National Aeronautics and Space Administration

Small Business

Innovation Research (SBIR)

Phase I

Fiscal Year 2023 Solicitation

Completed Proposal Package Due Date and Time:
March 13, 2023 - 5:00 p.m. ET

Contents

Executive Summary

This solicitation identifies the objectives for the Small Business Innovation Research (SBIR) Program Phase I projects, deadlines, funding information, eligibility criteria for projects, 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 offerors to submit a completed proposal package for the SBIR Program Phase I for fiscal year (FY) 2023. **The NASA SBIR areas of research are categorized by focus areas and subtopics in an integrated list in chapter 9.**

NASA uses an electronic submission system called the Electronic Handbook (EHB) https://sbir.gsfc.nasa.gov/submissions/login and all offerors must use the EHB for submitting a completed proposal package. The EHB guides offerors through the steps for submitting a complete proposal package. All submissions are through a secure connection and most communication between NASA and the offeror is through either the EHB or email via the helpdesk at sbir@reisystems.com. For more information see chapter 3.

The SBIR and STTR Extension Act of 2022 (https://www.congress.gov/bill/117th-congress/senate-bill/4900/text) reauthorizes through FY2025 and modifies the Small Business Innovation Research (SBIR) program, the Small Business Technology Transfer (STTR) program, and related pilot programs.

The bill requires agencies with an SBIR program to assess the security risks presented by offerors with financial ties or obligations to certain foreign countries. The programs may not make awards to businesses with certain connections to foreign entities. To comply with this requirement, the program will require all offerors selected for contract negotiation of a 2023 SBIR Phase I award to complete additional disclosures regarding ties to the People's Republic of China and other foreign countries prior to award and as needed during the life of the funding agreement.

These disclosures will include:

A. The identity of all owners and covered individuals of the small business concern who are a party to any foreign talent recruitment program of any foreign country of concern, including the People's Republic of China;
B. The existence of any joint venture or subsidiary of the small business concern that is based in, funded by, or has a foreign affiliation with any foreign country of concern, including the People's Republic of China;
C. Any current or pending contractual or financial obligation or other agreement specific to a business arrangement, or joint venture-like arrangement with an enterprise owned by a foreign state or any foreign entity;
D. Whether the small business concern is wholly owned in the People's Republic of China or another foreign country of concern;

E. The percentage, if any, of venture capital or institutional investment by an entity that has a general partner or individual holding a leadership role in such entity who has a foreign affiliation with any foreign country of concern, including the People’s Republic of China;
F. Any technology licensing or intellectual property sales to a foreign country of concern, including the People’s Republic of China, during the 5-year period preceding submission of the proposal; and
G. Any foreign business entity, offshore entity, or entity outside the United States related to the small business concern.

1. Program Description

1.1 Legislative Authority and Background

The SBIR and STTR Extension Act of 2022 (Pub. L. 117-183.) amended the Small Business Act (15 U.S.C. 638) to extend the SBIR/STTR programs until September 30, 2025. Policy is provided by the Small Business Administration (SBA) through the combined Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs Policy Directive. The main purpose of the legislation is to stimulate technological innovation in the Federal Research/Research and Development (R/R&D) sector and increase private sector commercialization in both the SBIR and STTR 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), hereforth called offerors to submit a 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 2023 solicitation period for Phase I submission of completed proposal packages begins on January 10, 2023 and ends at 5 p.m. Eastern Time on March 13, 2023.**

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 chapter 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 Phase I proposals. The aim of a Phase I project should be to 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/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 in a commercial market. 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	$850,000
Maximum Period of Performance	24 months

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 offeror 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 award. 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 2023.

It is anticipated the SBIR Phase I completed proposal packages will be selected for negotiation of firm-fixed-price contracts for a period of performance not to exceed six (6) months.

Under this SBIR Phase I solicitation, NASA will not accept more than 10 completed proposal packages from any one offeror 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 chapter 4.

1.5 Eligibility Requirements

1.5.1 Small Business Concern (SBC)

Each Phase I offeror 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 offeror, combined with its affiliates, must not have more than 500 employees.

1.5.3 SBIR Restrictions on Level of Small Business Participation

The offeror must be the primary performer of the proposed research effort. 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 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 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 Designated Country list. 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	For Phase I, the primary employment of the principal investigator/project manager must be with the SBC at the time of award and during the conduct of the proposed project. Primary employment means that more than one-half of the principal investigator/project manager's employment time is spent in the

	employ of the SBC (based on a 40-hour workweek). This precludes full-time employment with another organization.
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 a 19.9-hour or more workweek elsewhere to conflict with this rule. 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.

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 SBIR and STTR Extension Act of 2022 (https://www.congress.gov/bill/117th-congress/senate-bill/4900/text) reauthorizes through FY2025 and modifies the Small Business Innovation Research (SBIR) program, the Small Business Technology Transfer (STTR) program, and related pilot programs.

The bill requires minimum performance standards for more experienced firms.

Progress to Phase II - Increased Performance Standards for More Experienced Firms

This new Phase I to Phase II transition standard applies to firms that have won more than 50 Phase I awards during the five fiscal years preceding the most recent year. These firms must double their transition rate. The current minimum standard applies to firms with more than 20 Phase I awards and requires a minimum transition rate of 1 Phase II award per 4 Phase I awards. Firms with more than 50 awards, as detailed above, will now be required to meet an average of at least 2 Phase II awards per 4 Phase I awards.

Progress to Phase III - Increased Performance Standards for More Experienced Firms

Tier one applies to firms that have won more than 50 Phase II awards during the ten fiscal years preceding the two most recent. The performance standard would increase by 150% and require an average of $250,000 of sales and/or investments per Phase II award received during the covered period. The current standard is an average of $100,000 for firms that have won more than 15 Phase II awards during the covered period. This Act codifies the current practice that sales and/or investments shall result from awards within the covered period.

Tier two applies to firms that have won more than 100 Phase II awards during the ten fiscal years preceding the two most recent. The standard would increase by 350% and require an average of $450,000 of sales and/or investments per Phase II award received during the covered period. The current standard is an average of $100,000 for firms that have won more than 15 Phase II awards during the covered period. This Act codifies the current practice that sales and/or investments shall result from awards within the covered period.

Consequence of Failure to Meet Standard. If a firm does meet an increased performance standard, it may not receive more than 20 Phase I or Direct to Phase II awards at each agency in the following year. An agency may implement more restrictive limitations on the number of Phase I or Direct to Phase II awards. For example, the National Aeronautics and Space Administration (NASA) limits its SBIR program to 10 proposals and 5 awards, and its STTR program to 10 proposals and 2 awards; NASA would be permitted to continue those limitations.

Patents for Increased Standards. Unlike the existing minimum performance standard that allows firms to use sales and investments *or* patents to meet the commercialization standard, patents may not be used under the increased commercialization standards.

Documentation. A small business that is subject to the increased minimum performance standards for progress to Phase III commercialization shall submit supporting documentation to SBA to verify reported sales associated with their SBIR and STTR awards during the covered period; the requirement relates to the covered sales that the small business reports to SBA as helping to meet the standards. The sales do not include federal transactions because those can be verified through the federal database. The small business must provide documentation for such sales going back five fiscal years.

Waiver. SBA may grant a waiver for a topic that is critical to an agency's mission or relates to national security. For topics that receive waivers, all firms may compete and receive awards for the specific topic, including a firm that did not meet the increased performance standards and would otherwise be subject to a 20 award per agency cap.

Reporting. Not later than July 2023 and annually thereafter until the increased minimum performance standards expire, the Administrator shall submit to Congress a list of the small business concerns that do not meet the minimum performance standards or the increased performance standards and identify those that received an award because of a waiver. The list shall be confidential and exempt from section 552 of title 5, United States Code.

SBA must expand the SBIR/STTR annual report to Congress to include 1) the minimum and increased performance standards and the number of firms that have not met the transition and commercialization performance standards, and 2) the aggregate number and dollar amount of SBIR and STTR awards made pursuant to waivers for firms that did not meet the performance standards. SBA is prohibited from publishing personally identifiable information, the identity of the firm, or otherwise sensitive information.

Implementation. The Administrator (SBA) shall implement the increased minimum performance standards not later than April 1, 2023 (the Fiscal Year 2023 benchmark assessment).

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 an offeror 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 offerors 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 Offerors are encouraged to opt into and participate in this training if selected for an award. This training 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 offerors 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 with a modification with the Phase I contract.

NASA will conduct an abbreviated competition for I-Corps after Phase I offerors are selected for Phase I SBIR contracts. NASA anticipates making approximately 25 I-Corps awards to SBIR Phase I awardees. The amount of funding is up to $10,000 to support participation in the shortened I-Corps version for SBIR awardees.

