in future missions. Moreover, flexible embedded passive sensors created with conductive and functional fabrics are enabling new opportunities for sensing in surfaces and systems where sensing has been traditionally absent, such as parachutes and inflatable structures.

Wireless power transmission is being used commercially for charging cell phones using resonant magnetic couplings. Passive sensors do not require an external power source. Power generation from light, vibration, radio-frequency (RF) energy, and other methods is needed to eliminate batteries and power connections for wireless sensor systems.

Relevance / Science Traceability:
NASA and other space agencies are exploring the application of SmallSats for deep space missions. The availability of modular wireless data connectivity alleviates complexity in testing and integration of systems. Modular components allow easier reconfiguration and late additions to any design. This is a benefit conferred on any spacecraft of any size, with the larger systems benefiting from savings in mass due to a larger reduction in cable harnesses and connectors.

References:

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5. Backscatter Systems for WAIC: https://ntrs.nasa.gov/search.jsp?R=20180004760
6. NASA Armstrong Patent: https://technology.nasa.gov/patent/DRC-TOPS-42
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8. Passive Wireless Sensor Technology Workshops: https://attend.ieee.org/wisee-2019/program/workshops/

Scope Title: Modular Open Systems Architectures Applied to Small-Spacecraft Platforms

Scope Description:
This subtopic scope requests advances within modular open systems architectures for small spacecraft. As the most accessible spacecraft platform logistically and financially, small spacecraft benefit from a heritage based on rapid deployment and cost-effective missions. To further the state of the art (SOA) of both of these considerations, further cost savings may be found by standardizing the system architectures that drive the subsystems for these platforms. Such a realization would enable modular, hot-swappable spacecraft subsystems to accommodate the ever-increasing need for a wider definition of what small spacecraft are capable of and utilized for. Upon demonstration aboard small-spacecraft missions, these technologies could then be adopted by larger unmanned and manned spacecraft missions.

The development of standardized, hot-swappable interfaces should be compliant with and cognizant of NASA spacecraft standards. Of particular interest are designs acquiescent to the Agency standards existing between grounding, thermal, software, and data transfer interfaces.

The adaptability introduced by an open and modular, interchangeable commercial-off-the-shelf (COTS) architecture furthers the ability to tailor current spacecraft designs for novel applications without requiring significant modifications to existing platforms. Also, of interest are advances in modules that minimize complexity in spacecraft manufacturing (such as deterring geometrical modifications by virtue of manufacturing). Advances in additive manufacturing may enable critical enhancements to the performance of small-spacecraft systems by embedding otherwise impractical internal features (such as through holes and cavities for electronics integration). Concepts that can support high specific power generation and management as well as thermal control are also of particular interest.

Systems that are applicable to small spacecraft (CubeSats up to ESPA class (Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter class) but scalable to large vehicles can result in a significant reduction of risk for more complex and longer duration missions. Near-term missions include:

- Cislunar, lunar orbiting, lunar landed, and exploration precursor.
- Low Earth Orbit (LEO) “swarms” for Earth science and heliophysics.
- Disaggregated cooperative ensembles and sustained infrastructure for human exploration.

New applications might include manned spacecraft inspection, repair, communications support, and related areas. Proposals that provide reliable performance in extreme environments and that show a path to a flight demonstration are preferable.

The subtopic solicits developments in open modular architectures for small spacecraft and may include technologies that:

1. Provide interchangeable hardware and software with standardized interfaces.
2. Enable spacecraft to be built up from plug-and-play components.
3. Improve the state of the art of open interfacing platforms suitable for small spacecraft, leveraging COTS wherever possible.
4. Leverage novel manufacturing-in-the-loop considerations for small-spacecraft design standardization.

5. Increase the reliability and durability of small-spacecraft hardware and software by integrating subsystem considerations directly into the design process at the architectural level.
6. Demonstrate expanded adaptivity for small spacecraft, allowing for platforms to be rapidly varied with respect to altering objectives and variable risk postures.
7. Exhibit advances in onboard power generation and management and/or improvements in thermal mitigation and dissipation for small spacecraft.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.1 Avionics Component Technologies

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Promising platform architectures that enable the standardization of COTS hardware and software could be demonstrated through benchtop setups validating numerous protocols and compliance with existing NASA design standards for small spacecraft. A demonstration of ease of hot-swapping would be ideal, demonstrating how rapidly such a system could be adapted for altered requirements with new instrumentation and subsystems.

The deliverables should address improvements for ease of integration of varied hardware and software, plug-and-play integration of small-spacecraft subsystems, increased assembly speed of small spacecraft, utilization of advanced manufacturing for ease of integration, automated error assessment for targeted repairability of subsystems, reduced small-spacecraft design complexity, and reduction of small-spacecraft development cost through standardized COTS.

Phase I Deliverable:

Trade study for and demonstration of how NASA small-spacecraft standards, such as thermal, grounding, and software/data normalizations, could be implemented into hot-swappable, modular architecture.

These architectures must be cognizant of:

- NASA thermal interface standards to demonstrate necessary conductivity and respective thermal isolation.
- NASA grounding interface standards to mitigate unwanted currents through single- or multiple-point grounding framework.
- NASA software and data interfacing standards, complying with Unified S-Band (USB) or Consultative Committee for Space Data Systems (CCSDS) standards.

Phase II Deliverable:

A benchtop hardware demonstration of open and modular architectures functioning at TRL 5 or above and using the Standards developed during Phase I. The components should take advantage of supply-chain-compliant, heritage-relevant COTS whenever possible.

State of the Art and Critical Gaps:

The current SOA leverages COTS and compiled standards for integrating small spacecraft into a functional system meeting varied mission requirements. A number of in-house developments within NASA have complemented progress in academia and private industry to develop the infrastructure required to expand and normalize the definition of small-spacecraft-compliant subsystems and instrumentation. An issue arises with the software and hardware architecture regulating the agreement of these subsystems with NASA standards. Commercial vendors offering plug-and-play components are often only compliant with a limited number of subsystems, and consequently there exists a need to address this with an open modular architecture to enable more rapid, compliant, and consequently cost-effective small spacecraft that meet NASA's standards.

Relevance / Science Traceability:
NASA and other space agencies are exploring the application of SmallSats for deep space missions. Modular architectures would enable a hot-swap adaptivity to altering mission requirements and serve as low-cost, rapid solutions for emerging destinations as they arise. Modular components allow easier reconfiguration and late additions to any design. Small-spacecraft modularity can be analogous for larger systems as well by virtue of defining and standardizing interconnectivity of universal COTS systems, enabling new objectives to be realized with a wide variety of instrumentation with a wide scope of requirements.

References:

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Scope Title: Cost-Effective Modular Batch-Producible Small Spacecraft

Scope Description:
This subtopic scope requests proposals to address the need for industry collaboration to manufacture 30 to 100 small spacecraft for a wide variety of missions, addressing objectives ranging from heliophysics to constellation demonstrations and sensor web applications. The ability to fabricate relatively large "batches" of spacecraft will play an important role regarding the throughput required for addressing the needs of the subtopic mission objectives in a cost-effective manner. As an advent in tandem with small-spacecraft swarms, batch-producible spacecraft are an increasing need as larger spacecraft are replaced with many smaller spacecrafts, distributing sensing and collaboratively accomplishing objectives enabled novelty by variable topologies and network-based considerations.

Advances in batch producibility are in tandem with standardization of rapid manufacturing of small spacecraft by private industry and will likely take advantage of advances in throughput-favorable fabrication methods. The manufacturability of batch-producible small spacecraft would need to consider the required throughput of manufacturing as a factor intrinsic to the small-spacecraft design itself. Of particular interest are concepts that integrate reconfigurable subsystems (such as those for power generation) for increased manufacturing throughput as a virtue of reduced point-design. These systems must still remain compliant with existing NASA small-spacecraft protocols for thermal, electrical, communications, and redundancy considerations. However, batch-producible spacecraft should leverage design methodologies that would decrease the cost and increase the compatibility of these standardized requisites by virtue of the manufacturing process itself, exhibiting design-for-standardization through the engineering process.

Such a batch-producible set of small spacecraft should leverage cost-effective supply chain considerations wherever possible and should integrate commercial-off-the-shelf (COTS) components and instrumentation into the design of spacecraft architecture. The result of rapidly manufacturable batches of spacecraft should demonstrate a significant reduction in manufacturing costs for 30 to 100 buses, with quicker turnaround times than otherwise possible over a range of NASA-relevant projects.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.2 Avionics Systems and Subsystems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I Deliverable:
An overview and technical description of methods for batch producibility of small spacecraft within the range of 30 to 100 buses, demonstrating the integration of COTS as part of the framework. Successful demonstrations of this deliverable should demonstrate an increase in the competency of the following objectives:

- A standardized high-throughput manufacturing method to enable the fabrication of small spacecraft in batches of 30 to 100 buses (within the scope of CubeSats, up to and including ESPA-class spacecraft).
- A systematic decision tree that addresses fabrication turnaround-time considerations as a factor of spacecraft complexity.
- Demonstrated cost decreases for spacecraft batches with respect to the current state of the art (SOA).
- The integration and normalization of COTS relevant for batch production of small spacecraft as a function of supply chain availability and vendor capabilities.

Phase II Deliverable:
Integrating small-spacecraft standards into batch production and demonstrating an infrastructure that is modular, batch compliant, and cost effective. Successful demonstrations of this deliverable should demonstrate an increase in the competency of the following objectives:

- The integration of common NASA small-spacecraft standards (such as thermal, grounding, communications) directly into batch producibility.
- A method for rapid assembly of batch-produced small spacecraft that accounts for manufacturability directly into the architecture of common subsystems (such as power generation, communications, etc.).

State of the Art and Critical Gaps:
The current SOA of batch-produced small spacecraft relies heavily on the industry-demonstrated heritage of COTS for small satellites. These systems have limited throughput considerations and are currently inappropriate for meeting future mission requisites pertaining to small spacecraft requiring the fabrication and integration of 30 to 100 spacecraft at a time (such as those relevant to heliophysics missions, network demonstrations, and swarm considerations).

Relevance / Science Traceability:
Partnership with industry on batch production of spacecraft will be required for distributed missions including synthetic apertures, disaggregated science observations, rapidly established planetary communications

architectures, constellations, and sensor web applications; planned heliophysics missions call for 30 to 100 spacecraft. Technology development missions would also benefit from low-cost and shorter lead-time standardized bus platforms.

References:

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Z8.13 Space Debris Prevention for Small Spacecraft (SBIR)

Lead Center: MSFC
Participating Center(s): ARC

Scope Title: Onboard Devices for Deorbit and/or Disposal of Single Spacecraft

Scope Description:

The rise in individual small spacecraft launches alongside increased deployment of small spacecraft swarms is greatly contributing to congestion in Low Earth Orbit (LEO). Between 2012 and 2019, the number of small spacecraft launches increased 5x to ~500 put into orbit in 2019. To date, this number continues to grow, with some companies planning/implementing swarms of several thousand, even tens of thousands, of small spacecraft. In recognition of the threat posed by space debris to Earth's orbital environment and the greater space industry, orbital debris prevention has been incorporated in every U.S. National Space Policy since 1988, with the latest Space Policy (2020) providing the strongest language yet, outlining that "the United States shall … Limit the creation of new debris, consistent with mission requirements and cost effectiveness, during the procurement and operation of spacecraft, launch services, and conduct of tests and experiments in space" [Refs. 1, 2, 3]. Concern has grown as "the number of objects orbiting the Earth [has] grown substantially in recent years with well over 90% being dead objects (inoperative satellites, spent upper stages, and fragmentation debris)" [Ref. 4], and a number of studies from NASA and other national and international agencies and organizations have shown dire outcomes and possible "runaway debris situations" for "business-as-usual" scenarios in debris population growth predictions for the future [Ref. 5], as well as significant strain on the current space traffic management architectures to prevent such scenarios [Ref. 6]. Now there is significant concern that the situation will get worse with the ubiquitous emergence of small satellite (SmallSat) technologies and the planned deployment of swarms and constellations of thousands of satellites in LEO—many of which qualify as "SmallSats"—by multiple commercial companies, such as SpaceX, OneWeb, Theia, Boeing, Amazon Kuiper, Inmarsat, etc. Per Reference 4, "if all of these plans materialize, the population of operational satellites in LEO would jump by over a factor of ten—from ~1,000 today to over 16,000 within the next 10 to 20 years" and "has the potential to affect the space environment for generations and push any space traffic management system beyond its limits." As a result, all spacecraft LEO operators could be faced with disruptive numbers of conjunction alerts and collisions between spacecraft and/or orbital debris, further exacerbating the situation.

While the challenges posed by space debris and the management of large constellations within that environment is a multidimensional problem with multifaceted solutions, this subtopic scope focuses on technical solutions for the deorbit and/or disposal aspects that relate to the safe end-of-life operations of SmallSat swarms and constellations. The lifetime requirement for any spacecraft in LEO is 25 years post-mission, or 30 years after launch if unable to be stored in a graveyard orbit [Ref. 7]. With increased use of higher orbital regimes by small spacecraft and regulatory attention on long-term debris concerns, it is critical that the small spacecraft community responsibly manage deorbiting and disposal in a way that preserves both the orbital environment and efficiency of small missions. Development and demonstration of low size, weight, power, and cost (SWaP-C) deorbit capabilities that are compatible with common small spacecraft form factors is required to maintain the agility of Earth-orbiting small spacecraft missions while complying with regulatory activity. These low SWaP-C deorbit or disposal technologies are being solicited in this scope. In particular, deorbit/disposal technologies that enable higher orbits than currently possible are desired. Further, technologies that enable controlled deorbit/disposal are desired—that is, can actively be controlled throughout the disposal process to further protect against collisions and interferences with both active and inactive spacecraft and debris.