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 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: https://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:

Marvin Horne, Procurement Ombudsman
Office of Procurement
NASA Headquarters
Washington, DC 20546-0001
Telephone: 202-358-4483
Email: nhq-dl-op-comp-advocate-vendor-engagement@mail.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 questions requesting clarification of completed proposal package instructions and administrative matters is March 6, 2023, 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) Company Registry

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

After an offeror registers with SBA and/or updates their commercialization information, the offeror needs to obtain a portable document format (PDF) copy of the SBA Company Registry registration for their SBC. In addition, the offeror 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 SBA Company Registry registration in the EHB.

2.2 System for Award Management (SAM) Registration

Offerors are required to start the registration process with SAM prior to submitting a completed proposal package. To be eligible for SBIR awards, offerors 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 at the time of proposal selection will be ineligible for award. Offerors who started the registration process but did not complete the registration by the time of proposal selection 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, maintained by the GSA’s Federal Acquisition Service, is the primary repository for contractor information required to conduct business with NASA. To be registered in SAM, all mandatory information, including the Unique Entity Identifier (UEI) and a Commercial and Government Entity (CAGE) code, must be validated in SAM.

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 forms in the Electronic Handbook (EHB), answering “Yes” or “No” to certifications as applicable. Offerors 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 at the time of final payment. 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 that 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 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) 7150.2D, NASA Software Engineering Requirements, available online at https://nodis3.gsfc.nasa.gov/npg_img/N_PR_7150_002D_/N_PR_7150_002D__Preface.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

Offerors 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 201-3, 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.201-3.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 five (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 offeror. The Federal Government may, however, retain copies of all proposals in accordance with its records retention schedule. Public release of information in any proposal submitted will be subject to existing statutory and regulatory requirements. If proprietary information is provided by an offeror 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 offeror 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 offeror wishes to protect:

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

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 offerors through the steps for submitting a complete proposal package. All submissions are through a secure connection and most communication between NASA and the offeror 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 chapter 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: NASA administratively screens all elements of a completed proposal package and reserves the right to 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 letter size (8.5- by 11-inch or 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 comply 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 the SBC 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 decline 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. SBC-Level Forms (completed once for all proposals submitted to a single solicitation)

Firm Certifications

   a. Audit Information
   b. Prior Awards Addendum
   c. Commercial Metrics Survey (CMS)

11. Electronic Endorsement by the designated small business representative and principal investigator (PI) is completed before the deadline

For many of the required forms, offerors can view sample forms located in the NASA SBIR/STTR Resources website: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

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, PowerPoint Slide Decks, 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.*** A sample Contact Information form is provided in the NASA SBIR/STTR Resource website: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

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. A sample Proposal Certifications form is provided in the NASA SBIR/STTR Resource website: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

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. A sample Proposal Summary form is provided in the NASA SBIR/STTR Resource website: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

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 Technical and Business Assistance (TABA), see section 1.8 and 3.5.3.8 for more information on the TABA opportunity). A sample of the Proposal Budget form is provided in the NASA SBIR/STTR Resource website: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

Note:

- ***NASA is not responsible for any monies expended by the SBC 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 the proposed period of performance.
2. Signed letter on company letterhead from the offerors 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: Due to the complexity of and general length of time for the approval process to use a Federal laboratory/facility and the six-month period of performance of a Phase I contract, firms are strongly discouraged from requesting the use of a Federal laboratory/facility during the performance of a Phase I contract. Use of a Federal laboratory/facility will be allowed during a Phase II contract; however, firms should also indicate such intent in their Phase I proposal. Approval for use of Federal facilities and laboratories for a Phase I technical proposal requires a very strong justification at time of submission and will require approval by the Program Executive (PE) during negotiations if the proposal is selected for award.

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

Use of Subcontractors and Consultants
Subject to the restrictions set forth in section 1.5 and below, the offeror 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.

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 offeror'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 commitment letter must be from the institution's Office of Sponsored Programs.***

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	$150,000
	Profit	$15,000
	Total price less profit	$150,000 - $15,000 = $135,000
	Subcontractor cost	$40,000
	G&A	7%
	G&A on subcontractor cost	$40,000 x 7% = $2,800
	Subcontractor cost plus G&A	$40,000+ $2,800 = $42,800
	Percentage of subcontracting effort*	**$42,800/$135,000 = 31.7%**
	***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 a 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 **should consist of all 10 parts listed below in the given order. All 10 parts of the technical proposal should be numbered and titled. A completed proposal package omitting any part, other than the table of contents, 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 technical proposal (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 chapter 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 chapter 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 demonstrate 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 2023 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.

Note: Offerors are encouraged to utilize the following opportunities, TABA and NASA I-Corps, to address the market opportunities if selected for a Phase I award and to be well positioned to address additional commercialization requirements and metrics under future SBIR proposal submissions including Phase II and Phase III. See sections 3.5.3.8 for how to request TABA and 3.5.3.9 for opting into I-Corps.

Part 8: Facilities/Equipment *(Suggested page limit – 1 page)*
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. **<u>When purchasing equipment or a product under the SBIR funding agreement, the small business should purchase only American-made items whenever possible.</u>**

If using 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: Due to the complexity of and general length of time for the approval process to use a Federal laboratory/facility and the six-month period of performance of a Phase I contract, firms are strongly discouraged from requesting the use of a Federal laboratory/facility during the performance of a Phase I contract. Use of a Federal laboratory/facility will be allowed during a Phase II contract; however, firms should also indicate such intent in their Phase I proposal. Approval for use of Federal facilities and laboratories for a Phase I technical proposal requires a very strong justification at time of submission and will require approval by the Program Executive (PE) during negotiations if the proposal is 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 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 International Traffic in Arms Regulation (ITAR)-restricted data. An electronic form will be provided during the submissions process. For more information 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

Per section 1.8, offerors can request TABA at Phase I. The goal of TABA is for Phase I awardees to obtain support from a TABA vendor to improve the commercialization success of SBIR awardees. As indicated in Part 7: The Market Opportunity of the technical proposal, NASA considers commercialization of funded innovations as a high priority. The ability to commercialize the innovation with NASA SBIR funding shows a positive return on investment and can support the research effort throughout Phase I, II and beyond.

Offerors are encouraged to request TABA at Phase I and can choose their own TABA vendor. NASA does not have a TABA preferred vendor, however there are many TABA vendors that market their services and are well positioned to support NASA SBIR awardees. Although NASA cannot direct offerors to any specific TABA vendor or website, offerors should plan some time before the proposal is submitted to conduct research and learn about the TABA vendors that currently market their services and decide which vendor they may wish to use.

All requests for Phase I TABA must be included 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 during 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 awardee 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 – Phase I awardees 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 that future Phase II solicitation. 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 SBC's ability to commercialize the innovation and provide a level of confidence regarding the SBC'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:

Note: The following information must be provided for each TABA vendor

- Name of vendor
- Contact information of the vendor
- Vendor DUNS number or SAM.gov Unique Entity Identifier (UEI)
- 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 assist in the development of 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.**
- Description of 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 of the vendor's website, Dun 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 offeror 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 final 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 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 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 SBC Level Forms

All SBC level forms 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 website: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html.

A. Firm Certifications

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 website: http://sbir.gsfc.nasa.gov/sbir/firm_library/index.html. An electronic form will be provided during the submissions process.

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

B. Audit Information

Although offerors are not required to have an approved accounting system, knowledge that an SBC has an approved accounting system facilitates NASA’s determination that rates are fair and reasonable. To assist NASA, the offeror shall complete the questions in the Audit Information form regarding the offeror’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 SBC 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 SBC administrator, typically the first person to register your SBC, is the only individual authorized to update the audit information.

C. Prior Awards Addendum

If the offeror 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 SBC 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 SBC 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 SBC has received will be automatically populated in the electronic form, as well as any Phase II awards previously entered by the offeror during prior submissions (you may update the information for these awards). An electronic form will be provided during the submissions process.

Note: The designated SBC administrator, typically the first person to register your SBC, 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 offerors 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 the SBC to provide financial, sales, and ownership information, as well as any commercialization success the SBC 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 SBC-specific attribution. Password protected documents may not be submitted in response to the survey.

4. Method of Selection and Evaluation Criteria

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.

All Phase I proposals will be evaluated and judged on a competitive basis (as an "other competitive procedure" in accordance with FAR 6.102(d)(2) and FAR 35.016 (using the criteria and procedures set forth within this solicitation). Proposals will be initially screened to determine responsiveness. Proposals passing this initial screening will be technically evaluated by subject matter experts to determine the most promising technical and scientific approaches. Offerors should not assume that evaluators are acquainted with the offeror, key individuals, or with any experiments or other information. Each proposal will be judged on its own merit and NASA will not conduct any tradeoff analyses between or among competed proposals. NASA is under no obligation to fund any proposal or any specific number of proposals in each topic or subtopic. NASA may elect to fund several or none of the proposed approaches to the same topic or subtopic.

4.1 Phase I Selection 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:

4.1.1 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 chapters 3 and 6. A complete proposal package that is found to be noncompliant with the requirements in chapters 3 and 6 may 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.

4.1.2 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 offeror 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).

4.1.3 Technical Evaluation Criteria

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 investigator/project manager, 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
This 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).

4.1.4 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

In making such a selection determination, the SSO, in their discretion may consider additional programmatic balance factors such as portfolio balance across NASA programs, centers and mission directorates, available funding, first-time awardees/participants, historically underrepresented communities, and geographic distribution.

After the SSO selection has been finalized, the list of proposals selected for negotiation will be posted on the NASA SBIR/STTR website (http://sbir.nasa.gov). All SBCs selected by the SSO will receive a formal notification letter. Each proposal selected for negotiation will be evaluated for cost/price reasonableness. After completion of evaluation for cost/price reasonableness and a determination of responsibility, the Contracting Officer will negotiate and award 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 SBC 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 that submit an I-Corps proposal pursuant to sections 1.7 and 3.5.3.9, NASA will provide a programmatic assessment of SBCs 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 funding to the SSO. The SSO will make the final selections for I-Corps on awards that are completed and in alignment with I-Corps program offerings. NASA anticipates a total of approximately 25 SBIR SBCs 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 evaluation of the TABA request to determine if the request meets the requirements found in sections 1.8 and 3.5.3.8 and informs the Contracting Officer of 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 Requirements 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 SBC is registered with System for Award Management (SAM) (section 2.2).
3. Your SBC 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 SBC HAS NOT proposed a co-principal investigator.
5. Your SBC will provide timely responses to all communications from the NSSC Contracting Officer. **Note: Failure to respond in a timely manner to the NSSC Contracting Officer may result in the award being cancelled.**
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, 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 SBC 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 SBC 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
2022	1576	280	17.7%
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 Phase I award with the following items:

- 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
- Confirmation of Negotiation
- 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 website: 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 website: 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 (chapter 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 the 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 and 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 offeror 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: Due to the complexity of and general length of time for the approval process to use a Federal laboratory/facility and the six-month period of performance of a Phase I contract, firms are strongly discouraged from requesting the use of a Federal laboratory/facility during the performance of a Phase I contract. Use of a Federal laboratory/facility will be allowed during a Phase II contract; however, firms should also indicate such intent in their Phase I proposal. Approval for use of Federal facilities and laboratories for a Phase I technical proposal requires a very strong justification at time of submission and will require approval by the Program Executive (PE) during negotiations if the proposal is selected for award.

All offerors selected for award who require and receive approval from the SBIR Program Executive for 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 website (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 always 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 offerors 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 offerors through the steps for submitting a complete proposal package. All submissions are through a secure connection and most communication between NASA and the offeror is through either the EHB or email. To access the EHB go to https://sbir.gsfc.nasa.gov/submissions/login.

New offerors must register in the EHB to begin the submission process. Returning offerors can use the same account they have used for previous submissions unless the business name has changed. Offerors 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 SBC, will become the SBC administrator and will be the only individual authorized to update and change the SBC forms in the EHB.

For successful completed proposal package submission, offerors 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 Monday, March 13, 2023, via the EHB. See chapter 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

Offerors 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 chapter 3 for additional information on how to complete each of these parts.

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. SBC-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)

Offerors 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 may be considered an incomplete proposal package and may be declined.

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:

Kenneth Albright
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 NASA's technology needs 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/
Exploration Systems Development Mission Directorate (ESDMD)	https://www.nasa.gov/directorates/exploration-systems-development
Space Operations Mission Directorate (SOMD)	https://www.nasa.gov/directorates/space-operations-mission-directorate
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 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, email or write:

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312
URL: http://www.ntis.gov
E-mail: NTRLHelpDesk@ntis.gov

8. Submission Forms

Note: Previews of all forms and certifications are available via the NASA SBIR/STTR Resources website, 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 chapter 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 3.5.3.5.
    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. SBC-Level Forms (completed once for all completed proposal packages submitted to a single solicitation)
        i. SBC Certifications (labeled as Firm Certifications in the EHB)
        ii. Audit Information
        iii. Prior Awards Addendum
        iv. Commercialization Metrics Survey (CMS)
        v. 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).
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 SBC 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 13, 2023 (section 6.1.2).**

9. Research Subtopics for SBIR

Introduction

The SBIR subtopics are organized into 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 current 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 or 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 – Exploration Systems Development Mission Directorate (ESDMD) and Space Operations Mission Directorate (SOMD)
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 chapter 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.

Contents

Focus Area 5 Communications and Navigation

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 (ISRU).
This subtopic solicits proposals in the following areas, in order of priority:

1. Cryogenic flight weight valves (minimum Cv >50, goal to Cv of ~100) for low-pressure (<50 psi) liquid oxygen/methane/hydrogen with low internal (~10 sccm, goal of <1 sccm) and external (<1 sccm) leakage over multiple cycles (>100 cycles with a goal of 5,000 cycles) to maximize the lifetime of the valve. Proposals can include metallic or nonmetallic sealing elements. Proposals are encouraged, but not required, to consider additive manufacturing and/or compatibility with hypergolic propellants. If compatible with hypergolic propellants, valve should have minimum Cv <1.0, goal to Cv of ~15 for low-pressure (<250 psi), low internal (~$1x10^{-3}$ sccs, goal of <$1x10^{-4}$ sccs) and external (<$1x10^{-3}$ sccs) leakage over multiple cycles (>100 cycles with a goal of 5,000 cycles). 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.
2. Development of liquid hydrogen compatible composite tanks for reusable systems such as spacecraft, surface systems, and hydrogen aircraft for long-duration storage of liquid hydrogen. Development efforts should focus on liquid hydrogen compatibility, including minimization of permeation through the tank (<$1x10^{-3}$ sccm/m^2 of tank), capable of surviving >10,000 thermal cycles between 20 and 300 K, and >5,000 pressure cycles at cryogenic temperatures. Maximum expected operating pressures for tanks range from 25 to 50 psid. The inclusion of vacuum-jacketed composite tanks with thermal insulation capability included could also be considered. The vacuum jacket/insulation portion of the tank should be capable of maintaining vacuum pressures less than 10 millitorr for durations of several days with re-evacuation taking less than an hour. Key performance parameters such as mass compared

to metallic tank and gravimetric index should be tracked to demonstrate tank benefits. Phase I efforts should provide initial material characterization for compatibility with hydrogen along with analysis demonstrating the thermal and pressure cycle capability of the tank. Phase II efforts should include tank characterization using liquid hydrogen.

3. Liquid hydrogen pumps for high pressure ratio applications. Two classes of pumps are envisioned: tank-mounted, electrically powered booster pumps; and high-pressure pumps that may be driven by a motor or engine shaft. The booster class of pumps will provide sufficient head to prevent cavitation in the high-pressure pump, as well as potentially be used to supply LH_2 to a heat exchanger for vaporization to provide pressurant gas in the onboard hydrogen tank during operations. A single booster pump should be capable of delivering LH_2 initially saturated at 20 psia at a pressure rise of not less than 25 psid and not more than 45 psid and a rate of 0.6 kg/s. The high-pressure pumps will receive subcooled LH_2 at not less than 44 psia and provide an increase in pressure at a ratio of not less than 15:1, with a goal of 20:1, at a flow rate of 0.6 kg/s. Goals for pump life, not to be verified as a part of this effort, are 7,500 hr and 3,000 start/stop cycles. Phase I efforts should provide preliminary pump design and analysis including estimated performance, mass, power, and life for the concept. Phase II efforts should include final design, build, and performance test of a prototype with liquid hydrogen. If a single offeror desires to propose for both classes of pump, a separate proposal should be submitted for each pump class.

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
- Prototype
- Research

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, cryocooler electronics, liquid acquisition devices, phase separators, broad area cooling, and composite tanks.

Relevance / Science Traceability:

STMD has identified CFM as a key capability within its "Go" thrust that enables multiple outcomes, including Human Earth-to-Mars Transportation Systems and Reusable, Safe Launch and In-Space Propulsion Systems. Additionally, the CFM activities support the In-Situ Propellant and Consumable capability within the “Live” thrust.

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. For both liquid oxygen/liquid hydrogen and liquid oxygen/liquid methane systems, 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 has to be landed.

References:
No references for this subtopic.