Clear key performance parameters should be given as a part of the offeror's solution. These performance parameters (e.g., SWaP-C) should be quantified, compared to state of the art (SOA), and put into context of a planned, proposed, or otherwise hypothetical mission to highlight the advantages of the offered technology over SOA and other proposed solutions.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 09 Entry, Descent, and Landing
Level 2: TX 09.X Other Entry, Descent, and Landing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
In Phase I, a contextual study to further understand the feasibility of the proposed solution is desired. Ideally, Phase I would conclude with a basic proof-of-concept prototype (hardware or software as appropriate). Critical requirements and interfaces should be defined alongside refinements of the proposed key performance parameters in Phase I. The Phase I effort should provide evidence of the feasibility of key elements such as cost, assembly, integration, and operations. The concept should reach sufficient maturity to show strong feasibility for the defined mission environments and performance requirements. The prototype system design should reach sufficient maturity to define test objectives and map key performance parameters (mass, power, cost, etc.) from the prototype to the flight design. Hardware development during the Phase I effort should provide confidence in the design maturity and execution of the Phase II effort. Lastly, the Phase I effort should identify potential opportunities for mission infusion and initiate partnerships or cooperative agreements necessary for mission execution.

In Phase II, further development and technology maturation is desired. Ideally, Phase II would culminate with Technology Readiness Level (TRL) 5+ demonstration of the proposed solution. Both Phase I and Phase II should be approached with focus on infusion, ensuring solutions are being developed with the proper requirements, interfaces, performance parameters, partnerships, etc., such that they, through a Phase III award or otherwise, could be directly applied to real spacecraft and real missions.

State of the Art and Critical Gaps:

The 2020 NASA State of the Art of Small Spacecraft Technology report [8], Section 14.0, Deorbit Systems, gives a comprehensive overview of the SOA for both passive and active deorbit systems. The report details drag systems, including tethers, the Exo-Brake, and others. Drag sails have been the primary deorbit technology to date. They have been developed, demonstrated, and even commercialized/sold for mission use. However, capability needs to continue to grow, especially for higher orbital application as well as for more controlled deorbit and disposal.

Relevance / Science Traceability:

With increased use of higher orbital regimes by small spacecraft and regulatory attention on long-term debris concerns, it is critical that the small-spacecraft community responsibly manage deorbiting and disposal in a way that preserves both the orbital environment and the efficiency of small missions. Solutions are relevant to commercial space, national defense, and Earth science missions.

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8. NASA State of the Art of Small Spacecraft Technology. https://www.nasa.gov/smallsat-institute/sst-soa-2020. 2020.

Scope Title: Autonomous Space Traffic Management Technologies for Small Spacecraft Swarms and Constellations

Scope Description:

In recognition of the threat posed by space debris to Earth's orbital environment and the greater space industry, orbital debris prevention has been incorporated in every U.S. National Space Policy since 1988, with the latest Space Policy (2020) providing the strongest language yet, outlining that "the United States shall … Limit the creation of new debris, consistent with mission requirements and cost effectiveness, during the procurement and operation of spacecraft, launch services, and conduct of tests and experiments in space" [Refs. 1, 2, 3]. Concern has grown as "the number of objects orbiting the Earth [has] grown substantially in recent years with well over 90% being dead objects (inoperative satellites, spent upper stages, and fragmentation debris)" [Ref. 4], and a number of studies from NASA and other national and international agencies and organizations have shown dire outcomes and possible "runaway debris situations" for "business-as-usual" scenarios in debris population growth predictions for the future [Ref. 5], as well as significant strain on the current Space Traffic Management architectures to prevent such scenarios [Ref. 6]. Now there is significant concern that the situation will get worse with the ubiquitous emergence of small satellite (SmallSat) technologies and the planned deployment of swarms and constellations of thousands of satellites in Low Earth Orbit (LEO)—many of which qualify as "SmallSats"—by multiple commercial companies, such as SpaceX, OneWeb, Theia, Boeing, Amazon Kuiper, Inmarsat, etc. Per Ref. 4, “if all of these plans materialize, the population of operational satellites in LEO would jump by over a factor of ten—from ~1,000 today to over 16,000 within the next 10 to 20 years” and “has the potential to affect the space environment for generations and push any space traffic management system beyond its limits.” As a result, all spacecraft LEO operators could be faced with disruptive numbers of conjunction alerts and collisions between spacecraft and/or orbital debris, further exacerbating the situation.

While the challenges posed by space debris and the management of large constellations within that environment is a multidimensional problem with multifaceted solutions, this subtopic scope focuses on technical solutions for autonomous space traffic management aspects that relate to the safe operations of SmallSat swarms and constellations, with the aim of reducing the strain on current space traffic management architectures, particularly by removing the “human-in-the-loop” and replacing it with faster decision-making autonomous systems; improving the accuracy of conjunction alerts, particularly reducing the number of ”false alarms”; and ultimately reducing the risk of collision and generation of orbital debris by the collision of spacecraft with other spacecraft or debris.

As part of this scope, the following technologies are being solicited:

- Low size, weight, power, and cost (SWaP-C) small spacecraft systems for cooperative identification and tracking: Development and demonstration of low SWaP-C and low-complexity identification and tracking aids for small spacecraft that can be scaled, produced, and readily standardized under the paradigm of small spacecraft ecosystems. With increased demands on existing space situational awareness capabilities, and with regulatory attention on the threat of spacecraft that are unidentified, misidentified, or too small to track, the small spacecraft community needs such technologies to allow the community to operate with lower risk to all spacecraft in orbit—without negatively impacting the efficiency of small missions—and to minimize the risk of space debris generation.
- Low SWaP-C spacecraft systems for autonomous reactive operations of small spacecraft swarms and constellations: Development and demonstration of low SWaP-C small spacecraft technologies, such as sensors and coupled maneuvering systems, that enable small spacecraft swarms and constellations to operate in formation, in close proximity to other objects (cooperative or uncooperative), or beyond where the capacity of human-in-the-loop control will be required to process input onboard and execute correct responses autonomously, ensuring the safety of both spacecraft and object.
- Supporting software modules that enable the above: Development and demonstration of software to be hosted aboard single spacecraft, across the spacecraft swarm/constellation, or on the ground, that enable the cooperative identification and tracking and/or autonomous reactive operations, and whose primary functions can be developed and demonstrated within the budget of standard NASA Phase I and II SBIR awards. This includes artificial intelligence/machine learning (AI/ML) techniques and applications that can enable autonomous orbit adjustment and other actions to mitigate the potential for in-orbit collisions. Also included are software applications and/or network applications that enable:
    1. Efficient information exchange between individual spacecraft.
    2. Minimal reliance on ground commanding.
    3. Efficient use of space-qualified computing architectures.
    4. High-precision swarm navigation and control.
- Supporting ground systems that enable the above: Development and demonstration of ground systems that enable the cooperative identification and tracking and/or autonomous reactive operations, and whose primary functions can be developed and demonstrated within the budget of standard NASA Phase I and II SBIR awards.

In the above descriptions, the terms “SmallSat” and “small spacecraft” are to be interpreted as interchangeable and apply to Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) class spacecraft and below, including CubeSats, with masses of 180 kg and less. Where applicable, technologies that apply to CubeSats are highly desirable, as that would favor greater adoption of the technology.

In all of the above, clear key performance parameters should be given as a part of the offeror's solution. These performance parameters (e.g., SWaP-C) should be quantified, compared to state of the art, and put into context of a planned, proposed, or otherwise hypothetical mission. Technologies that, in addition to performing the requirements outlined above, can also be ported from LEO to deep space environments—enabling new science and exploration SmallSat swarms/constellation-based missions—are highly desirable.

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
Level 2: TX 17.2 Navigation Technologies

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
In Phase I, a contextual study to further understand the feasibility of the proposed solution is desired. Ideally, Phase I would conclude with a basic proof-of-concept prototype (hardware or software as appropriate). Critical requirements and interfaces should be defined alongside refinements of the proposed key performance parameters in Phase I. The Phase I effort should provide evidence of the feasibility of key elements such as cost, assembly, integration, and operations. The concept should reach sufficient maturity to show strong feasibility for the defined mission environments and performance requirements. The prototype system design should reach sufficient maturity to define test objectives and map key performance parameters (mass, power, cost, etc.) from the prototype to the flight design. Hardware development during the Phase I effort should provide confidence in the design maturity and execution of the Phase II effort. Lastly, the Phase I effort should identify potential opportunities for mission infusion and initiate partnerships or cooperative agreements necessary for mission execution.

In Phase II, further development and technology maturation is desired. Ideally, Phase II would culminate with Technology Readiness Level (TRL) 5+ demonstration of the proposed solution. Both Phase I and Phase II should be approached with focus on infusion, ensuring solutions are being developed with the proper requirements, interfaces, performance parameters, partnerships, etc., such that they, through a Phase III award or otherwise, could be directly applied to real spacecraft and real missions.

State of the Art and Critical Gaps:
Current space traffic management architectures typically have a significant involvement of "humans-in-the-loop" for the identification of conjunction threats, for making the decision on if and how to respond, and for implementation of the response. Currently the U.S. Air Force 18th Space Control Squadron provides conjunction advisories to virtually all space operators worldwide following measurements taken with its assets. The operators then assess and weigh the risks to their assets and the resources to be expended to mitigate those risks. This is a time-consuming process, typically on timescales that do not allow for rapid reaction to a rapidly evolving threat. It is further aggravated by the large uncertainties associated with the conjunctions, which can lead to many false alarms, resulting in an inability for operators to respond to all alerts, as it would consume too many resources, as well as "complacency that naturally occurs when the mission analysts are inundated with large numbers of alerts that turn out to be false alarms" [Ref. 4]. For instance, "under current tracking accuracies, the actual collision between Iridium-33 and Cosmos 2251 did not

stand out from other conjunctions that week as being noticeably dangerous" and therefore was not acted upon, with the impact only identified after its occurrence.

To help address such situations, various stakeholders have been implementing solutions of their own, but these solutions are likely to run into limitations, particularly as more spacecraft are deployed and systems need to be scaled further and start interacting with each other:

- For example, to help protect its nonhuman spaceflight assets, NASA established its Conjunction Assessment and Risk Analysis (CARA) program, with operational interfaces with the 18th Space Control Squadron to receive close-approach information in support of NASA mission teams. As a whole, however, the system still features humans in the loop, and if further investments are not made, it may run into combined scalability and time-responsiveness issues as more commercial and/or noncooperative foreign assets deploy and/or pass through the operational orbits of NASA spacecraft. While regulatory solutions are part of the mix to help resolve the issues encountered, such as the Space Act Agreement between NASA and SpaceX to identify how each party will respond [Ref. 7], those solutions are slow to implement and have legislative limitations. Technical solutions will inevitably be necessary to address gaps posed by regulatory means.
- Deployers of SmallSat swarms and constellations are increasingly implementing software solutions for spacecraft to autonomously decide and implement collision-avoiding maneuvers. However, given the large capital and labor-intensive investment required to implement them, such systems may not be within the reach of all spacecraft operators, especially startup or single-spacecraft mission operators. Furthermore, with such technologies in their infancy, and with commercial operators racing to deploy and scale their spacecraft constellations to achieve market dominance, there is a very real risk that such systems may struggle to interface adequately with other autonomous and nonautonomous constellations, as was experienced by OneWeb and SpaceX [Ref. 8]. There may even be a risk of enhanced collision risk as each autonomous system independently takes evasive action that, unbeknownst to the other, increases the risk of collision, much like two persons unsuccessfully trying to avoid each other in a corridor.

Relevance / Science Traceability:

- Low SWaP-C small spacecraft systems for cooperative identification and tracking: With increased demands on existing space situational awareness capabilities, and with regulatory attention on the threat of spacecraft that are unidentified, misidentified, or too small to track, the small spacecraft community needs low SWaP-C identification and tracking aids. Employing such methods would allow the community to operate with lower risk to all spacecraft in orbit without negatively impacting the efficiency of small missions. There is a clear need to develop and demonstrate low-cost and low-complexity identification and tracking aids that can be scaled, produced, and readily standardized under the paradigm of small spacecraft ecosystems.
    - Technologies used for identification and tracking aids in LEO may also have extensibility to the growing number of cislunar missions.
- Low SWaP-C spacecraft systems for autonomous reactive operations of small spacecraft swarms and constellations: Small spacecraft operating in formation, in close proximity to other objects, or beyond the capacity of human-in-the-loop control will be required to process input onboard and execute correct responses autonomously.
    - These sensor-driven operations will be enabling for safe proximity operations with spacecraft or small bodies as well as the detection and reaction to transient events for observation, such as would be required for sampling a plume from Enceladus. Furthermore, enabling multiple small spacecraft operating in coordinated orbital geometries or performing relative station-keeping can further expand human knowledge deeper into the universe by performing coordinated occultation, acting as virtual telescopes, and forming distributed apertures that would be prohibitively complex and expensive to launch into space as monolithic structures. Small spacecraft formation flight can also enable swarm gravimetry, synchronized observation of transient phenomena, and proximity operations for inspection of other assets.

References:

1. Orbital Debris Mitigation and Challenges to the Space Community, J.-C. Liou, Chief Scientist for Orbital Debris, NASA, 58th Session of the Scientific and Technical Subcommittee, Committee on the Peaceful Uses of Outer Space, United Nations, 19-30 April 2021.
2. U.S. National Space Policy, 1988.
3. U.S. National Space Policy, 2020.
4. Aerospace Corps, Space Traffic Management in the Age of New Space, 2018.
5. State of Space Environment, H. Krag, Head of ESA's Space Debris Office, 25 June 2019.
6. Space Traffic Management in the New Space Era, T. Muelhaupt, Principal Director, Center for Orbital and Reentry Debris Studies, Center for Space Policy and Strategy, The Aerospace Corporation, Journal of Space Safety Engineering, Volume 6, Issue 2, June 2019.
7. NASA, SpaceX Sign Joint Spaceflight Safety Agreement: https://www.nasa.gov/press-release/nasa-spacex-sign-joint-spaceflight-safety-agreement
8. OneWeb, SpaceX satellites dodged a potential collision in orbit: 'Red alerts' of a potential disaster were sent to the companies: https://www.theverge.com/2021/4/9/22374262/oneweb-spacex-satellites-dodged-potential-collision-orbit-space-force

Focus Area 22 Low Earth Orbit Platform Utilization and Microgravity Research

The Human Exploration and Operations Mission Directorate (HEOMD) provides mission critical space operations services to both NASA customers and to other partners within the U.S. and throughout the world: operating the International Space Station (ISS); ensuring safe and reliable access to space; and ensuring the health and safety of astronauts. Additionally, the HEOMD is chartered with enabling the development of a robust commercial economy in low-Earth orbit (LEO) by enabling technologies that will provide the foundation for the future of American leadership in space. In this topic area, NASA is seeking technologies that utilize the ISS National Lab as a platform for commercial in-space production for terrestrial applications.