Z10.03: Space Nuclear Propulsion (SBIR)

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

Scope Title: Nuclear Electric Propulsion

Scope Description:
Space Nuclear Propulsion (SNP) is a subtopic that develops low-TRL systems that use fission energy, rather than combustion, for propulsion. Nuclear Thermal Propulsion (NTP) uses fission energy in a heat exchanger to directly heat a propellant for thermal expansion through a traditional nozzle. Nuclear Electric Propulsion (NEP) uses a fission reactor electric power system to run electric thrusters.
NEP is a propulsion concept being investigated by the SNP project. A nuclear fission reactor heats a working fluid. A power conversion system transforms the working fluid heat to electricity, and the radiator disposes of the waste heat. An electric thruster uses the electric power to accelerate ionized propellant to high velocities and provides continuous thrust. NEP is a concept that can be utilized for cislunar missions, Mars missions, and outer solar system science missions. Reference 1 recommended NASA raise the TRL of NEP technologies to allow informed trades for future missions. NASA has identified five technology areas that must be integrated for a complete NEP system. The five technology areas are the Reactor Subsystem (RXS), Power Conversion Subsystem (PCS), Power Management and Distribution (PMAD), Electric Propulsion Subsystem (EPS), and Primary Heat Rejection Subsystem (PHRS). This subtopic seeks to advance the TRL of specific elements within three of these subsystems with targeted research and development. This subtopic focuses on technologies specific to high-power NEP systems but does not include the electric thruster itself.
All NEP subsystems and components must be designed to withstand launch load environments and space environment effects. Specific technologies being sought include:

1. PHRS: High emissivity leads to smaller radiator area. Radiators for NEP significantly contribute to the total mass of the vehicle. NASA seeks high-emissivity coatings and/or surface treatments for space radiators operating at temperatures up to 750 K with lifetimes of 25,000 hr. The coating or surface treatment process needs to be able to be applied to an individual modular radiator panel (~15 m^2). Coatings or surface treatments should also be resilient and experience a minimal loss of properties within the relevant environment, i.e., long-duration, high-temperature operation in a vacuum, cold soak, and exposure to sunlight, radiation, and the exhaust of the EPS. Coatings need to be compatible with radiator substrate material to include titanium and carbon-carbon composites.
2. PMAD: NEP systems use high-power electricity and need rapid switching for management of fault conditions and redistribution of power. These need to be high-power, flight-weight, vacuum-rated switches (mechanical contactors) capable of switching 1,000 amps AC (frequency of 1-2 kHz) at 1,000 volts (i.e., holding off 1,000 V in the open state and conducting 1,000 A in the closed state). The switch

should be capable of closure within tens of milliseconds and operating for at least 100 close/open cycles.

3. EPS: A power-processing unit (PPU) efficiently (>90%) converts the polyphase AC power coming from the generator to low-ripple DC power required for the electric thrusters. NASA seeks high-power PPU components for MW capable electric thrusters: components to include rectifying diodes and solid-state switches. Input polyphase AC power can be assumed to be 1,000 V; 1,000 to 2,000 A; and at a frequency of 1 to 2 kHz.

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:

- Prototype
- Hardware
- Research

Desired Deliverables Description:

Desired deliverables for this technology would include research that can be conducted to determine technical feasibility of the technology during Phase I and show a path toward a Phase II hardware demonstration. Testing the technology in a simulated (as close as possible) NEP operating environment as part of Phase II is preferred. Delivery of a prototype test unit at the completion of Phase II allows for follow-up testing by NASA.

Phase I Deliverables: Feasibility analysis and/or small-scale experiments proving the proposed technology to develop a given product (TRL 2 to 3). The final report includes a Phase II plan to raise the TRL. The Phase II plan includes a verification matrix of measurements to be performed at the end of Phase II, along with specific quantitative pass-fail ranges for each quantity listed.

Phase II Deliverables: A full report of component and/or breadboard validation measurements, including populated verification matrix from Phase I (TRL 3 to 5). Also delivered is a prototype of the proposed technology for NASA to do further testing if Phase II results show promise for NEP application. Opportunities and plans should also be identified and summarized for potential commercialization of the proposed technology. Unique government facilities can be used as part of Phase II.

State of the Art and Critical Gaps:

The NEP concept is a much larger scale system than any SEP system to date. The larger scale NEP has significant technology gaps to the required subsystems. Current space radiators do not operate at the required high temperatures needed for NEP. The kind of switch gear required for high-power NEP has been used for terrestrial systems but does not meet the requirements needed for use in space. PPUs for low-power EPSs have been used in the past, but there are no high-TRL PPUs for a high-power EPS. This scope is only addressing a few of the NEP gaps.

Relevance / Science Traceability:

STMD (Space Technology Mission Directorate) is supporting the SNP project to investigate and mature critical technologies needed for NTP and NEP.

Future mission applications:

- Human missions to Mars.
- Science missions to the outer planets.
- Planetary defense.

Some technologies may have applications for fission surface power systems.

References:

1. “Space Nuclear Propulsion for Human Mars Exploration,” A Consensus Study Report of the National Academies of Sciences, Engineering, and Medicine, February 2021. https://www.nationalacademies.org/news/2021/02/for-humans-to-reach-mars-advances-are-needed-in-space-nuclear-propulsion-technologies
2. “Independent Assessment of the Technical Maturity of Nuclear Electric Propulsion (NEP) and Nuclear Thermal Propulsion (NTP) Systems,” NASA Engineering & Safety Center, June 2020.
3. NEP Technology Interchange Meetings (TIM), 2020-2021. NASA Technical Memorandum in process; notes for individual TIMs available through the Space Nuclear Propulsion (SNP) Project, NASA MSFC.
4. NEP Technology Maturation Plan (TMP) will be made available through SNP, NASA MSFC; likely publication date is late 2022/early 2023.

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

Lead Center: GRC
Participating Center(s): JPL

Subtopic Introduction:
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 scopes 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.

Scope Title: High-Temperature, High-Voltage Electric Propulsion Harness Connectors and Cables

Scope Description:
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 sub-kilowatt) thrusters. This solicitation seeks advancements in connector and cable materials and designs to support harness assembly solutions addressing the following requirements set:

- Voltages (after derating) of at least 600 VDC; extensibility to support the full range of Hall-effect thruster (up to 800 VDC) and gridded-ion thruster (up to 2 kVDC) operations is desirable.
- Operating temperatures of at least 300 °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) of at least 10 A; extensibility to support high-power EP thrusters (up to 200 A) is desirable.
- 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.
- For connectors: features (e.g., venting of connectors and backshells) to mitigate Paschen or corona discharges due to materials or trapped volume outgassing at operating temperatures.
- For cables: 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 a component or assembly-level 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 solution, including a functional demonstration in an operating thruster environment (in which partnering with EP developers may be necessary).
2. Prototype harness component or 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 in order 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 Exploration System Development Mission Directorate (ESDMD) 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 (e.g., comets, asteroids, and near-Earth objects) 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 ESDMD, 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 ESDMD 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: Cost-Effective, Wear-Resistant Electrodes for High-Power, High-Performance Gridded Ion Thrusters

Scope Description:

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 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. Alternative materials besides carbon that allow for improvements in wear resistance over refractory metals such as molybdenum are also desired. These solutions must be capable of producing electrodes with the following geometries, operating voltages, and thermomechanical 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: Both dome and flat geometries are 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}).
- 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.

Proposals are desired that offer solutions which are applicable for manufacturing of both screen and accelerator electrodes. However, proposals that focus only on 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 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 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. 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 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 electrodes have been rather varied and complex and have included methods such as chemical vapor deposition and carbonization. Apertures in carbon electrodes have been created using laser drilling, electric discharge machining (EDM), or conventional machining. As such, innovative solutions are desired that would result in manufacturing processes for carbon electrodes that are less complex and/or more cost effective than prior efforts. Alternatively, solutions are desired involving other materials that can provide improved erosion resistance while having comparable manufacturing cost or complexity compared to existing electrode materials such as molybdenum.

Relevance / Science Traceability:

Both NASA's Science Mission Directorate (SMD) and Exploration Systems Development Mission Directorate (ESDMD) 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 (e.g., comets, asteroids, and near-Earth objects) 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 ESDMD, 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 ESDMD 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.
10. 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
11. Snyder, J. S., Anderson, J. R., Van Noord, J. L., and Soulas, G. C. "Environmental Testing of NASA's Evolutionary Xenon Thruster Prototype Model 1 Reworked Ion Engine," *Journal of Propulsion and Power*, Vol. 25, No. 1, 2009, pp. 94-104.

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) various power generation and storage technologies for planetary science missions, particularly in extreme environments. 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 some similar power technology development needs at higher power levels for electrified aircraft propulsion which are covered in Focus Area 18, Air Vehicle Technology.