NASA seeks to accomplish these objectives by achieving following goal:

- Enabling development of advanced manufacturing technologies and materials that benefit from use of the unique space environment of the ISS to make products for terrestrial use that benefit the nation, humanity, and the LEO economy. It is expected that these projects will lead to a commercially viable and scalable production enterprise operating in a future LEO commercial platform or destination (i.e. private space station)

Through the potential projects spurred by this topic, NASA hopes to incorporate SBIR-developed technologies into current and future commercial in space manufacturing and production efforts to contribute to the development of the low-Earth orbit economy, with a high standard of safety, reliability, and affordability.

References:

- Space Station Research & Technology: https://www.nasa.gov/mission_pages/station/research/experiments/explorer
- ISS National Lab Research Opportunities: Solicitations for ISS National Lab Research Opportunities: https://www.issnationallab.org/research-on-the-iss/solicitations/
- Low-Earth Orbit Economy: https://www.nasa.gov/leo-economy/low-earth-orbit-economy/
- NASA Research Announcement for In Space Production: LEO Opportunities: In-Space Production Applications | NASA: https://www.nasa.gov/feature/nasa-outlines-areas-of-interest-announces-research-opportunities-for-in-space-production

H8.01 Low-Earth Orbit Platform and Microgravity Utilization for Terrestrial Applications (SBIR)

Lead Center: JSC
Participating Center(s): ARC, GRC, JPL, KSC, LaRC, MSFC

Scope Title: Use of the International Space Station (ISS) to Foster Commercialization of Low Earth Orbit (LEO) Space

Scope Description:
Background: The White House letter to the appointee for the Office of Space Technology Policy included a number of significant challenges from the President that are intended to ensure the United States is "the world leader in the technologies and industries of the future that will be critical to our economic prosperity and national security." These challenges can be addressed through continued NASA investment in new and promising commercial In-Space Production Applications (InSPA) that utilize the ISS National Lab (ISS NL). NASA has been investing in such commercial technologies for many years, including through use of Small Business Innovation Research (SBIR) topic H8, and is seeing great possibilities for the commercial in-space production of materials that can be made in microgravity to levels of performance and quality that exceed those made on Earth. These technologies not only help to maintain and strengthen U.S. leadership in this area, but they support development of a strong U.S.-led commercial space economy in LEO.

Scope: This subtopic seeks proposals that advance NASA's objective of leveraging the unique capabilities (microgravity, exposure to space) of the ISS to maintain and strengthen the U.S. leadership in the area of commercial in-space production of materials, technologies, and industries of the future that will be critical to our economic prosperity amid increasing global competition. Proposals should describe how the commercial technologies benefit from the space environment to produce a level of quality and performance superior to that which is possible on Earth, while also supporting NASA’s objective to catalyze emerging markets leading to a broad non-NASA demand for use of U.S.-based LEO commercial destinations in the future. Of specific interest are proposals that could lead to valuable terrestrial applications and foster a scalable and sustainable demand for commercial markets in LEO. Use of the ISS will facilitate validation of these applications and enable development of a commercial product at reduced cost in order to attract significant capital and lead to growth of new and emerging LEO commercial markets in the following areas: thin-layer deposition, crystal production, tissue engineering and regenerative medicine, and advanced materials production. Phase I proposals for this subtopic should include increased emphasis (beyond the suggested page limit) on the anticipated business case as defined in Part 7 (The Market Opportunity) of this SBIR Solicitation. This subtopic is not intended for use by applications seeking a TRL 9 flight demonstration for a system or technology not aligned with in-space production goals.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.4 Manufacturing

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

For Phase I, as a minimum, development and test of a bench-top prototype and a written report detailing evidence of demonstrated prototype technology in the laboratory or in a relevant environment and stating the future path toward hardware demonstration in orbit. A preliminary assessment of the technology business case (cost and revenue forecast, market size, potential customers, etc.) is also required.

Desired deliverables at the end of Phase II would be a preliminary design and concept of operations, development and test of an engineering development unit in a relevant environment (ground or space), and a report containing detailed science requirements, results of testing, and an updated business case analysis and/or application plan. Concepts that can achieve flight demonstration on a suborbital flight or on the ISS during Phase II are especially valuable.

State of the Art and Critical Gaps:
The ISS is being used to stimulate both the supply and demand of commercial marketplace as NASA supports the development of the LEO space economy, while being aligned with the national goal to ensure the United States remains a world leader of in-space manufacturing and production of advanced materials.

Relevance / Science Traceability:
This subtopic is in direct support of NASA’s recent policy to enable commercial and marketing activities to take place aboard the ISS. The ISS capabilities will be used to further stimulate the demand for commercial products development and strengthen U.S. leadership in in-space manufacturing and production.

References:

1. NASA LEO Economy Strategy: https://cms.nasa.gov/leo-economy/low-earth-orbit-economy and Opportunities to Stimulate Demand | NASA
2. Space Station Research & Technology at: https://www.nasa.gov/mission_pages/station/research/experiments/explorer
3. Center for the Advancement of Science In Space, Inc. at: https://www.issnationallab.org and In-Space Production Applications (issnationallab.org). Both links are external.
4. President's Letter to Dr. Eric Lander (OSTP Nominee): A Letter to Dr. Eric S. Lander, the President's Science Advisor and nominee as Director of the Office of Science and Technology Policy | The White House

Focus Area 24 Dust Mitigation and Extreme Lunar Environment Mitigation Technologies

A number of space exploration missions to planetary bodies have noted significant deleterious effects due to fine particulates. This fine dust can foul mechanisms, alter thermal properties, and obscure optical systems. It can abrade textiles and scratch surfaces. With near term goals to return to the Moon, lunar dust is of particular concern. It has the potential to negatively affect every lunar architecture system. In addition, temperatures on the lunar surface vary from 35 K to 400 K imposing extreme operational constraints on architectural elements. The goal of this focus area is to develop dust mitigation and extreme lunar environment mitigation technologies that can be incorporated into space exploration systems.

All planetary exploration missions require a proactive strategy to lessen the effects of dust, extreme temperature variations, plasma, and radiation. Passive and active dust mitigation technologies and novel engineering design are needed to form a complete dust mitigation strategy. Spacesuits and mechanisms must be developed for operation in the extreme environments of the Moon. Proposed research may focus on development of new technologies, but there is particular interest in technologies that are approaching readiness for space environment testing.

Exploration systems require dust mitigation and extreme lunar environment mitigation technologies within the following capability areas:

- Optical Systems – Viewports, camera lenses, solar panels, space suit visors, mass spectrometers, other sensitive optical instruments.
- Thermal Surfaces – Thermal radiators, thermal painted surfaces, thermal connections.
- Fabrics – Space suit fabrics, soft wall habitats, mechanism covers.
- Mechanisms – Linear actuators, bearings, rotary joints, hinges, quick disconnects, valves, linkages.
- Seals and Soft Goods – Space suit interfaces, hatches, connectors, hoses; and,
- Gaseous Filtration – Atmosphere revitalization and ISRU processes.
- Specific dust mitigation innovations being sought in this solicitation will be outlined in the subtopic descriptions.

Z13.01 Active and Passive Dust Mitigation Surfaces (SBIR)

Lead Center: KSC
Participating Center(s): JSC, LaRC

Scope Title: Advanced Technologies for Active Dust Mitigation

Scope Description:
Proposals are sought that use unique methods that may require power, gases, mechanisms, vibrations, or other means necessary to keep vital surfaces clean under space conditions while not interfering with the form/fit/function of the surface they are acting upon. Self-cleaning surfaces that require minimal effort by astronauts are highly desired. Proposals that address removal of dust on passive (low surface energy) dust mitigation surfaces are also sought. Proposers are expected to show an in-depth understanding of the current state-of-the-art (SOA) and quantitatively describe improvements over relevant SOA technologies that substantiate investment in the new technology. Proposers must also quantitatively explain the operational benefit of the new technology from the perspective of improving or enabling mission potential. Some examples of active dust mitigation technologies include but are not limited to:

- Brushing: A self-cleaning brush to mechanically remove dust from surfaces. The brush can be mechanically operated using power or can be temperature activated, such as shape memory alloys.
- Electrostatic removal: Methods to use direct-current (DC) electric fields to remove dust from surfaces, either internal to the surface (embedded) or external using a removed high-voltage source.
- Vacuum: Methods to remove particles from surfaces using suction of gases.
- Jets: High-velocity gas jet that blows dust particles from surfaces.
- Spinning surfaces: Surface rotates in a manner that does not allow collection of dust on it.
- Vibrational surfaces: Vibrating surface bounces the particles off of the surface.
- Electrodynamic removal: The surface contains embedded electrodes with varying high-voltage signals applied to lift and transport dust off of the surface.

Proposals are highly sought in which the active dust mitigation strategy could be combined with the SOA of passive dust mitigation technologies. For example, passive dust mitigation strategies include:

- Electrostatic discharge (ESD) coatings and films: Statically dissipative coatings are less likely to accumulate charge, and hence dust, in dry environments.
- Superhydrophobic coatings: Materials with a very high contact angle can lower the adhesion of water-based contaminants, not allowing the capillary forces to take hold.
- EVA- and robotic-compatible dustproof electrical, fluid, and gas connectors.
- Lotus leaf coating: Microscopic nanostructures used to limit the van der Waals force of adhesion.
- Peel-away coating: Removable surface coatings.
- Gradient surfaces that direct dust adhesion away from vital surfaces.

Strong proposals are those that identify the active dust removal strategy in coordination with other dust prevention and removal methods as listed above. Strong proposals will also include a brief description of an infusion plan for a flight demonstration using Phase II funding.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.3 Mechanical Systems

Desired Deliverables of Phase I and Phase II:

- Hardware
- Prototype

Desired Deliverables Description:
At the end of the Phase I research period, it is expected that a material or technology will be identified and initial characterization results collected. Initial characterization should indicate whether further development of the technology would be scalable and should exhibit a dramatic reduction (>90% relative to full dust loading of a reference material surface such as an aerospace aluminum alloy or polymeric film surface such as Kapton® or Teflon®) in particulate adhesion for microparticles, specifically those described as lunar dust simulant, with diameters <50 µm. At the end of Phase II, it is expected that promising technologies will have been demonstrated through relevant environmental test conditions. The materials or technology should be demonstrated to be scalable to quantities sufficient for application beyond laboratory research requirements, i.e., at kilogram or greater quantities for materials or a similar measure for a passive technology. Cost analysis for scaling to mission-requirements level, as will be elucidated through the course of this research, will also be required.

If a Phase II is awarded, further development of the technology shall be required, including a prototype delivered to NASA at the end of the 2-year project with a goal of achieving Technology Readiness Level (TRL) 6. A prototype of the new technology must be provided that shows the feasibility of the dust removal method. The technology must be demonstrated in a laboratory environment removing and/or keeping dust from adhering to a surface. The mass, power, volume, and potential costs associated with the implementation of this technology must be addressed. A well-developed infusion plan resulting in a flight demonstration must also be provided.

State of the Art and Critical Gaps:
All new technologies for Active Dust Mitigation must include a full knowledge base of the SOA, and proposals that advance the current SOA are encouraged. For example, NASA has developed the Electrodynamic Dust Shield (EDS), which lifts, and transports dust off of surfaces with embedded electrodes within a dielectric. A brief but not complete introduction to the technology can be found in the references provided.

The EDS can be incorporated into a variety of configurations addressing many of NASA's needs. However, several potential improvements and technologies that can further the development of the EDS technology are also highly sought within this call. Some potential advances include:

- High dielectric breakdown strength for both glues/epoxies and the coating material: The efficiency of dust removal for the EDS is limited to the amount of voltage that can be applied to the electrodes. The electrical breakdown occurs across the 2D surface because of the dielectric strength limitation of the adhering material as well as the coating material.
- Flexible transparent surfaces with high current capabilities: The optically transparent version of the EDS uses indium tin oxide (ITO) as the main conductive medium for its electrode. Although the EDS is not a high-current DC device, the displacement current ($I \sim dV/dt$) can be quite high. Transparent electrode materials are sought that can replace ITO as the conductive medium that have higher current capabilities and lower overall resistivities. Another shortcoming of ITO is its range of

flexibility. Many ITO coatings cannot be bent past a certain degree and are not compatible with numerous folds and bends.

- Electrical attachment: Most EDS systems have issues with the electrical connections between the high-voltage power supply (HVPS) and the electrodes. Any possibility of arcing and/or sparking because of slight differences between the wiring from one material configuration to another is exacerbated when powered with EDS waveforms. Proposals are highly sought that address this key issue for attaching high-voltage wires to electrodes embedded in an EDS circuit. EDS circuit electrodes are made using a variety of materials such as copper (wires or vapor deposited), ITO, silver paint wires, carbon nanotube (CNT), and graphene, to name a few. Likewise, these and other electrodes are usually resting on or embedded into a substrate such as glass, polyimide (Kapton®), clothing fibers, polyethylene terephthalate (PET), polytetrafluoroethylene (PTFE), polyamide (nylon), poly(methyl methacrylate) (PMMA, e.g., acrylic, LUCITE®), and other surfaces.
- Minimizing electromagnetic interference (EMI): Most EDS designs can generate electrical noise that would be disadvantageous if incorporated into a system. Methods to reduce electrical noise and EMI are highly sought.
- Safety: With all EDS systems, the use of high voltage requires safety measures for the astronaut and the equipment. Methods to improve the safety and reliability of the EDS in the case of arcing is highly sought.
- Smart EDS technology: As with all dust mitigation technologies, methods to include adaptive techniques are highly sought. The system should be able to check its environment to see if dust clearing is necessary and, if it is, apply power to the system until the cleanliness requirements are met for reliability and power minimization.

Other active systems also require maturation. Critical gaps in these areas include:

- Effective and scratch-resistant brushing techniques. Apollo astronauts used brushes that are largely ineffective for large surface areas and tend to scratch sensitive equipment, such as astronaut visors.
- Gaseous removal of dust on the lunar surface may contaminate other sensitive equipment. A better approach to gaseous or fluidized removal of dust is needed.
- Simple mechanical or vibrational dust mitigation implementations are required. As particles move, they also become highly electrostatically charged, further causing dust adhesion.

Relevance / Science Traceability:

Adhesion of granular materials and the technologies that address mitigation through this subtopic will advance the state of knowledge of this difficult research subject. The interplay between the surface’s energy, chemistry, and mechanical properties and the particle’s surface is a fascinating but not well-understood science. This call will not only extend exploration missions on the lunar surface but will enable exploration missions that would not have been possible. For example, every mechanical seal was compromised on the Apollo missions over 3 days due to exposure to the dust. Research that elucidates this complex behavior toward lunar dust adhesion could be vital for realization of a sustained lunar presence, and although our understanding of the lunar environments has continued to improve, materials and technologies that arise from this research will expand our survival on dusty surfaces in space.

Ideally, a universal lunar simulant will be identified by NASA and should be used for performance verification of developed technologies. If no universal simulant is identified, the specific properties of the utilized particulate material should be identified and related to known properties of lunar dust.

References:

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9. Afshar-Mohajer, N., et al.: Review of dust transport and mitigation technologies in lunar and Martian atmospheres. Advances in Space Research, 56(6), Sept. 15, 2015, 1222-1241.
10. Gaier, J.: The effects of lunar dust on EVA systems during the Apollo missions. National Aeronautics and Space Administration, 2005, NASA/TM-213610.
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12. Gaier, J. R., Siamidis, J., Larkin, E. M. G.: Effect of simulated lunar dust on the properties of thermal control surfaces. J Spacecraft Rockets 2010, 47 (1): 147-152.
13. Proctor, M. P., Dempsey, P.: Survey of dust issues for lunar seals and the RESOLVE project. 2006, NASA/TM-0010457.
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15. Wohl, C., Belcher, M., Ghose, S., Hopkins, J., Connell, J.: Topographical modification of materials for mitigation of lunar dust adhesion. In 40th Lunar and Planetary Science Conference, The Woodlands, Texas, United States, 2009.
16. Gaier, J. R., Meador, M. A., Rogers, K. J., Sheehy, B. H.: Abrasion of candidate spacesuit fabrics by simulated lunar dust. National Aeronautics and Space Administration, 2009, TM-215800.

Scope Title: Advanced Technologies for Passive Dust Mitigation

Scope Description:
This call seeks unique research proposals focused on passive approaches, i.e., those that do not require external stimulus, that will minimize the potential impact lunar dust will have on future exploration missions. These approaches may include novel materials and surfaces as well as technologies that require no external input (a self-activating system) while not interfering with the form/fit/function of the surface they are acting upon. Novel materials may include high-performance plastics, metals, ceramics, etc. Surfaces may be homogeneous or heterogeneous (i.e., nonisotropic surface properties resulting in directional dust adhesion control), and rough or smooth with topography imparted by any number of approaches, including, but not limited to: lithography, embossing, roll-to-roll processing, etc. Surfaces can incorporate strategies for mitigation of adhesion contributions from van der Waals interactions, electrostatic forces, and chemically reactive or mechanical interactions. Both the material and surface modification approach must be demonstrated to be scalable and exhibit a dramatic reduction (>90% relative to a reference material surface such as an aerospace aluminum alloy or polymeric film surface such as Kapton® or Teflon®) in particulate adhesion for microparticles, specifically those described as lunar dust simulant, with diameters <50 µm.

Strong proposals will seek to demonstrate the efficacy of lunar dust adhesion mitigation and the durability to retain these properties in a simulated environment. Strong proposals will include characterization of the solar reflectivity and infrared (IR) emissivity of the passive approach applied, if applicable. Strong proposals will also include a brief description of an infusion plan for a flight demonstration using Phase II funding.

Expected TRL or TRL Range at completion of the Project: 3 to 6

Primary Technology Taxonomy:
Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2: TX 12.1 Materials

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
At the end of the Phase I research period, it is expected that a material or technology will be identified, and initial characterization results collected. Initial characterization should indicate whether further development of the technology would be scalable and should exhibit a dramatic reduction (>90% relative to full dust loading of a reference material surface such as an aerospace aluminum alloy or polymeric film surface such as Kapton® or Teflon®) in particulate adhesion for microparticles, specifically those described as lunar dust simulant, with diameters <50 µm. At the end of Phase II, it is expected that promising technologies will have been demonstrated through relevant environmental test conditions. The materials or technology should be demonstrated to be scalable to quantities sufficient for application beyond laboratory research requirements, i.e., at kilogram or greater quantities for materials or a similar measure for a passive technology. Cost analysis for scaling to mission-requirements level, as will be elucidated through the course of this research, will also be required.

If a Phase II award is made, further development of the technology shall be required, including a prototype delivered to NASA at the end of the 2-year project with a goal of achieving Technology Readiness Level (TRL) 6. A prototype of the new technology must be provided that shows the feasibility of the dust removal method. The technology must be demonstrated to remove adhered dust or prevent dust adhesion in a laboratory environment simulating some aspects of lunar environmental conditions. Durability of the material surface toward lunar dust abrasion, thermal cycling, and other environmental considerations should also be addressed. The mass, power, volume, and potential costs associated with the implementation of this technology must be addressed. A well-developed infusion plan resulting in a flight demonstration must also be provided.

State of the Art and Critical Gaps:
Although a myriad of materials and technologies exist for mitigation of surface contamination for a variety of terrestrial applications, requirements for mitigation of lunar dust adhesion indicate diminished efficacy of many materials. As an example, silicones are used ubiquitously to reduce adhesive interactions and can be effective for contamination prevention across a range of contaminants; however, these relatively soft materials would exhibit deleterious properties in a traditional manifestation arising from particulate embedding due to the sharp edges and hardness of the lunar dust. Likewise, hard traditional ceramic materials have been shown to be beneficial for terrestrial applications; however, triboelectrification of an insulating material would increase adhesion interactions with lunar dust. Beyond these specific lunar dust properties, magnetic interactions, chemical activity, and the velocity of the lunar dust, especially at the lunar terminator, all contribute to adhesion and therefore must be addressed for a material to be expected to perform well in this environment.

Critical technology gaps in passive dust adhesion mitigation include:

- Nanotechnology in permanently shadowed regions.
- Flexible materials with adhesion and abrasion resistance demonstrated across the thermal range of the lunar surface, -170 to 125 °C.
- Nonisotropic materials with directional dust adhesion control.

- Dust removal technologies integrated with passive dust mitigation materials.
- Materials and technologies for transition spaces from surface operations to habitat interior spaces.

Relevance / Science Traceability:
Adhesion of granular materials and the technologies that address mitigation through this subtopic will advance the state of knowledge of this difficult research subject. The interplay between the surface's energy, chemistry, and mechanical properties and the particle's surface is a fascinating but not well-understood science. This call will not only extend exploration missions on the lunar surface but will enable exploration missions that would not have been possible. For example, every mechanical seal was compromised on the Apollo missions in the course 3 days due to exposure to the dust. Research that elucidates this complex behavior toward lunar dust adhesion could be vital for realization of a sustained lunar presence, and although our understanding of the lunar environments has continued to improve, materials and technologies that arise from this research will expand our survival on dusty surfaces in space.

Ideally, a universal lunar simulant will be identified by NASA and should be used for performance verification of developed technologies. If no universal simulant is identified, the specific properties of the utilized particulate material should be identified and related to known properties of lunar dust.

References:

1. Gaier, J., et al.: Evaluation of surface modification as a lunar dust mitigation strategy for thermal control surfaces. 41st International Conference on Environmental Systems. 2011.
2. Wagner, S.: An assessment of dust effects on planetary surface systems to support exploration requirements. 2004.
3. Afshar-Mohajer, N., et al.: Review of dust transport and mitigation technologies in lunar and Martian atmospheres. Advances in Space Research, 56(6), Sept. 15, 2015, 1222-1241.
4. Gaier, J.: The effects of lunar dust on EVA systems during the Apollo missions. National Aeronautics and Space Administration, 2005, NASA/TM-213610.
5. Lee, L.-H.: Adhesion and cohesion mechanism of lunar dust on the Moon's surface. J. Adhes. Sci. Technol. 1995, 9 (8): 1103-1124.
6. Gaier, J. R., Siamidis, J., Larkin, E. M. G.: Effect of simulated lunar dust on the properties of thermal control surfaces. J Spacecraft Rockets 2010, 47 (1): 147-152.
7. Proctor, M. P., Dempsey, P.: Survey of dust issues for lunar seals and the RESOLVE project. 2006, NASA/TM-0010457.
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9. Wohl, C., Belcher, M., Ghose, S., Hopkins, J., Connell, J.: Topographical modification of materials for mitigation of lunar dust adhesion. In 40th Lunar and Planetary Science Conference, The Woodlands, Texas, United States, 2009.
10. Gaier, J. R., Meador, M. A., Rogers, K. J., Sheehy, B. H.: Abrasion of candidate spacesuit fabrics by simulated lunar dust. National Aeronautics and Space Administration, 2009, TM-215800.

Z13.02 Mechanisms for Extreme Environments (SBIR)

Lead Center: KSC
Participating Center(s): GRC, JSC, LaRC

Scope Title: Dust-Tolerant Mechanisms

Scope Description:
A return to the Moon to extend human presence, pursue scientific activities, use the Moon to prepare for future human missions to Mars, and expand Earth's economic sphere will require investment in developing new technologies and capabilities to achieve affordable and sustainable human exploration. From the

operational experience gained and lessons learned during the Apollo missions, conducting long-term operations in the lunar environment will be a particular challenge given the difficulties presented by the unique physical properties and other characteristics of lunar regolith, including dust. The Apollo missions and other lunar exploration have identified significant lunar-dust-related problems that will challenge future mission success. Lunar dust is composed of regolith particles ranging in size from tens of nanometers to microns, and lunar dust concerns are a manifestation of the complex interaction of the lunar soil with multiple mechanical, electrical, and gravitational effects.

Mechanical systems will need to operate on the dusty surface of the Moon for months to years. These systems will be exposed to the harsh regolith dust and will have little to no maintenance. This scope seeks technologies that can function with or tolerate dust intrusion in the following areas:

- Actuators and power transfer components (motors, pistons, shape memory alloy, gear, belt, chain, steering, suspension, hinges, bearings, etc.).
- Fastening, joining, and securing components and hardware (structural connections, threaded fasteners, quick pins, latches, restraint systems).
- Sealing materials and techniques that can keep out regolith and operate in the harsh Moon/Mars environments.
- Dust-tolerant fluid and electrical connectors (quick disconnects, umbilicals, modular commodity interfaces).
- Moving components for dust protection (iris, hatch, covers, airlocks, closures, fabric/flexible protection).
- Tools and devices for exploration and in situ resource utilization (ISRU) (sample tools, dust cleaning, landing gear, pointing actuator).
- Material handling and transportation components (hoist, lift, pallet, pick and place, common transport interface, etc.).

Successful solutions will have the following performance characteristics:

- Operational for extended service of 10 to 100 months with limited or no maintenance.
- Linear and static joints will function and perform the designed actuation/motion/mate-demate cycles of 1,000 or higher.
- Linear and static joints will function with minimal solid film or without lubrication.
- Rotational joints will have operational lifetimes on the order of hundreds of thousands of cycles.
- All mechanisms will function throughout lunar temperature cycles between 127 °C (260 °F) and -173 °C (-280 °F).
- All mechanisms will function in the extreme cold of permanently shadowed regions (-238 °C).
- All mechanisms will function reliably with lunar regolith (simulant) coating the exposed mechanism surfaces.
- All mechanisms will function in the high vacuum lunar environment of 10^{-9} Torr.
- All mechanisms and materials will function in the lunar electrostatic and radiation environment.

Expected TRL or TRL Range at completion of the Project: 2 to 6

Primary Technology Taxonomy:
Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.2 Mission Infrastructure, Sustainability, and Supportability

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward Phase II demonstration, with delivery of a demonstration package for NASA testing in operational test environments at the completion of the Phase II contract.

Phase I Deliverables: Research, identify, and evaluate candidate technologies or concepts for dust-tolerant mechanisms. Simulations or laboratory-level demonstrations are desirable. Deliverables must include a report to document findings.

Phase II Deliverables: Emphasis should be placed on developing, prototyping, and demonstrating the technology under simulated operational conditions (regolith, thermal, vacuum). Deliverables shall include a report outlining the path showing how the technology could be matured and applied to mission-worthy systems, functional and performance test results, and other associated documentation. Deliverable of a functional prototype is expected at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a Technology Readiness Level (TRL) of 6 or higher.

State of the Art and Critical Gaps:
Previous solutions used in the Apollo program did not address the current need of long-term usage. Terrestrial solutions often employ materials or methods that are incompatible with the lunar environment.