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 during 14-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 nonrechargeable (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 $Li\text{-}SO_2$ and $Li\text{-}SOCl_2$ batteries 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 also suffer from capacity loss at lower temperatures. The lower limit of temperature range of rechargeable cells can be extended through the use of 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:

- NASA Science: https://science.nasa.gov/
- 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 those of 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 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 (SOA) 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:

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), Exploration Systems Development Mission Directorate (ESDMD), or Space Operations Mission Directorate (SOMD) 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:

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

S16.02: Dynamic Power Conversion (SBIR)

Lead Center: GRC
Participating Center(s): N/A

Scope Title: Dynamic and Solid-State Power Conversion

Scope Description:
NASA is developing thermoelectric and dynamic radioisotope power systems (DRPSs) for unmanned robotic missions to the Moon and other solar system bodies of interest. This technology directly aligns with the Science Mission Directorate (SMD) strategic technology investment plan for space power and energy storage and could be infused into a highly efficient RPS for missions to dark, dusty, or distant destinations where solar power is not practical. Current work in RPS is focused on advanced thermoelectric (TE) materials and dynamic cycle machines, including Stirling and Brayton convertors that would be integrated with one or more 250-W_{th} general-purpose heat source (GPHS) modules or 1-W_{th} lightweight radioisotope heater units (LWRHU) to provide high thermal-to-electric efficiency, low mass, long life, and high reliability for planetary spacecraft, landers, and rovers. Heat is transferred from the radioisotope heat source assembly to the power convertor hot end using conductive or radiative coupling. Power convertor hot-end temperatures would generally range from 300 to 500 °C for RHU applications and 500 to 1,000 °C for GPHS applications. Waste heat is removed from the cold end of the power convertor at temperatures ranging from 20 to 175 °C, depending on the application, using conductive coupling to radiator panels. The NASA projects target power systems able to produce a range of electrical power output levels based on the available form factors of space-rated fuel sources. These include a very low range of 0.5 to 2.0 W_e that would utilize one or more RHU, a moderate range of 40 to 70 W_e that would utilize a single GPHS Step-2 module, and a high range of 100 to 500 W_e that would utilize multiple GPHS Step-2 modules. For these power ranges, one or more power convertors could be used to improve overall system reliability. The current solicitation is focused on innovations that enable efficient and robust power conversion systems. Areas of interest include:

1. Robust, efficient, highly reliable, and long-life thermal-to-electric power convertors that would be used to populate a generator of a prescribed electric power output ranges.
2. Electronic controllers applicable to Stirling, Brayton, or Rankine power convertors.
3. Multilayered metal insulation (MLMI) for minimizing environmental heat losses and maximizing heat transfer from the radioisotope heat source assembly to the power convertor.
4. Advanced dynamic power conversion components and RPS integration components, including efficient alternators able to survive extended exposure to 200 °C, robust high-temperature-tolerant Stirling

regenerators, robust highly effective recuperators, integrated heat pipes, and radiators that improve system performance and improve the margin, reliability, and fault tolerance for existing components.
5. Advanced solid-state thermal-to-electric power conversion components and RPS integration components, including advanced thermoelectric and thermionic devices that advance performance, reliability, and efficiency; enable long life operation (greater than 20 years); and/or enhance manufacturing processes for materials and components.

Expected TRL or TRL Range at completion of the Project: 2 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: results of feasibility study, modeling, and/or component testing to demonstrate basic feasibility.
Phase II deliverables: prototype hardware that has demonstrated basic functionality in a laboratory environment, the appropriate research and analysis used to develop the hardware, and maturation options for flight designs.

State of the Art and Critical Gaps:
Radioisotope power systems are critical for long-duration NASA missions in dark, dusty, or harsh environments. Thermoelectric systems have been used on the very successful RPSs flown in the past but are limited in efficiency. Advances in solid-state power conversion components are desired to increase performance, reliability, efficiency, and life for RPSs. Dynamic thermal energy conversion provides significantly higher efficiency, and through implementation of noncontacting moving components, can eliminate wear mechanisms and provide long life. Although high-efficiency performance of dynamic power convertors has been proven, reliable and robust systems tolerant of off-nominal operation are needed. In addition to convertors appropriate for GPHS RPSs, advances in much smaller and lower power dynamic power conversion systems are sought that can utilize RHUs for applications such as distributed sensor systems, small spacecraft, and other systems that take advantage of lower power electronics for the exploration of surface phenomenon on icy moons and other bodies of interest. Although the power convertor advances are essential, to develop reliable and robust systems for future flight advances in convertor components as well as RPS integration components is also needed. These would include efficient and robust thermoelectric couple configurations, efficient alternators able to survive 200 °C; robust high-temperature-tolerant regenerators; robust high-efficiency recuperators; heat pipes for heat addition or rejection; radiators; and controllers applicable to Stirling flexure-bearing, Stirling gas-bearing, or Brayton convertors.

Relevance / Science Traceability:
This technology directly aligns with the Science Mission Directorate, Planetary Science Division, for space power and energy storage. Investments in more mature technologies through the Radioisotope Power System Program is ongoing. This SBIR subtopic scope provides a lower TRL technology pipeline for advances in this important power capability that improves performance, reliability, and robustness.

References:

- NASA: "Radioisotope Power Systems," https://rps.nasa.gov/about-rps/overview/
- Oriti, Salvatore: "Dynamic Power Convertor Development for Radioisotope Power Systems at NASA Glenn Research Center," AIAA Propulsion and Energy 2018, AIAA 2018-4498.
- Wilson, Scott D.: "NASA Low Power Stirling Convertor for Small Landers, Probes, and Rovers Operating in Darkness," AIAA Propulsion and Energy 2018, AIAA 2018-4499.
- Wong, Wayne: "Advanced Stirling Convertor (ASC) Technology Maturation," AIAA Propulsion and Energy 2015, AIAA 2015-3806.
- Fleurial, Jean-Pierre, Bux, Sabah, and Caillat, Thierry: "Engineering of Novel Thermoelectric Materials and Devices for Next Generation, Long Life, 20% Efficient Space Power Systems," *IECEC 2013*, AIAA 2013-3927.

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

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

Subtopic Introduction:
The recent NASA Moon to Mars Objectives (2022) detail NASA’s plans for future human-rated space missions, especially Lunar Infrastructure Goal 1: "Develop an incremental lunar power grid that is evolvable to support continuous human/robotic operations and is capable of scaling to global power utilization and industrial power levels." While initial surface assets will need to bring their own power to enable initial operations, eventually multiple power sources must be connected together into a grid in order to enable continuous presence and operations. These assets are expected to be located remotely from each other, so power must be efficiently transferred over significant distances. The International Space Station (ISS) has the highest power (100 kW) and largest 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 multiple power sources, storage, science, and habitation modules, 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 radiation-tolerant and high-voltage-power electronic regulators, switchgear, cabling, and connectors. The technologies of interest would need to operate in extreme temperature environments, including lunar night, and could experience temperature changes from -153 °C to 123 °C for lunar applications, and from -125 °C 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, both total dose and high-energy single event upset).

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 Hybrid Gas Electric Propulsion. 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.

Scope Title: Radiation-Tolerant, High-Voltage Converters for Lunar and Mars Missions

Scope Description:

NASA seeks technologies that will enable high-voltage power transmission on the lunar surface. While advancements in high-voltage, wide-bandgap devices have made great progress in terrestrial uses, we are finding that these new devices are particularly vulnerable to high-energy single-event upsets that are prevalent outside the Earth's protective Van Allen belts. As such, we seek development of high-voltage converters that are composed of proven, radiation-tolerant components. Converters of interest are bidirectional isolated 100-Vdc to 1,000-Vdc converters and bidirectional 100-Vdc to 3,000-Vdc converters in the 1- to 10-kW power range. Other important characteristics are wide temperature (-150 ºC to 150 ºC) operation, high power density (>2 kW/kg), and high efficiency (>96%).

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 03.3 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 of the high-fidelity design and analysis is a minimum requirement for Phase I, but selected component development and test results are preferred. Deliverables for Phase II should include hardware prototypes that prove performance and feasibility of the design for potential 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, Commercial Lander Payload Services (CLPS), Exploration Systems Development Mission Directorate (ESDMD), Space Operations Mission Directorate (SOMD), and Flexible Lunar Architecture for Exploration (FLARE).

References:

- NASA Moon to Mars Objectives, May 2022: https://www.nasa.gov/press-release/update-nasa-seeks-comments-on-moon-to-mars-objectives-by-june-3

- The Global Exploration Roadmap, January 2018: https://www.nasa.gov/sites/default/files/atoms/files/ger_2018_small_mobile.pdf
- 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

Scope Title: Low-Mass, Highly Conductive Power Transmission Cables for Lunar and Mars Missions

Scope Description:

- Low-mass, highly conductive wires and terminations that provide reliable small gauges for long-distance power transmission in the 1- to 10-kW range, low-mass insulation materials with increased dielectric breakdown strength and void reductions with 1,000- to 3,000-V or greater ratings, and low-loss/low-mass shielding.
- Electrical connectors that can survive the harsh lunar environments, such as extreme temperatures ranges (-150 ºC to 150 ºC); can be exposed to the lunar dust; and can be connected by either robots or astronauts (while wearing protective gloves). Primary power transmission lines can carry up to 50 kW of power at either (a) 1,000 Vdc or (b) 3.0 kVAC 3-phase (line to line) with a frequency of 1,000 Hz.

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 03.3 Power Management and Distribution

Desired Deliverables of Phase I and Phase II:

- Hardware
- Prototype
- Analysis
- Research

Desired Deliverables Description:

Typically, deliverables under Phase I proposals are geared toward a technology concept with associated analysis and design. A final report of the high-fidelity design and analysis is a minimum requirement for Phase I, but selected component development and test results are preferred. Deliverables for Phase II should include hardware prototypes that prove performance and feasibility of the design for potential 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, Commercial Lander Payload Services (CLPS), Exploration Systems Development Mission Directorate (ESDMD), Space Operations Mission Directorate (SOMD), 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:

- The Global Exploration Roadmap, January 2018: https://www.nasa.gov/sites/default/files/atoms/files/ger_2018_small_mobile.pdf
- 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

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

Scope Description:

- Power-beaming concepts to enable highly efficient flexible/mobile power transfer in the range of 100 to 1,000 W, including the fusion of power/communication/navigation.
- Wireless power transfer in a lunar environment in the range of 100 to 1,000 W.

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 03.3 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), Exploration Systems Development Mission Directorate (ESDMD), Space Operations Mission Directorate (SOMD), 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:

- The Global Exploration Roadmap, January 2018: https://www.nasa.gov/sites/default/files/atoms/files/ger_2018_small_mobile.pdf
- 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

Focus Area 3 Autonomous Systems for Space Exploration

The exploration of space requires advanced technologies that will better enable both humans and robotic spacecraft to maintain a sustained lunar presence, support Mars exploration, operate in deep space, and explore other destinations in our solar system. 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 communication delays, for example up to 42 minutes round-trip between Earth and Mars, do not permit time-critical control decisions to be made from Earth mission control centers. Rather, time-critical control decisions for spacecraft operating in deep space must be made by onboard humans, by autonomous systems, or by some combination of 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 onboard automation that teams with astronauts to autonomously manage spacecraft and habitats. For outer planet robotic explorers, the technical challenge is to develop cognitive systems to provide astronauts with improved situational awareness and autonomous systems that can rapidly respond to dynamic environments.

Specific innovations being sought in this solicitation are described below:

- Neural net software pipelines and radiation hard neuromorphic processing hardware to support 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 to enable decision-making under uncertainty and to improve system performance through learning over time.
- Onboard fault management capabilities, such as onboard sensing, computing, algorithms, and models to improve the prognostic health management of future spacecraft.
- Multi-agent Cyber-Physical-Human (CPH) systems that operate autonomously from humans or under human direction. This capability will help to address the need for integrated data uncertainty management and a robust representation of "trustworthy and trusted" autonomy in space.
- Technologies for the control and coordination of swarms of planetary rovers, flyers, or in-space vehicles for future space missions.
- Autonomy and artificial intelligence technologies for Gateway operations and health management, for either fully autonomous or crew-supervised operations.

The descriptions and references of each subtopic provide further detail to guide the development of proposals.

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

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

Subtopic Introduction:
Neuromorphic computing (meaning mapping of lessons from neuroscience to silicon) and deep neural net processors have already achieved substantial advances for artificial intelligence (AI) and machine learning on Earth that could bring new capabilities to aerospace platforms. These capabilities include advances in onboard signal and data processing, advances in automated operations, and advances in control. Neuromorphic computing will enable 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, neuromorphic processing architectures show promise for addressing the power requirements that traditional computing architectures now struggle to meet in space applications.
The goal of this subtopic is to develop neuromorphic processing hardware, algorithms, architectures, simulators, and software techniques as an enabling capability for autonomous space operations. As compared to terrestrial applications, the hardware emphasis is on low power and robustness for the space environment. The challenge is to provide high throughput (teraops of AI operations, e.g., multiply-add), low power (a watt or less per teraop), and robustness across wide temperature variation, radio frequency interference (RFI), launch vibration, and especially the radiation encountered in space and the lunar/Martian surface. One of the prominent aspects of the brain is the extraordinary, estimated throughput—exascale computing—at extremely low power—20 W. In addition, the brain does this computation with significant noise at the level of individual neurons. In space, radiation imposes noise at the level of individual computing elements. Hence, the neuromorphic principle of mapping lessons from neuroscience to silicon is relevant to achieving all three criteria simultaneously.

Radiation tolerance can be addressed at the device level, layout and fabrication level, hardware architecture level, firmware level, software level, and avionics system level. New radiation-tolerant device technology, such as memristors, magnetic spin transfer torque random access memory (STT-RAM), and phase-transition devices are especially interesting. Traditional radiation-tolerant layout techniques can include buried guard rings that act similar to lightning rods for dissipating charge buildup from radiation hits, and wider clock paths. Fabrication techniques include silicon-on-insulator, which significantly reduces the possibility of destructive latch up, such as the 22-nm fully depleted silicon on insulator (FDSOI) technology node that is being used for automotive chip fabrication and shows promise for space processors. At the hardware architecture level and above, selective use of redundancy and voting architectures can provide a means for radiation tolerance at the expense of more power. New radiation tolerance approaches, perhaps inspired by neuroscience, can likely be found. Neural computing is already inherently more tolerant to computation errors such as radiation-induced bit flips than traditional computing. Innovation for radiation tolerance that maximizes the throughput-power-robustness combined metrics is a goal for this subtopic.

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 yet robust platforms opens up 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 challenging space environments including the Moon and Mars. Proposed innovations should justify their SWaP advantages and target combined throughput-SWAP-robustness metrics over the comparable relevant state of the art (SOA).

There are three scopes for this subtopic:

1) Deep neural net and neuromorphic processors that are capable of in situ adaptation and learning, and robust for normal lunar, Martian, and deep space environments (excluding solar flares, i.e., radiation tolerant with normal shielding).
2) Deep neural net and neuromorphic processors that are minimally capable of neural inference in extreme space environments—that enable neural computing through solar flares and in the trapped planetary radiation belts of Earth, Jupiter, and Saturn (i.e., radiation hard).
3) System-level configurations of neuromorphic hardware and software that demonstrate integrated autonomous space capabilities.

Scope Title: Radiation Tolerant Neuromorphic Learning Hardware

Scope Description:

This hardware scope is for embedded radiation tolerant neuromorphic processors and neural net accelerators that provide hardware support for efficient adaptation and learning in the space environment. The adaptation can be deep learning, reinforcement learning, Hebbian learning, or other machine learning paradigms. To qualify, the hardware must be substantially more power-efficient at learning than central processing units (CPUs) and graphics processing units (GPUs) at comparable technology nodes. Efficiency is primarily measured through trillions of AI operations per watt, where an AI operation is typically a multiply-add. The arithmetic precision expected for digital deep learning is BFLOAT 16 or better, hardware proposals for other learning paradigms or analog hardware should justify their level of precision. The hardware needs to be qualifiable for the space environment, encompassing vibration, temperature extremes, RFI, as well as radiation tolerance for lunar, Martian, and deep space missions. Radiation tolerance includes total ionizing dose (TID) immunity at or above 50 krad and no destructive latch up. Note that commercial unhardened devices (COTS) are typically rated below 10 krad. Single-event latch up or unrecoverable faults shall be rare outside of solar flares. The hardware shall be designed to detect and recover from most single event effects encountered in the space environment. Specifically, the number of uncorrected errors in the 90% worst-case GEO environment should be targeted for no more than 1×10^{-5} uncorrected errors per device-day. In the rare event of an unrecoverable error, the hardware shall support fast reboots. The hardware needs to support the large number of write cycles for synaptic values expected during machine learning. Finally, the hardware needs to support neural net inference in addition to machine learning, preferably within an integrated AI paradigm for in situ adaptation during operations.

The innovation, as compared to terrestrial processors, is to incorporate the mechanisms for fault tolerance in an edge processor capable of machine learning with high power efficiency. Some type of redundancy will likely be needed. The reference for Johann Schumann's incorporation of triple modular redundancy for Loihi is one example mechanism that masks faults, but at the expense of an overall 3x reduction in power efficiency. In a neuromorphic context with stochasticity, innovations for more efficient fault tolerance techniques might be developed.

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

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:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I deliverables shall include at the minimum hardware simulation at the Verilog level sufficient for proof of concept of throughput, expected energy efficiency, and redundancy mechanisms for radiation tolerance. Detailed simulations or a tape-out at coarser technology nodes would be a preferable Phase I proof of concept.

Phase II deliverables shall include a prototype processor whose fault tolerance is tested in ground facilities including TID and proton radiation. The prototype processor and its support circuitry shall be suitable to incorporate on an experimental CubeSat mission, in other words, the printed circuit board (PCB) should fit within 10 × 10 cm. The preference is for a prototype processor fabricated in a technology node suitable for the space environment, such as 22-nm FDSOI, which has become increasingly affordable.

The Phase II delivery should include a maturation plan for a ruggedized production processor fabricated at a competitive technology node with high performance metrics, that could be funded through some combination of outside capital and NASA post Phase II programs.

State of the Art and Critical Gaps:

Neuromorphic and deep neural net computing is a broad field with many technology gaps for space avionics. Through previous and ongoing research and development (R&D), especially under this Small Business Innovation Research (SBIR) subtopic, the SOA in neuromorphic processors for space has advanced to include high throughput, low SWaP, and radiation tolerance—but for neural inference only.

Extended space missions need in situ adaptation and learning for autonomy, otherwise Earth operations are continually remotely updating software in response to unexpected and changing conditions. This adaptation, which characterizes biological systems, requires hardware support for machine learning.