Critical Gaps:

- Seals at rotary and linear joints are very common for actuation in dusty environments. Most of these seals, however, use elastomers that would off-gas and become brittle in a lunar radiation environment and at lunar temperatures. Solutions are needed that employ advanced materials, metallic seals, or nontraditional techniques that can operate in the lunar environment for an extended period of time (months to years).
- Bearings that are tolerant of dust infiltration. Regolith getting past the protective seals and into bearings is a common failure point. Solutions are needed for bearings that are highly dust tolerant to reduce the risk of failures due to dust intrusion.
- Operations on the lunar surface will include assembly, construction, and extravehicular activity (EVA) tasks. These tasks will involve the mating/demating of various structural, electrical, and fluid connections. Dust on the surface of these joints will impede their proper function and lead to failures. Solutions are needed to protect these joints from dust contamination.
- Dust-protective enclosures, hatches, and moving covers are needed to protect delicate components. Materials and coatings are needed that eliminate or minimize the adherence of lunar dust to these surfaces. Solutions are needed for self-cleaning shapes, materials, and mechanisms that can clean/remove/reject regolith from vital moving parts of mechanisms as they operate.

Relevance / Science Traceability:
Dust will be one of the biggest challenges for operation on the lunar surface for the Artemis program.

“I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust.” Gene Cernan, Apollo 17 Technical Debrief.

References:

1. Dust Mitigation Gap Assessment Report, International Space Exploration Coordination Group (ISECG): https://www.globalspaceexploration.org/wordpress/docs/Dust%20Mitigation%20Gap%20Assessment%20Report.pdf

Z13.03 Technologies for Spacesuits in Extreme Surface Environments (SBIR)

Lead Center: JSC

Participating Center(s): N/A

Scope Title: Portable Life Support System (PLSS) Dust Protection

Scope Description:

For spacesuits, challenges presented by lunar dust include damage from abrasion, the effects of dust's electrostatic charge on the suit system, and dust intrusion to the suit system. Regarding the effects of dust intrusion, there is a need to protect components that must be exposed to, operate in, or operate after exposure to the lunar dust environment. There are multiple spacesuit components that require access to the environment for gas flow, both in nominal and off-nominal operations. Some of these components require specialized covers that prevent dust intrusion while at the same time allowing for sufficient gas flow. These components are:

1. PLSS Cover Vapor Vent Ports: The PLSS Cover has two ports to allow evaporated water from the Spacesuit Water Membrane Evaporator (SWME) and its backup, the Mini-Membrane Evaporator (Mini-ME), to vent to the surrounding vacuum. The operation of these components is dependent on a low backpressure, and each of the vent ports must have an effective flowthrough area of at least 7 $in.^2$ to maintain the appropriate pressure for evaporation within the PLSS cover. The vents (two total, symmetrically located on each side of the PLSS cover) need to accommodate a water-vapor mass flow of at least 2.6 lb/hr. The total area available for the vent ports is approximately 10 by 2.5 in. on either side.
2. PLSS Vacuum Access Pigtail Umbilical: The Rapid Cycle Amine (RCA) is a component that resides in the Exploration Extravehicular Mobility Unit (xEMU) PLSS. The responsibility of the RCA unit is to remove carbon dioxide (CO_2) and water (H_2O) from the PLSS ventilation loop. The RCA unit functions in a swing-bed regenerative manner to adsorb CO_2 and H_2O in one bed and desorb to vacuum in another bed. The PLSS Vacuum Access Pigtail Umbilical provides the vent path to vacuum for the RCA desorption cycle. This umbilical is 3 ft long with a diameter of 1.25 in. and is equipped with a free-flowing quick disconnect (QD) on the end. A specialized dust cover is needed for this umbilical to prevent dust intrusion. For efficient desorption, the pressure in the vacuum access line needs to decrease quickly and allow the flow of 0.65 L of ullage gas to the vacuum environment. The ullage gas can be assumed to be 100% oxygen (O_2) at 2.15 psi. Without a specialized cover, this gas dissipates within about 2 sec. After the ullage gas has dissipated, the desorbed gas consists of CO_2 and water (H_2O) with a mass flow of 325 to 360 g/min, depending on the bed loading and metabolic rate of the crewmember. Between 210 and 230 g/min of that flow is CO_2. For efficient operation of the RCA, the rapid decompression of the vacuum line is essential, as is the subsequent diffusion of desorbed gas away from the absorber beds. The specialized dust cover must not impede either of these processes.
3. Purge Valves: The xEMU is equipped with two purge valves to perform pre-extravehicular activity (EVA) denitrogenation purge or to convert the closed-loop ventilation operation into an open-loop operation as a contingency life-support function during the termination of an EVA resultant from a system failure. The Display and Control Unit (DCU) Purge Valve is located on top of the DCU on the chest of the spacesuit, such that the crew can visually observe the valve as well as reach/activate it with either hand. This is the primary valve. A secondary valve, available in the event of a primary valve failure, is the Hard Upper Torso (HUT) Purge Valve, which is located over the crewmember's right shoulder. This is a blind operation, accessible with only the right hand. Both of these valves will be exposed to the lunar dust environment and must be able to be activated and vent while operating in that environment. Both valves have a similar flow capability and function, providing an O_2 flow rate of 1.55 to 1.69 lb/hr at 3.5 psi. Both valves include a two-motion activation that can be performed with EV-gloved hands: pinch and lift.
4. Positive Pressure Relief Valve (PPRV): The PPRV prevents over-pressurization of the suit in the event of a failed open primary or secondary oxygen regulator. The xEMU has two PPRVs, both located on the HUT on the crewmember's lower right side below the shoulder. The two valves do not function under nominal circumstances during EVA but, depending on the vehicle pressure schedule and depress rate, could actuate during airlock depress. Current vehicle pressure

schedules for human landing systems would make this unlikely with the current 8.6- to 8.8-psid cracking/reseat pressure. The full-open flow rate requirement for the PPRV is 7.49 lb/hr of dry O_2 at 70 °F with suit internal pressure of 10.1 psia and vacuum as the external reference. The valve includes an inlet filter inside the suit and requires a venting protective cover on the outside of the suit that minimizes backpressure on the valve during venting operations.

5. Negative Pressure Relief Valve (NPRV): The NPRV prevents the suit from becoming too negatively pressurized during a rapid airlock repress such as that performed in the event of a suit emergency. Under this circumstance, the valve is designed to maintain the suit pressure at no more than a negative 0.5 psid. The requirement for the NPRV is 49 lb/hr of dry air at 70 °F, with the airlock pressure at 6.5 psia and a suit pressure at 6.0 psia. The NPRV is not used under nominal EVA operations but is exposed to the environment as it is located on the outside of the HUT, under the crewmember’s left shoulder. It must be capable of being exposed to dust with subsequent function if needed in this contingency.
6. Service and Cooling Connector (SCC): The SCC serves as the suit's main interface to vehicle services: O_2, H_2O, and power/data. The SCC is disconnected from the vehicle services umbilical at the beginning of an EVA and reconnected at its conclusion. While disconnected, the SCC must be protected from dust intrusion while operating in the dust environment. The protection must then be installed after disconnection and removed or inactivated during reconnection. The SCC includes two 3,000-psi O_2 recharge QDs, three H_2O QDs, and a 54-pin electrical connector ganged together in a single interface. The SCC presents a flat, outward-facing plane that is 2.5 by 4.0 in., located centrally on the DCU on the anterior of the suit.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
Phase I Deliverables: Reports demonstrating proof of concept, test data from proof-of-concept studies, and concepts and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

Phase II Deliverables: Delivery of technologically mature hardware, including components, subsystems, or treatments that demonstrate performance over the range of expected suit conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data and analysis. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to NASA.

State of the Art and Critical Gaps:
Good dust-mitigation technologies and strategies are nonexistent for the spacesuit.

Relevance / Science Traceability:
This scope is included under the Space Technology Mission Directorate (STMD) for Dust Mitigation. The project customer for this scope is the Exploration Extravehicular Mobility Unit (xEMU) project, which is under the Human Exploration and Operations Mission Directorate (HEOMD). Therefore, this scope has traceability to HEOMD as well.

References:
Note to offeror:

- PLSS schematics and hardware drawings shall be provided if offeror is selected for award.
- Dust simulant characteristics shall be provided if offeror is selected for award.

For further information on lunar regolith simulant materials, offerors may access NASA Technical Publication 2006-214605, Lunar Regolith Simulant Materials: Recommendations for Standardization, Production, and Usage: https://www.nasa.gov/sites/default/files/atoms/files/nasa_tp_2006_214605.pdf

Scope Title: Dust Removal Aids for Spacesuits

Scope Description:
The Exploration Extravehicular Mobility Unit (xEMU) Environmental Protection Garment (EPG) is a multilayered softgoods (textile material) system. Its primary function is to protect the xEMU suit system from the extreme extravehicular activity (EVA) environment while enabling suit functionality. The EPG system itself must survive the environment and protect the suit from the environment while enabling xEMU functionality of its three subsystems—the pressure garment system (PGS), portable life support system (PLSS), and informatics system. The EPG shell fabric is the suit's first line of defense as well as the source of regolith introduction back into lunar landers.

NASA is in search of cleaning aids for spacesuits. One part of a lunar dust mitigation solution involves cleaning off as much regolith dust as possible while still in the EVA environment. The more dust a crewmember can leave outside, the less intravehicular cleaning will be required, and less strain put on vehicle-level air filters. Projects currently underway are looking at numerous ways to improve suit cleaning beyond the capabilities used during Apollo. Examples include improved brush materials and geometry and a compressed gas system for forced dust removal.

Ortho-Fabric, the three-fiber shell fabric developed for the space shuttle suit outer layer, was designed for the shuttle airlock oxygen concentration of 30% at 10.2 psi (70.3 kPa) and for durability. While Ortho-Fabric does not support combustion in an exploration environment of 36% oxygen atmosphere at 8.2 psi, it is a woven fabric. The interstices of the weave (gaps between yarns) allow for some amount of lunar dust to penetrate, and therefore it is a poor barrier to dust. In addition, the GORE-TEX® expanded polytetrafluoroethylene (ePTFE) film is easily abraded by the dust. Although GORE-TEX® is a PTFE (Teflon®) and inert, it can accumulate a charge.

In short, NASA is without an adequate solution for removing lunar regolith from the outermost layer of the EPG system that covers the xEMU suit system. NASA is looking for innovative solutions for cleaning aids to address dust removal from the EPG and other external suit areas prone to dust contamination.

Expected TRL or TRL Range at completion of the Project: 3 to 4

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Prototype

Desired Deliverables Description:
Phase I Deliverables: Reports demonstrating proof of concept, test data from proof-of-concept studies, and concepts and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

Phase II Deliverables: Delivery of technologically mature hardware, including components, subsystems, or treatments that demonstrate performance over the range of expected suit conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and test data and analysis. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to NASA.

State of the Art and Critical Gaps:
Currently, Apollo-like brushes are being used for cleaning off dust on the spacesuits. Also, compressed gases are being assessed.

Relevance / Science Traceability:
This technology will support the lunar mission where dust is a potential hazard to operating the spacesuit on the lunar surface safely.

This scope is included under the Space Technology Mission Directorate (STMD) for Dust Mitigation. The project customer for this scope is the Exploration Extravehicular Mobility Unit (xEMU) project, which is under the Human Exploration and Operations Mission Directorate (HEOMD). Therefore, this scope has traceability to HEOMD as well.

References:
None

Z13.04 Lunar Dust Filtration and Monitoring (SBIR)

Lead Center: GRC
Participating Center(s): JSC, KSC

Scope Title: Lunar Dust Filtration and Monitoring

Scope Description:
Advances in the removal, management, and monitoring of airborne particulates and external dust are sought to address the intrusion into and containment of lunar dust within the pressurized habitable volumes and compartments in crewed spacecraft systems. Specifically, advances in particle filtration and separation techniques, barrier techniques, and monitoring instruments are integral to maintaining conditions conducive to crew health and safety as well as protecting spacecraft systems from dust-related fouling during crewed surface exploration missions.

Currently on the International Space Station (ISS), astronauts must vacuum protective screens covering filters weekly to remove larger particles and lint fibers, which are generated by their daily activities, particularly exercising. In the early, shorter Artemis missions, the crew will have to contend with very small amounts of typical spacecraft cabin aerosols and with large amounts of the new contaminant, lunar dust. Lunar dust particles will carry some level of charge which is not well understood or quantified at this time, and other cabin aerosols may be charged as well. Particles are irregularly shaped and jagged, with abrasive properties that can damage mechanisms and equipment.

In the long-range goal of establishing a sustainable human presence on the Moon in habitats, air quality in the larger living areas will be challenged by all the aerosols that come from longer term human occupancy and aerosols generated by the equipment and processes that keep the habitat operational. In this scenario, the time spent on cleaning should be minimal for the crew. Therefore, filtration and separation systems should be as maintenance free as possible, and potentially regenerable, to avoid the cost of flying spares and consumables. Based on the level of lunar dust contamination, even short missions (on the order of 30 days) may require some form of regeneration or autonomous maintenance to minimize or eliminate crew intervention. Specific needs on this front are particle-flow barriers, filtration media, and inertial cleaning prefilter devices that are self-cleaning and/or regenerable.

Another risk of suspended particulate matter (PM) in spacecraft is false smoke alarms. On ISS, the smoke detectors are disabled during vacuuming and other housekeeping activities for this reason. Ideally, this would not be the practice during extensive dust cleaning in the lander after extravehicular activities (EVAs), and creative solutions in particle monitors should address this issue.

PM monitoring technologies are sought to measure a wide range of particle concentrations that will exist in different stages of lunar missions. The lunar lander missions allow only minimal equipment within the small habitable volume but will have much higher concentrations of lunar dust. Therefore, miniaturized aerosol instruments should be capable of measurements in the range of tens of milligrams per cubic meter (mg/m^3) for particle sizes up to 20 µm and should be sensitive enough to verify small concentrations to prove that air cleaning systems are effective. Once cleaning has progressed, lunar dust mass concentrations may be very low, but large numbers of individual ultrafine particles may still be present. The Gateway outpost that will orbit the Moon will have some lunar dust contamination by way of the lander docking and exchanging air, as well as settled dust in the lander, which may be reentrained into Gateway air upon ascent, but overall, particle concentrations are expected to be much lower. The monitoring of this habitable space requires more sensitivity, with the ability to accurately measure down to 0.05 mg/m^3 for particles 10 µm and below.