Relevance / Science Traceability:

- 02-10 (Radiation-tolerant Neuromorphic Machine Learning Processors)
- 02-11 (Radiation-tolerant High-performance Memory)
- 03-09a (Autonomous self-sensing)
- 04-23 (Robotic actuators, sensors, and interfaces)
- 10-04 (Integrated system fault/anomaly detection, diagnosis, prognostics)
- 10-05 (On-Board "thinking" autonomy)

References:

- Henessy, J., Patterson, D. A new golden age for computer architecture, domain-specific hardware/software co-design, enhanced security, open instruction sets, and agile chip development. 2017 ACM A.M. Turing Award. Lecture presented 45th ISCA, Los Angles 2018
- Bengio, Y., Lecun, Y., and Hinton, G. Deep Learning for AI. 2018 Turing Award. Communications of the ACM, 64(7) 58-65. (2021)
- Davies, M. et al. Loihi: A neuromorphic manycore processor with on-chip learning. IEEE Micro 38(1) 82-99. (2018)
- Davies, M. et al. Advancing neuromorphic computing with Loihi: A survey of results and outlook. Proceedings of the IEEE 109(5), 911-934. (2021)
- ACM digital library: proceedings for annual International Conference on Neuromorphic Systems (ICONS)
- Cognitive Communications for Aerospace Applications (CCAA) workshop papers available at: http://ieee-ccaa.com
- Alena, R. Mission Radiation Environment Modeling and Analysis Avionics Trade Study for Rad-Neuro. NASA Technical Memorandum 20220011775, August 2022
- Schumann, J. Radiation Tolerance and Mitigation for Neuromorphic Processors. NASA Technical Memorandum 20220013182, November 2022
- NASA short course: Radiation Hardness Assurance: Evolving for NewSpace available at: https://nepp.nasa.gov/
- Papers for annual NASA Electronics Technology Workshop (ETW) for NASA Electronic Parts and Packaging (NEPP) Program available at https://nepp.nasa.gov/pages/pubs.cfm
- Rolls, E. and Deco, G. The Noisy Brain 2010 Oxford University Press. Available for free download at: https://www.oxcns.org/b9_text.html

Scope Title: Extreme Radiation Hard Neuromorphic Hardware

Scope Description:

There are two primary differences between this Scope, Extreme Radiation Hard Neuromorphic Hardware, and the Scope titled: Radiation Tolerant Neuromorphic Learning Hardware.

First, the processor is required to have greater radiation hardness. The goal is to develop a processor that is capable of operating through solar flares and the trapped radiation belts of planets such as Earth, Jupiter, and Saturn. This capability means, for example, that a lunar mission does not need to incorporate sheltering in place during a solar flare into its concept of operations. A lunar mission could count on the neuromorphic processor for critical phases, such as entry, descent, and landing (EDL), even during unexpected solar flares. It also enables missions to the outer planets and their scientifically interesting moons. In contrast to the first category, the processor needs to incorporate radiation mitigation measures that meet or exceed TID 200 krad and provide reliable embedded computation during solar flares in deep space. In deep space, the radiation flux during a solar flare can exceed 100 times the background radiation flux, and there are many more highly energetic protons and ion species that penetrate shielding—some up to 100 MeV. Specifically, the number of uncorrected errors should be no more than 1×10^{-3} per device-minute, for the worst 5-minute period of the October 1989 design case flare in CRÈME 96. See the references on space radiation and electronic effects to calibrate this level of radiation hardness.

Second, the processor could be neural inference-only, relaxing the requirements to support in situ adaptation and learning. To qualify, the hardware must be significantly more power-efficient at inference than radiation hard CPUs, GPUs, and field programmable gate arrays (FPGAs) at comparable technology nodes. Efficiency is primarily measured through trillions of AI operations per watt, where an AI operation is typically a multiply-add. The arithmetic precision expected for digital multiplies is Int8 or better, hardware proposals for analog inference should justify their level of precision. The hardware needs to be qualifiable for the space environment, encompassing vibration, temperature extremes, RFI, as well as radiation hardness for lunar, Martian, and deep space missions during solar flares. Radiation tolerance includes TID support at or above 200 krad, and no destructive latch up even under the extreme environment of Jupiter and Saturn. Single-event latch up or unrecoverable faults shall be rare even during solar flares, and the hardware shall support fast reboots.

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

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:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I deliverables shall include at the minimum hardware simulation at the Verilog level sufficient for proof of concept of throughput, expected energy efficiency, and redundancy mechanisms for radiation hardness to single event effects. Detailed simulations or a tape-out at coarser technology nodes would be a preferable Phase I proof of concept. Simulation of radiation performance would enhance Phase I deliverables.

Phase II deliverables shall include a prototype processor whose fault tolerance is tested in ground facilities including TID, proton, and heavy ion. The prototype processor and its support circuitry shall be suitable to incorporate on an experimental GTO (GeoTransfer orbit) CubeSat mission, in other words, the PCB should fit within 10 × 10 cm. In a GTO mission, the CubeSat experiences daily transitions through the Van Allen belts—roughly comparable to the radiation during a solar flare. The preference is for a prototype processor fabricated in a technology node suitable for the space environment, such as 22-nm FDSOI, which has become increasingly affordable.

The Phase II delivery should include a maturation plan for a ruggedized production processor fabricated at a competitive technology node for radiation hard processors with high performance metrics, that could be funded through some combination of outside capital and NASA post Phase II programs.

State of the Art and Critical Gaps:

Neuromorphic and deep neural net computing is a broad field with many technology gaps for space avionics. Through previous and ongoing R&D, especially under this SBIR subtopic, the SOA in neuromorphic processors for space has advanced to include radiation tolerance but not radiation hardness.

Radiation hardness enables computing during extreme space environment and events such as solar flares. In order for neuromorphic processors to be used during critical mission phases such as EDL that cannot be postponed, a higher level of environmental robustness is needed. This also opens up these processors for missions such as icy moons of the outer planets.

Radiation hardness could be addressed through techniques similar to radiation hardness for general purpose processors, but also through potentially new neuromorphic techniques. For example, Dual Interlocked Storage Cells (DICE) resist bit flips by requiring simultaneous transition of redundant memory elements, thus masking any radiation noise on one element. However, in a neuromorphic context with stochasticity, a more efficient radiation hardening technique might be to mask noise at the neural equivalent level.

Relevance / Science Traceability:

- 02-03 (Radiation-tolerant High-Performance General-Purpose Processors)
- 02-10 (Radiation-tolerant Neuromorphic Machine Learning Processors)
- 02-11 (Radiation-tolerant High-performance Memory)

- 03-09a (Autonomous self-sensing)
- 04-23 (Robotic actuators, sensors, and interfaces)
- 04-77 (Low SWaP, “End of arm” proximity range sensors)
- 10-05 (On-Board "thinking" autonomy)
- 10-16 (Fail operational robotic manipulation)

References:

- Henessy, J., Patterson, D. A new golden age for computer architecture, domain-specific hardware/software co-design, enhanced security, open instruction sets, and agile chip development. 2017 ACM A.M. Turing Award. Lecture presented 45th ISCA, Los Angles 2018
- Bengio, Y., Lecun, Y., and Hinton, G. Deep Learning for AI. 2018 Turing Award. Communications of the ACM, 64(7) 58-65. (2021)
- Davies, M. et al. Loihi: A neuromorphic manycore processor with on-chip learning. IEEE Micro 38(1) 82-99. (2018)
- Davies, M. et al. Advancing neuromorphic computing with Loihi: A survey of results and outlook. Proceedings of the IEEE 109(5), 911-934. (2021)
- ACM digital library: proceedings for annual International Conference on Neuromorphic Systems (ICONS)
- Cognitive Communications for Aerospace Applications (CCAA) workshop papers available at: http://ieee-ccaa.com
- Alena, R. Mission Radiation Environment Modeling and Analysis Avionics Trade Study for Rad-Neuro. NASA Technical Memorandum 20220011775, August 2022
- Schumann, J. Radiation Tolerance and Mitigation for Neuromorphic Processors. NASA Technical Memorandum 20220013182, November 2022
- NASA short course: Radiation Hardness Assurance: Evolving for NewSpace available at: https://nepp.nasa.gov/
- Papers for annual NASA Electronics Technology Workshop (ETW) for NASA Electronic Parts and Packaging (NEPP) Program available at: https://nepp.nasa.gov/pages/pubs.cfm
- Rolls, E. and Deco, G. The Noisy Brain 2010 Oxford University Press. Available for free download at: https://www.oxcns.org/b9_text.html

Scope Title: Neuromorphic Software for Cognition and Learning for Space Missions

Scope Description:
This scope seeks integrated neuromorphic software systems that together achieve a space mission capability. Such capabilities include but are not limited to:

- Cognitive communications for constellations of spacecraft.
- Spacecraft health and maintenance from anomaly detection through diagnosis; prognosis; and fault detection, isolation, and recovery (FDIR).
- Visual odometry, path planning, and navigation for autonomous rovers.
- Science data processing from sensor denoising, through sensor fusion and super resolution, and finally output the generation of science information products such as planetary digital elevation maps.