Any monitoring technology is at risk of clogging from larger lunar dust particles or possibly even lint or other cabin aerosols. To avoid this, effective designs will have one or more precut features, such as size-selective inlets and screens, which should not require consumables or frequent maintenance and would potentially have self-cleaning features. Note that the ingestion of abrasive particles can cause damage to the internal components of a particulate monitor.

The performance of technologies should be evaluated through testing and/or analysis under relevant environmental conditions using aerosol reference instruments and relevant particle-size distributions of lunar dust simulants.

Measurement ranges for monitoring and permissible limits for filtration in lunar missions:

- Levels of suspended PM (cabin dust and lunar dust) must be maintained below 3 mg/m^3, and the respirable fraction of the total dust (smaller than 2.5 µm in aerodynamic diameter) must be below 1 mg/m^3, per the standards in NASA-STD-3001 Vol. 2, Rev. B.
- More specifically:
    - During intermittent daily exposure periods that may persist up to 6 months in duration, lunar dust must be maintained below a time-weighted average of 0.3 mg/m^3 for particles less than 10 µm.
    - For 7-day lander missions, lunar dust must be maintained below a time-weighted average of 1.6 mg/m^3 for particles less than 10 µm.

Specific needs in each area of interest are given below.

Bulk Particle Filtration and Separation Techniques:

Techniques and methods are sought for compact, low-power, autonomous, regenerable bulk PM separation and collection. Techniques should be suitable for general spacecraft cabin air purification and removal of planetary or lunar (surface) dust in main cabin quarters and airlock compartments. The hardware developed needs to operate at reduced cabin pressures down to 56 kPA. The PM removal techniques and methods must accommodate high volumetric flow rates up to 3.4 m^3/min (for distributed ventilation architectures with multiple supply and return branches) and with pressure drop not to exceed 125 Pa. The system needs to meet requirements for both lunar dust and spacecraft cabin dust (derived from materials in the spacecraft, Environmental Control and Life Support System (ECLSS) processes, and biological matter and debris generated by the crew).

The proposed techniques and methods should provide the cleanliness levels stated above, either as a standalone unit or in conjunction with a high-efficiency filter stage. The overall filtration performance of the filtration system (which may include a high-efficiency stage) should be at minimum 99.97% collection efficiency for particles 0.3 µm in diameter (or HEPA efficiency standard). The filter and separation system also needs to provide microbial and fungal control as outlined in NASA-STD-3001 Vol. 2, Rev. B requirements. These standards must be maintained for a particulate generation rate of 0.31 mg/min per person and a surface dust intrusion rate of 50 g per EVA person (according to EVA-EXP-0070). The systems need to be capable of handling the total PM and planetary dust load over the broad size range of particles generated throughout the mission (up to hundreds of micrometers) and must operate in the surface environment for periods ranging from 2 weeks to 500 days or more. The filter and/or separation technology should provide sufficient capacity to collect and contain tens to hundreds of grams of lunar dust over its service life (which can include multiple regeneration cycles). If regenerable, the technology should provide an effective means of containing or preventing the release of the collected bulk PM during the regeneration process.

Barrier Techniques:

There is a need for PM management systems specifically designed to collect and remove lunar dust from airlocks, suit preparation compartments, or staging areas. These should provide a >99.5% effective barrier to surface dust transfer between different volumes or compartments. The barrier technique may include filtration, separation, and other mitigation techniques used within these smaller pressurized compartments, and/or techniques that prevent the transport or transfer of surface dust between compartments, to main cabin areas, or to orbiting habitats and crew transport vehicles.

Monitoring Instrumentation:

Instruments, or instrument technologies, that measure PM concentrations in particle size ranges specified in the cleanliness requirements (stated above) are desired. The instrument, or combination of instruments, will need to measure lunar dust and normal cabin dust in landers, airlocks, and habitable spaces at lunar gravity, as well as in the microgravity environment in the Gateway orbiter. Real-time measurement instruments must be compact and low power, require minimal maintenance, and be able to maintain calibration for 1 year. The instrument also needs to be compatible with reduced pressure environments (26.2 kPa < pressure ≤ 103 kPa) in the cabin and airlocks of the transit and lander vehicles. The different environmental parameters may necessitate different modes of operation within one instrument (preferred to minimize payload and operational resources), or it may require different sensor types combined in one unit. PM sensors that measure size-segregated mass concentration (PM2.5 and PM10) over a wide range of mass concentrations and are capable of distinguishing between different material types (lunar dust, typical spacecraft cabin dust and smoke) are highly desirable.

In the long term, future integration of monitoring technologies with filtration or other cleaning technologies may drive the design and development of initially proposed technology solutions. Future autonomous vehicles are expected to use feedback loops for remediation of dirty air as well as monitoring filter and sensor health and performance.

Expected TRL or TRL Range at completion of the Project: 2 to 4

Primary Technology Taxonomy:
Level 1: TX 06 Human Health, Life Support, and Habitation Systems
Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:
For Phase I, research, numerical modeling, and preliminary breadboard results in a report are feasible.

For Phase II, firms should deliver a working prototype and accompanying test data to NASA, demonstrating performance to specifications using lunar simulants and other relevant test aerosols.

State of the Art and Critical Gaps:
The state of the art (SOA) for filtration relies on consumables, and there are few incentives for making regenerable filtration or prefilter barriers. Self-cleaning prefilter devices are not requirements for most commercial and residential filtration scenarios. The price for such systems is not justified when simple replacement filters are available. This solicitation specifies quantities of lunar dust loading in filters that far exceed the capacity of any commercially available filters.

The SOA for particulate monitoring includes miniaturized instruments, which may have very poor performance compared to reference-quality instruments. So-called "low-cost" sensors typically sacrifice accuracy for small-size and low-power needs and are only appropriate for environments that are relatively clean in comparison with the expected lunar dust contamination in the lander cabin after EVAs. In particular, it is difficult to accurately measure PM10 (particulate matter 10 µm and below) with commercially available miniaturized sensors. Instruments that are sensitive to single-digit mg/m^3 mass concentrations are typically not capable of measuring high concentrations. Size-selective inlets to instruments typically require cleaning and maintenance, and self-cleaning options are nonexistent. There is no commercially available instrument that can distinguish between aerosol types (dust, smoke).

Relevance / Science Traceability:
Human Exploration and Operations Mission Directorate (HEOMD) and Life Support Systems (LSS) can use this technology. It is absolutely necessary for Artemis or any other dusty planetary destination.

References:

1. NASA. NASA Spaceflight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health, NASA-STD-3001, Volume 2, Revision B, 2019-09-09.
2. NASA. Human Landing System EVA Compatibility IRD, EVA-EXP-0070 (DRAFT), September 23, 2019.
3. Agui, Juan, R. Vijayakumar, and Jay Perry. Particulate Filtration Design Considerations for Crewed Spacecraft Life Support Systems. 46th International Conference on Environmental Systems, 2016.
4. Apollo 17 Technical Crew Debriefing, page 20-12, NASA Manned Spacecraft Center, January 4, 1973, MSC-07631.

Appendices

Appendix A: Technology Readiness Level (TRL) Descriptions

The Technology Readiness Level (TRL) describes the stage of maturity in the development process from observation of basic principles through final product operation. The exit criteria for each level document that principles, concepts, applications, or performance have been satisfactorily demonstrated in the appropriate environment required for that level. A relevant environment is a subset of the operational environment that is expected to have a dominant impact on operational performance. Thus, reduced gravity may be only one of the operational environments in which the technology must be demonstrated or validated in order to advance to the next TRL.

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard	A medium fidelity system/component brassboard is built and	End-to-end software elements implemented and interfaced with existing	Documented test performance demonstrating

	validation in relevant environment.	operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in a relevant environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.

Definitions

Brassboard: A medium-fidelity functional unit that typically tries to make use of as much operational hardware/software as possible and begins to address scaling issues associated with the operational system. It does not have the engineering pedigree in all aspects but is structured to be able to operate in simulated operational environments in order to assess performance of critical functions.

Breadboard: A low-fidelity unit that demonstrates function only, without respect to form or fit in the case of hardware, or platform in the case of software. It often uses commercial and/or ad hoc components and is not intended to provide definitive information regarding operational performance.

Engineering Unit: A high-fidelity unit that demonstrates critical aspects of the engineering processes involved in the development of the operational unit. Engineering test units are intended to closely resemble the final product (hardware/software) to the maximum extent possible and are built and tested so as to establish confidence that the design will function in the expected environments. In some cases, the engineering unit will become the final product, assuming proper traceability has been exercised over the components and hardware handling.

Laboratory Environment: An environment that does not address in any manner the environment to be encountered by the system, subsystem, or component (hardware or software) during its intended operation. Tests in a laboratory environment are solely for the purpose of demonstrating the underlying principles of technical performance (functions), without respect to the impact of environment.

Mission Configuration: The final architecture/system design of the product that will be used in the operational environment. If the product is a subsystem/component, then it is embedded in the actual system in the actual configuration used in operation.

Operational Environment: The environment in which the final product will be operated. In the case of spaceflight hardware/software, it is space. In the case of ground-based or airborne systems that are not directed toward spaceflight, it will be the environments defined by the scope of operations. For software, the environment will be defined by the operational platform.

Proof of Concept: Analytical and experimental demonstration of hardware/software concepts that may or may not be incorporated into subsequent development and/or operational units.

Prototype Unit: The prototype unit demonstrates form, fit, and function at a scale deemed to be representative of the final product operating in its operational environment. A subscale test article provides fidelity sufficient to permit validation of analytical models capable of predicting the behavior of full-scale systems in an operational environment

Relevant Environment: Not all systems, subsystems, and/or components need to be operated in the operational environment in order to satisfactorily address performance margin requirements. Consequently, the relevant environment is the specific subset of the operational environment that is required to demonstrate critical "at risk" aspects of the final product performance in an operational environment. It is an environment that focuses specifically on "stressing" the technology advance in question.

Appendix B: SBIR and the Technology Taxonomy

NASA’s technology development activities expand the frontiers of knowledge and capabilities in aeronautics, science, and space, creating opportunities, markets, and products for U.S. industry and academia. Technologies that support NASA’s missions may also support science and exploration missions conducted by the commercial space industry and other Government agencies. In addition, NASA technology development results in applications for the general population, including devices that improve health, medicine, transportation, public safety, and consumer goods.

The 2020 NASA Technology Taxonomy is an evolution of the technology roadmaps developed in 2015. The 2020 NASA Technology Taxonomy provides a structure for articulating the technology development disciplines needed to enable future space missions and support commercial air travel. The 2020 revision is composed of 17 distinct technical-discipline-based taxonomies (TX) that provide a breakdown structure for each technology area. The taxonomy uses a three-level hierarchy for grouping and organizing technology types. Level 1 represents the technology area that is the title of that area. Level 2 is a list of the subareas the taxonomy is a foundational element of NASA’s technology management process. NASA’s mission directorates reference the taxonomy to solicit proposals and to inform decisions on NASA’s technology policy, prioritization, and strategic investments.

The 2020 NASA Technology Taxonomy can be found at:
(https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy_lowres.pdf).

The research and technology subtopics for the SBIR program are identified annually by mission directorates and center programs. The directorates identify high-priority research and technology needs for respective programs and projects.

The table on the following pages relates the current SBIR subtopics to the Technology Taxonomy.

2020 TX Mapping Level 1	2020 TA Mapping Level 2	SBIR Subtopic Number	Subtopic Title
TX01 - Propulsion Systems	TX01.1 - Chemical Space Propulsion	Z8.09	Small Spacecraft Transfer Stage Development
	TX01.2 - Electric Space Propulsion	Z10.04	Materials, Processes, and Technologies for Advancing In-Space Electric Propulsion Thrusters
	TX01.3 - Aero Propulsion	A1.02	Quiet Performance - Aircraft Propulsion Noise
		A1.03	Low Emissions/Clean Power - Environmentally Responsible Propulsion
		A1.04	Electrified Aircraft Propulsion
		A1.06	Vertical Lift Technology for Urban Air Mobility -Electric Motor Fault Mitigation Technology
		A1.08	Aeronautics Ground Test and Measurement Technologies
	TX01.4 - Advanced Propulsion	Z10.05	Rotating Detonation Rocket Engines (RDRE)
TX02 - Flight Computing and Avionics	TX02.1 - Avionics Component Technologies	S16.06	Command, Data Handling, and Electronics
	TX02.2 - Avionics Systems and Subsystems	Z2.03	Human Interfaces for Space Systems
		Z8.10	Modular Systems for Cost-Effective Spacecraft Missions
	TX02.X - Other Flight Computing and Avionics	Z2.02	High-Performance Space Computing Technology
TX03 - Aerospace Power and Energy Storage	TX03.1 - Power Generation and Energy Conservation	S16.01	Photovoltaic Power Generation and Conversion
	TX03.2 - Energy Storage	S13.07	Energy Storage for Extreme Environments
		Z1.08	Space-Rated Fuel Cell Technologies
	TX03.3 - Power Management and Distribution	Z1.05	Lunar and Planetary Surface Power Management and Distribution
		Z1.06	Radiation-Tolerant High-Voltage, High-Power Electronics
TX04 - Robotics Systems	TX04.2 - Mobility	S13.03	Extreme Environments Technology
		S16.04	Unpiloted Aerial Platforms and Technologies for NASA Science Missions
	TX04.3 - Manipulation	S13.01	Robotic Mobility, Manipulation and Sampling
		S13.02	Spacecraft Technology for Sample Return Missions
	TX04.6 - Robotics Integration	H10.02	Autonomous Operations Technologies for Ground and Launch Systems
	TX04.X - Other Robotic Systems	Z5.04	Intravehicular Robot (IVR) Technologies

TX05 - Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	TX05.1 - Optical Communications	H9.01	Long-Range Optical Telecommunications
	TX05.5 - Revolutionary Communications Technologies	H9.07	Cognitive Communication
	TX05.X - Other Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	Z8.02	Communications and Navigation for Distributed Small Spacecraft Beyond Low Earth Orbit (LEO)
TX06 - Human Health, Life Support, and Habitation Systems	TX06.1 - Environmental Control & Life Support Systems (ECLSS) and Habitation Systems	H3.08	Challenges in Carbon Dioxide Removal and Reduction: Carbon Particulate and Thermal Management
		H3.09	Human Accommodations
		Z13.04	Lunar Dust Filtration and Monitoring
	TX06.2 - Extravehicular Activity Systems	H4.06	Low-Power Multi-Gas Sensor for Spacesuits
		H4.07	Low Volume, Power and Mass CO2 and Humidity Control for xEMU
		Z13.03	Technologies for Spacesuits in Extreme Surface Environments
	TX06.3 - Human Health and Performance	H12.07	Protective Pharmaceutical Packaging
TX07 - Exploration Destination Systems	TX07.1 - In-Situ Resource Utilization	Z12.01	Extraction of Oxygen, Metal, and Water from Lunar Regolith
	TX07.2 - Mission Infrastructure, Sustainability, and Supportability	Z13.02	Mechanisms for Extreme Environments
	TX07.3 - Mission Operations and Safety	S13.04	Contamination Control and Planetary Protection
	TX07.X - Other Exploration Destination Systems	Z14.01	Lunar Surface Excavation
TX08 - Sensors and Instruments	TX08.1 - Remote Sensing Instruments/Sensors	S11.01	Lidar Remote-Sensing Technologies
		S11.02	Technologies for Active Microwave Remote Sensing
		S11.03	Technologies for Passive Microwave Remote Sensing
		S11.04	Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter
		S12.06	Detector Technologies for Ultraviolet (UV), X-Ray, and Gamma-Ray Instruments
		S14.03	Remote Sensing Instrument Technologies for Heliophysics
		S16.07	Cryogenic Systems for Sensors and Detectors
	TX08.2 - Observatories	S12.01	Exoplanet Detection and Characterization Technologies

		S12.03	Advanced Optical Systems and Fabrication/Testing/Control Technologies for Extended-Ultraviolet/Optical and Infrared Telescope
		S12.04	X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics
	TX08.3 - In-Situ Instruments/Sensor	A2.04	AERONAUTICAL INFORMATION SYSTEM SECURITY (AISS): Aircraft Systems
		S11.05	Suborbital Instruments and Sensor Systems for Earth Science Measurements
		S13.05	In Situ Instruments/Technologies for Lunar and Planetary Science
		S13.06	In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection
		S15.01	Plant Research Capabilities in Space
		S16.08	Atomic Quantum Sensor and Clocks
	TX08.X - Other Sensors and Instruments	S14.02	Particle and Field Sensors and Instrument-Enabling Technologies
		Z4.05	Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis
TX09 - Entry, Descent, and Landing	TX09.1 - Aeroassist and Atmospheric Entry	Z7.03	Entry and Descent System Technologies
	TX09.3 - Landing	Z7.04	Landing Systems Technologies
	TX09.X - Other Entry, Descent, and Landing	Z7.01	Entry, Descent, and Landing Flight Sensors and Instrumentation
		Z8.13	Space Debris Prevention for Small Spacecraft
TX10 - Autonomous Systems	TX10.1 - Situational and Self Awareness	H6.22	Deep Neural Net and Neuromorphic Processors for In-Space Autonomy and Cognition
	TX10.2 - Reasoning and Acting	S17.03	Fault Management Technologies
	TX10.3 - Collaboration and Interaction	H6.23	Spacecraft Autonomous Agent Cognitive Architectures for Human Exploration
	TX10.X - Other Autonomous Systems	A2.02	Enabling Aircraft Autonomy
TX11 - Software, Modeling, Simulation, and Information Processing	TX11.2 - Modeling	S17.04	Application of Artificial Intelligence for Science Modeling and Instrumentation
	TX 11.X Other Software, Modeling, Simulation, and Information Processing	A2.03	Advanced Air Mobility (AAM) Integration
		S11.06	Earth Science Decision Support Tools Focused on the Mitigation of Climate Change Impacts
		S14.01	Space Weather Research-to-Operations/Operations-to-Research (R2O/O2R) Technology Development
		S17.02	Integrated Science Mission Modeling

TX12 - Materials, Structures, Mechanical Systems, and Manufacturing	TX12.1 - Materials	H5.02	*Hot Structure* Technology *for Aerospace Vehicles*
	TX12.2 - Structures	H5.01	Lunar Surface 50 kW-Class Solar Array Structures
		H5.05	Inflatable Softgoods for Next Generation Habitation Systems
		S12.02	Precision Deployable Optical Structures and Metrology
	TX12.3 - Mechanical Systems	Z13.01	Active and Passive Dust Mitigation Surfaces
	TX12.4 - Manufacturing	H8.01	Low-Earth Orbit Platform and Microgravity Utilization for Terrestrial Applications
	TX12.X - Other Manufacturing, Materials, and Structures	Z4.07	Advanced Materials and Manufacturing for In-Space Operations
		Z14.02	Extraterrestrial Surface Construction
TX13 - Ground, Test, and Surface Systems	TX13.1 - Infrastructure Optimization	H10.01	Advanced Propulsion Systems Ground Test Technology
TX14 - Thermal Management Systems	TX14.1 - Cryogenic Systems	Z10.01	Cryogenic Fluid Management
	TX14.2 - Thermal Control Components and Systems	Z2.01	Spacecraft Thermal Management
	TX14.3 - Thermal Protection Components and Systems	S16.05	Thermal Control Systems
TX15 - Flight Vehicle Systems	TX15.1 - Aerosciences	A1.01	Aeroelasticity and Aeroservoelastic Control
		A1.05	Computational Tools and Methods
	TX15.2 - Flight Mechanics	A2.01	Flight Test and Measurement Technologies
		H9.03	Flight Dynamics and Navigation Technologies
TX16 - Air Traffic Management and Range Tracking Systems	TX16.1 - Safe All Vehicle Access	A3.03	Future Aviation Systems Safety
	TX16.3 - Traffic Management Concepts	A3.01	Advanced Air Traffic Management System Concepts
		A3.02	Increasing Autonomy in the National Airspace System (NAS)
		A3.04	Nontraditional Airspace Operations and Aerial Wildfire Response
TX17 - Guidance, Navigation, and Control (GN&C)	TX17.X - Other Guidance, Navigation, and Control	S16.03	Guidance, Navigation, and Control

Appendix C: Potential Transition and Infusion Opportunities

NASA has several programs and initiatives that help to drive the Agency's overall mission and goals. Many of the subtopics within the SBIR program touch on these mission and goals and are possible areas for SBIR funded firms to consider for future technology transition and infusion opportunities. Some examples of where NASA is making investments to meet these goals are:

Climate - NASA is increasing investments in climate research due to the dangers to humanity posed by climate change, including the economic and national security impacts of this threat. These investments increase our ability to better understand our own planet and how it works as an integrated system. This will require an array of instruments, platforms, and missions to deliver the highest priority data to create a 3D view of our Earth, from atmosphere to bedrock. It will also require innovation in clean energy technology, particularly technologies that enable sustainable aviation.

Moon to Mars - NASA will lead an innovative and sustainable program of exploration with commercial and international partners to send humans farther into space and bring back to Earth new knowledge and opportunities.

In addition to those listed above, NASA is making investments in the areas of Commercial Lunar Payload Services (CLPS) and working with several American companies to deliver science and technology to the lunar surface through the CLPS initiative. NASA's Flight Opportunities rapidly demonstrates promising technologies for space exploration, discovery, and the expansion of space commerce through suborbital testing with industry flight providers. The program matures capabilities needed for NASA missions and commercial applications while strategically investing in the growth of the U.S. commercial spaceflight industry. And lastly, conducting experiments on the International Space Station (ISS) is a unique opportunity to eliminate gravity as a variable, provide exposure to vacuum and radiation, and have a clear view of the Earth and space.

Below is a listing of all the SBIR subtopics by focus area and a designation if there are potential transition and infusion opportunities that exist within each subtopic. Offerors should think of this as a guide while understanding that NASA is not placing any priority on subtopics or awards that fall under these specific opportunities. Offerors that submit a proposal under a subtopic that is aligned with these opportunities do not increase their chance for an award.

Subtopic #	Subtopic Title	Climate	Moon to Mars	CLPS	Flight Opps	ISS
Focus Area 1 In-Space Propulsion Technologies						
Z10.01	Cryogenic Fluid Management		Yes			
Z10.04	Materials, Processes, and Technologies for Advancing In-Space Electric Propulsion Thrusters		Yes		Yes	
Z10.05	Rotating Detonation Rocket Engines (RDRE)		Yes			
Focus Area 2 Power, Energy and Storage						
S16.01	Photovoltaic Power Generation and Conversion		Yes	Yes		
S13.07	Energy Storage for Extreme Environments		Yes	Yes		
Z1.05	Lunar and Planetary Surface Power Management and Distribution		Yes	Yes		

Subtopic #	Subtopic Title	Climate	Moon to Mars	CLPS	Flight Opps	ISS
Z1.06	Radiation-Tolerant High-Voltage, High-Power Electronics		Yes	Yes		
Z1.08	Space-rated fuel cell technologies		Yes	Yes		
S16.01	Photovoltaic Power Generation and Conversion		Yes	Yes		
Focus Area 3 Autonomous Systems for Space Exploration						
H6.22	Deep Neural Net and Neuromorphic Processors for In-Space Autonomy and Cognition		Yes			Yes
H6.23	Spacecraft Autonomous Agent Cognitive Architectures for Human Exploration		Yes			Yes
S17.03	Fault Management Technologies		Yes	Yes		
Focus Area 4 Robotic Systems for Space Exploration						
S13.01	Robotic Mobility, Manipulation and Sampling		Yes	Yes		
Z5.04	Intravehicular Robot (IVR) Technologies		Yes			Yes
Z14.01	Lunar Surface Excavation	Yes	Yes			
Focus Area 5 Communications and Navigation						
H9.03	Flight Dynamics and Navigation Technologies		Yes	Yes	Yes	
H9.01	Long-Range Optical Telecommunications		Yes		Yes	
H9.07	Cognitive Communication		Yes			Yes
S16.03	Guidance, Navigation, and Control					
Focus Area 6 Life Support and Habitation Systems						
H3.08	Challenges in Carbon Dioxide Management		Yes		Yes	Yes
H3.09	Human Accommodations	Yes	Yes		Yes	Yes
H4.06	Low-Power Multi-Gas Sensor for Spacesuits		Yes	Yes	Yes	Yes
H4.07	Low Volume, Power and Mass CO2 and Humidity Control for xEMU	Yes	Yes	Yes	Yes	Yes
Focus Area 7 Human Research and Health Maintenance						
H12.07	Protective Pharmaceutical Packaging		Yes	Yes		Yes
Focus Area 8 In-Situ Resource Utilization						
Z12.01	Extraction of Oxygen, Metal, and Water from Lunar Regolith		Yes	Yes		
Focus Area 9 Sensors, Detectors, and Instruments						
S16.08	Atomic Quantum Sensor and Clocks					
S11.04	Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter	Yes				
S12.06	Detector Technologies for Ultraviolet (UV), X-Ray, and Gamma-Ray Instruments					
S14.02	Particle and Field Sensors and Instrument-Enabling Technologies					
S11.03	Technologies for Passive Microwave Remote Sensing	Yes				
S13.05	In Situ Instruments/Technologies for Lunar and Planetary Science		Yes	Yes		

Subtopic #	Subtopic Title	Climate	Moon to Mars	CLPS	Flight Opps	ISS
S11.02	Technologies for Active Microwave Remote Sensing	Yes	Yes			
S16.07	Cryogenic Systems for Sensors and Detectors		Yes	Yes		
S14.03	Remote Sensing Instrument Technologies for Heliophysics					
S13.06	In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection					
S11.05	Suborbital Instruments and Sensor Systems for Earth Science Measurements	Yes			Yes	
S11.01	Lidar Remote-Sensing Technologies	Yes	Yes			
S15.01	Plant Research Capabilities in Space					Yes
Focus Area 10 Advanced Telescope Technologies						
S12.02	Precision Deployable Optical Structures and Metrology					
S12.01	Exoplanet Detection and Characterization Technologies					
S12.04	X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics					
S12.03	Advanced Optical Systems and Fabrication/Testing/Control Technologies for Extended-Ultraviolet/Optical and Infrared Telescope					
Focus Area 11 Spacecraft and Platform Subsystems						
S16.06	Command, Data Handling, and Electronics					
S13.03	Extreme Environments Technology		Yes	Yes		
S13.02	Spacecraft Technology for Sample Return Missions		Yes	Yes		
S13.04	Contamination Control and Planetary Protection		Yes	Yes		
S16.04	Unpiloted Aerial Platforms and Technologies for NASA Science Missions	Yes			Yes	
Z2.02	High-Performance Space Computing Technology		Yes	Yes		Yes
Z2.03	Human Interfaces for Space Systems		Yes			Yes
Focus Area 12 Entry, Descent, and Landing Systems						
Z7.01	Entry, Descent, and Landing Flight Sensors and Instrumentation		Yes	Yes	Yes	
Z7.04	Landing Systems Technologies		Yes	Yes	Yes	
Z7.03	Entry and Descent System Technologies		Yes	Yes	Yes	
Focus Area 13 Information Technologies for Science Data						
S14.01	Space Weather Research-to-Operations/Operations-to-Research (R2O/O2R) Technology Development					
S17.02	Integrated Science Mission Modeling	Yes	Yes			
S17.04	Application of Artificial Intelligence for Science Modeling and Instrumentation	Yes				
S11.07	Earth Science Decision Support Tools Focused on the Mitigation of Climate Change Impacts	Yes				
Focus Area 15 Materials Research, Advanced Manufacturing, Structures, and Assembly						

Subtopic #	Subtopic Title	Climate	Moon to Mars	CLPS	Flight Opps	ISS
H5.01	Lunar Surface 50 kW-Class Solar Array Structures		Yes	Yes		
H5.02	Hot Structure Technology for Aerospace Vehicles		Yes	Yes	Yes	
H5.05	Inflatable Softgoods for Next Generation Habitation Systems	Yes		Yes	Yes	
Z4.05	Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis	Yes	Yes	Yes		
Z4.07	Advanced Materials & Manufacturing for In-Space Operations		Yes	Yes	Yes	
Z14.02	Extraterrestrial Surface Construction		Yes	Yes		
Focus Area 16 Ground & Launch Processing						
H10.02	Autonomous Operations Technologies for Ground and Launch Systems		Yes	Yes	Yes	
H10.01	Advanced Propulsion Systems Ground Test Technology		Yes			
Focus Area 17 Thermal Management Systems						
S16.05	Thermal Control Systems		Yes	Yes		
Z2.01	Spacecraft Thermal Management		Yes	Yes		
Focus Area 18 Air Vehicle Technology						
A1.01	Aeroelasticity and Aeroservoelastic Control	Yes				
A1.02	Quiet Performance - Aircraft Propulsion Noise	Yes				
A1.03	Low Emissions/Clean Power - Environmentally Responsible Propulsion	Yes				
A1.04	Electrified Aircraft Propulsion	Yes				
A1.05	Computational Tools and Methods					
A1.06	Vertical Lift Technology for Urban Air Mobility - Electric Motor Fault Mitigation Technology	Yes				
A1.08	Aeronautics Ground Test and Measurement Technologies					
Focus Area 19 Integrated Flight Systems						
A2.01	Flight Test and Measurement Technologies					
A2.02	Enabling Aircraft Autonomy					
A2.03	Advanced Air Mobility (AAM) Integration	Yes				
A2.04	AERONAUTICAL INFORMATION SYSTEM SECURITY (AISS)					
Focus Area 20 Airspace Operations and Safety						
A3.01	Advanced Air Traffic Management System Concepts	Yes				
A3.02	Increasing Autonomy in the National Airspace System (NAS)					
A3.03	Future Aviation Systems Safety					
A3.04	Nontraditional Airspace Operations and Aerial Wildfire Response	Yes				
Focus Area 21 Small Spacecraft Technologies						

Subtopic #	Subtopic Title	Climate	Moon to Mars	CLPS	Flight Opps	ISS
Z8.10	Modular Systems for Cost-Effective Spacecraft Missions		Yes	Yes	Yes	Yes
Z8.02	Communications and Navigation for Distributed Small Spacecraft Beyond Low Earth Orbit (LEO)		Yes	Yes	Yes	
Z8.09	Small Spacecraft Transfer Stage Development		Yes	Yes	Yes	
Z8.13	Space Debris Prevention for Small Spacecraft				Yes	Yes
Focus Area 22 Low Earth Orbit Platform Utilization and Microgravity Research						
H8.01	Low-Earth Orbit Platform and Microgravity Utilization for Terrestrial Applications		Yes		Yes	Yes
Focus Area 24 Dust Mitigation and Extreme Lunar Environment Mitigation Technologies						
Z13.03	Technologies for Spacesuits in Extreme Surface Environments		Yes			Yes
Z13.02	Mechanisms for Extreme Environments		Yes	Yes		
Z13.01	Active and Passive Dust Mitigation Surfaces		Yes			Yes
Z13.04	Lunar Dust Filtration and Monitoring		Yes			Yes

Appendix D: List of NASA SBIR Phase I Clauses, Regulations and Certifications

Introduction

Offerors who plan to submit a completed proposal package to this solicitation will be required to meet specific rules and regulations as part of the submission and if awarded a contract. Offerors should ensure that they understand these rules and requirements before submitting a completed proposal package to NASA.

Below are the all the clauses, regulations and certifications that apply to Phase I submissions and contracts. Each clause, regulation and certification contain a hyperlink to the webpages from the NASA FAR Supplement, SBIR/STTR Policy Directive, and www.acquisition.gov where you can read about the requirements.

On December 7, 2021, the United States District Court for the Southern District of Georgia Augusta Division (hereinafter "the Court") ordered a nationwide injunction enjoining the Government from implementing Executive Order 14042 in all covered contracts. As a result, NASA will take no action to enforce the clause implementing requirements of Executive Order 14042, absent further written notice from the agency, where the place of performance identified in the contract is in a U.S. state or outlying area subject to a court order prohibiting the application of requirements pursuant to the Executive Order (hereinafter, "Excluded State or Outlying Area"). A current list of such Excluded States and Outlying Areas is maintained at https://www.saferfederalworkforce.gov/contractors/

Federal Acquisition Regulations (FAR) Clauses for Phase I

52.203-19 PROHIBITION ON REQUIRING CERTAIN INTERNAL CONFIDENTIALITY AGREEMENTS OR STATEMENTS.

52.204-6 UNIQUE ENTITY IDENTIFIER.

52.204-7 SYSTEM FOR AWARD MANAGEMENT.

52.204-8 ANNUAL REPRESENTATIONS AND CERTIFICATIONS (DEVIATION 20-02A)

52.204-10 REPORTING EXECUTIVE COMPENSATION AND FIRST-TIER SUBCONTRACT AWARDS.

52.204-13 SYSTEM FOR AWARD MANAGEMENT MAINTENANCE.

52.204-16 COMMERCIAL AND GOVERNMENT ENTITY CODE REPORTING.

52.204-18 COMMERCIAL AND GOVERNMENT ENTITY CODE MAINTENANCE.

52.204-19 INCORPORATION BY REFERENCE OF REPRESENTATIONS AND CERTIFICATIONS.

52.204-22 ALTERNATIVE LINE ITEM PROPOSAL.

52.204-23 PROHIBITION ON CONTRACTING FOR HARDWARE, SOFTWARE, AND SERVICES DEVELOPED OR PROVIDED BY KASPERSKY LAB AND OTHER COVERED ENTITIES.

52.204-24 REPRESENTATION REGARDING CERTAIN TELECOMMUNICATIONS AND VIDEO SURVEILLANCE SERVICES OR EQUIPMENT

52.204-25 PROHIBITION ON CONTRACTING FOR CERTAIN TELECOMMUNICATIONS AND VIDEO SURVEILANCE SERVICES OR EQUIPMENT.

52.204-26 COVERED TELECOMMUNICATIONS EQUIPMENT OR SERVICES - REPRESENTATION.

52.209-6 PROTECTING THE GOVERNMENT'S INTEREST WHEN SUBCONTRACTING WITH CONTRACTORS DEBARRED, SUSPENDED, OR PROPOSED FOR DEBARMENT.

52.215-1 INSTRUCTIONS TO OFFERORS—COMPETITIVE ACQUISITION.

52.215-8 ORDER OF PRECEDENCE—UNIFORM CONTRACT FORMAT.

52.216-1 TYPE OF CONTRACT.

52.219-6 NOTICE OF TOTAL SMALL BUSINESS SET-ASIDE

52.219-28 POST-AWARD SMALL BUSINESS PROGRAM REREPRESENTATION.

52.222-3 CONVICT LABOR.

52.222-21 PROHIBITION OF SEGREGATED FACILITIES.

52.222-26 EQUAL OPPORTUNITY.

52.222-36 EQUAL OPPORTUNITY FOR WORKERS WITH DISABILITIES.

52.222-50 COMBATING TRAFFICKING IN PERSONS.

52.223-6 DRUG-FREE WORKPLACE.

52.223-18 ENCOURAGING CONTRACTOR POLICIES TO BAN TEXT MESSAGING WHILE DRIVING.

52.223-99 ENSURING ADEQUATE COVID-19 SAFETY PROTOCOLS FOR FEDERAL CONTRACTORS (DEVIATION 21-03)

52.225-13 RESTRICTIONS ON CERTAIN FOREIGN PURCHASES.

52.227-1 AUTHORIZATION AND CONSENT.

52.227-11 PATENT RIGHTS—OWNERSHIP BY THE CONTRACTOR.

52.227-20 RIGHTS IN DATA—SBIR PROGRAM.

52.232-2 PAYMENTS UNDER FIXED-PRICE RESEARCH AND DEVELOPMENT CONTRACTS.

52.232-9 LIMITATION ON WITHHOLDING OF PAYMENTS.

52.232-12 ADVANCE PAYMENTS.

52.232-23 ASSIGNMENT OF CLAIMS.

52.232-25 PROMPT PAYMENT.

52.232-33 PAYMENT BY ELECTRONIC FUNDS TRANSFER—SYSTEM FOR AWARD MANAGEMENT.

52.232-39 UNENFORCEABILITY OF UNAUTHORIZED OBLIGATIONS.

52.232-40 PROVIDING ACCELERATED PAYMENTS TO SMALL BUSINESS SUBCONTRACTORS. (DEVIATION 20-03A)

52.233-1 DISPUTES.

52.233-3 PROTEST AFTER AWARD.

52.233-4 APPLICABLE LAW FOR BREACH OF CONTRACT CLAIM.

52.242-15 STOP-WORK ORDER.

52.243-1 CHANGES—FIXED PRICE.

52.246-7 INSPECTION OF RESEARCH AND DEVELOPMENT—FIXED PRICE.

52.246-16 RESPONSIBILITY FOR SUPPLIES.

52.244-6 SUBCONTRACTS FOR COMMERCIAL ITEMS. (DEVIATION 20-03A)

52.249-1 TERMINATION FOR CONVENIENCE OF THE GOVERNMENT (FIXED-PRICE) (SHORT FORM).

52.252-1 SOLICITATION PROVISIONS INCORPORATED BY REFERENCE.

52.252-5 AUTHORIZED DEVIATIONS IN PROVISIONS.

52.253-1 COMPUTER GENERATED FORMS.

52.252-2 CLAUSES INCORPORATED BY REFERENCE.

52.252-6 AUTHORIZED DEVIATIONS IN CLAUSES.

NASA Clauses

Phase I

1852.216-78 FIRM FIXED PRICE.

1852.203-71 REQUIREMENT TO INFORM EMPLOYEES OF WHISTLEBLOWER RIGHTS

1852.204-76 SECURITY REQUIREMENTS FOR UNCLASSIFIED INFORMATION TECHNOLOGY RESOURCES. (DEVIATION 21-01)

1852.215-84 OMBUDSMAN.

1852.219-80 LIMITATION ON SUBCONTRACTING – SBIR PHASE I PROGRAMT. (OCT 2006)

1852.219-83 LIMITATION OF THE PRINCIPAL INVESTIGATOR – SBIR PROGRAM. (OCT 2006)

1852.225-70 EXPORT LICENSES

1852.225-71 RESTRICTION ON FUNDING ACTIVITY WITH CHINA

1852.225-72 RESTRICTION ON FUNDING ACTIVITY WITH CHINA – REPRESENTATION. (DEVIATION 12-01A)

1852.215-81 PROPOSAL PAGE LIMITATIONS.

1852.227-72 DESIGNATION OF NEW TECHNOLOGY REPRESENTATIVE AND PATENT REPRESENTATIVE.

1852.232-80 SUBMISSION OF VOUCHERS FOR PAYMENT.

1852.233-70 PROTESTS TO NASA.

1852.235-70 CENTER FOR AEROSPACE INFORMATION.

1852.239-74 INFORMATION TECHNOLOGY SYSTEM SUPPLY CHAIN RISK ASSESSMENT. (DEVIATION 15-03D)

1852.235-73 FINAL SCIENTIFIC AND TECHNICAL REPORTS.

1852.235-74 ADDITIONAL REPORTS OF WORK - RESEARCH AND DEVELOPMENT.

1852.237-73 RELEASE OF SENSITIVE INFORMATION.

PCD 21-02 FEDERAL ACQUISITION REGULATION (FAR) CLASS DEVIATION – PROTECTION OF DATA UNDER THE SMALL BUSINESS INNOVATIVE RESEARCH/SMALL TECHNOLOGY TRANSFER RESEARCH (SBIR/STTR) PROGRAM

PCD 21-04 CLASS DEVIATION FROM THE FEDERAL ACQUISITION REGULATION (FAR) AND NASA FAR SUPPLEMENT (NFS) REGARDING REQUIREMENTS FOR NONAVAILABILITY DETERMINATIONS UNDER THE BUY AMERICAN STATUTE

Additional Regulations

SOFTWARE DEVELOPMENT STANDARDS

HUMAN AND/OR ANIMAL SUBJECT

HOMELAND SECURITY PRESIDENTIAL DIRECTIVE 12 (HSPD-12)

RIGHTS IN DATA DEVELOPED UNDER SBIR FUNDING AGREEMENT

INVENTION REPORTING, ELECTION OF TITLE, PATENT APPLICATION FILING, AND PATENTS

SBA Certifications required for Phase I

(1) CERTIFICATIONS.

(2) PERFORMANCE OF WORK REQUIREMENTS.

(3) EMPLOYMENT OF THE PRINCIPAL INVESTIGATOR/PROJECT MANAGER.

(4) LOCATION OF THE WORK.

(5) NOVATED/SUCCESSOR IN INTERESTED/REVISED FUNDING AGREEMENTS.

(6) MAJORITY-OWNED BY MULTIPLE VCOCS, HEDGE FUNDS OR PRIVATE EQUITY FIRMS [SBIR ONLY].

(7) AGENCY BENCHMARKS FOR PROGRESS TOWARDS COMMERCIALIZATION.

(8) LIFE CYCLE CERTIFICATIONS