In this scope, it is expected that a provider will pipeline together a number of neural nets from different sources to achieve a space capability. The first challenge is to achieve the pipelining in a manner that achieves high overall throughput and is energy efficient. The second challenge is to put together a demonstration breadboard integrated hardware/software system that achieves the throughput incorporating neuromorphic or neural net accelerators perhaps in combination with conventional processors such as CPUs, GPUs, and FPGAs. Systems on a chip (SOC), could be another demonstration hardware platform. In either case, the neural cores should do the heavy computational lifting, and the CPUs, GPUs, and FPGAs should play a supportive role. The total power requirements shall be commensurate with the space domain, for example, 10 W maximum for systems expected to operate on CubeSats 24/7 and even less wattage for lunar systems that need to operate on battery power over the 2-week-long lunar night.

The third optional challenge is to evolve the neural net individual applications and pipeline through adaptive learning over the course of a simulated mission.
Radiation tolerance and space environment robustness are not addressed directly through this scope. Rather, a provider is expected to use terrestrial grade processors and only after Phase II target radiation tolerant neuromorphic processors potentially developed under Scopes 1 or 2 or from another source. The goal is to achieve space mission capabilities that require system integration of individual neural nets together with minimal overhead conventional software. The continuous mission-long learning complements the capability of Earth operations to adapt software over the course of a mission.

As background, development of individual neural net software is now state of the practice, and a large number of neural net applications can be downloaded in standard formats such as pseudo-assembly level or programming languages such as Tensorflow^{TM} (Google Inc), PyTorch^{TM} (Linux Foundation), Nengo^{TM} (Applied Brain Research), Lava^{TM} (Intel Cooporation), and others. Published neural nets for aerospace applications can be found, ranging from telescope fine-pointing control to adaptive flight control to medical support for astronaut health. In addition, there are many published neural nets for analogous terrestrial capabilities, such as autonomous driving. Transfer learning and other state-of-practice techniques enable adaptation of neural nets from terrestrial domains, such as image-processing for the image net challenge, to space domains such as Mars terrain classification for predicting rover traction.

Expected TRL or TRL Range at completion of the Project: 2 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
- Hardware
- Software

Desired Deliverables Description:
The deliverables for Phase I should include at minimum the concept definition of a space capability that could be achieved through a dataflow pipeline/graph of neural nets and identification of at least a portion of the pipeline that can be achieved with existing neural nets that are either already suited for the space domain or provide an analogous capability from an Earth application. The pipeline should at a minimum be mocked up and characterized by parameterized throughput requirements for the individual neural nets, a description of the dataflow and control flow integration of the system of neural nets, and an assignment and mapping from the individual software components to the hardware elements, and an energy/power/throughput estimate for the entire pipeline. Enhanced deliverables for Phase I would include a partial demonstration of the pipeline on some terrestrial hardware platform. A report that illustrates a conceptual pipeline of neural nets for autonomous rovers can be found in the reference authored by Eric Barszcz.

The deliverables for Phase II should include at minimum a demonstration hardware system, using terrestrial grade processors and sensors, that performs a significant portion of the overall pipeline needed for the chosen space capability, together with filling in at least some of the neural net applications that needed to be customized, adapted, or developed from scratch. It is expected that the hardware system would include one or more terrestrial grade neuromorphic processors that do the primary processing, with support from CPUs, GPUs, and FPGAs. An alternative would be an SOC that incorporates a substantial number of neural cores. The demonstration shall include empirical measurement and validation of throughput and power. Enhanced deliverables for Phase II would be a simulation of continuous in situ mission-long adaptation and learning that exhibits significant evolution.

State of the Art and Critical Gaps:
Neuromorphic and deep neural net software for point applications has become widespread and is state of the art. Integrated solutions that achieve space-relevant mission capabilities with high throughput and energy efficiency is a critical gap. For example, terrestrial neuromorphic processors such as Intel Corporation's Loihi^{TM}, Brainchip's Akida^{TM}, and Google Inc's Tensor Processing Unit (TPU^{TM}) require full host processors for integration for their software development kit (SDK) that are power hungry or limit throughput. This by itself is inhibiting the use of neuromorphic processors for low SWaP space missions.

The system integration principles for integrated combinations of neuromorphic software is a critical gap that requires R&D, as well as the efficient mapping of integrated software to integrated avionics hardware. Challenges include translating the throughput and energy efficiency of neuromorphic processors from the component level to the system level, which means minimizing the utilization and processing done by supportive CPUs and GPUs.

Relevance / Science Traceability:

- 03-09a (Autonomous self-sensing)
- 04-15 (Collision avoidance maneuver design)
- 04-16 (Consolidated advanced sensors for relative navigation and autonomous robotics)
- 04-23 (Robotic actuators, sensors, and interfaces)
- 04-77 (Low SWaP, "End of arm" proximity range sensors)
- 04-89 (Autonomous Rover GNC for mating)
- 10-04 (Integrated system fault/anomaly detection, diagnosis, prognostics)
- 10-05 (On-Board "thinking" autonomy)
- 10-06 (Creation, scheduling and execution of activities by autonomous systems)
- 10-16 (Fail operational robotic manipulation)

References:

- Mead, C. Neuromorphic electronic systems. Proceedings of the IEEE 78(10) 1629-1636. (1990)
- Henessy, J., Patterson, D. A new golden age for computer architecture, domain-specific hardware/software co-design, enhanced security, open instruction sets, and agile chip development. 2017 ACM A.M. Turing Award. Lecture presented 45th ISCA, Los Angles 2018
- Bengio, Y., Lecun, Y., and Hinton, G. Deep Learning for AI. 2018 Turing Award. Communications of the ACM, 64(7) 58-65. (2021)
- Davies, M. et al. Loihi: A neuromorphic manycore processor with on-chip learning. IEEE Micro 38(1) 82-99. (2018)
- Davies, M. et al. Advancing neuromorphic computing with Loihi: A survey of results and outlook. Proceedings of the IEEE 109(5), 911-934. (2021)
- ACM digital library: proceedings for annual International Conference on Neuromorphic Systems (ICONS)

- Cognitive Communications for Aerospace Applications (CCAA) workshop papers available at: http://ieee-ccaa.com
- Alena, R. Mission Radiation Environment Modeling and Analysis Avionics Trade Study for Rad-Neuro. NASA Technical Memorandum 20220011775, August 2022
- Barszcz, E. Neural Network Pipelines for Autonomous Rovers in Space Applications. NASA Technical Memorandum 20220013240, November 2022
- NASA short course: Radiation Hardness Assurance: Evolving for NewSpace available at: https://nepp.nasa.gov/
- Papers for annual NASA Electronics Technology Workshop (ETW) for NASA Electronic Parts and Packaging (NEPP) Program available at: https://nepp.nasa.gov/pages/pubs.cfm
- Rolls, E. and Deco, G. The Noisy Brain 2010 Oxford University Press. Available for free download at: https://www.oxcns.org/b9_text.html

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

Lead Center: ARC
Center(s): JSC

Scope Title: Spacecraft Autonomous Agent Cognitive Architectures for Human Exploration

Scope Description:
Autonomous and partially-autonomous systems promise the opportunity for a future with self-driving automobiles, air taxis, packages delivered by unmanned aerial vehicles (UAVs), and more revolutionary Earth applications. At the same time, it is expected that future NASA deep space missions will happen at distances that put significant communication barriers between the spacecraft and Earth, including lag due to light distance and intermittent loss of communications. As a result, it will be difficult to control every aspect of spacecraft operation from an Earth-based mission control, and thus, the crews will be required to manage, plan, and execute the mission and to respond to unanticipated system failure and anomaly more autonomously. Similarly, there is also opportunity for unmanned vehicles on Earth to benefit from autonomous, cognitive agent architectures that can respond to emergent situations without the aid of human controllers. For this reason, it is advantageous for operational functionality currently performed by external human-centric control stations (e.g., mission control) to be migrated to the vehicle and crew (if piloted). Since spacecraft operations will consist of a limited number of crewmembers who each operate with a limited performance capacity (in terms of both cognition and tasks), it will be necessary for the spacecraft to have assistive, autonomous, and semi-autonomous agents to be responsible for a large proportion of spacecraft operations so as not to overburden the crew.

Cognitive agents could provide meaningful help for many tasks performed by humans. Novel operational capabilities required by deep space missions, such as spacecraft and systems health, crew health, maintenance, consumable management, payload management, and activities such as food production and recycling could benefit from the assistance of autonomous agents, which could interface directly with the crew and onboard systems, reducing cognitive load and scheduling time on the crew. Additionally, cognitive agents could contribute to many general operational tasks in collaboration with the crew, such as training, inspections, and mission planning. Finally, autonomous agents could increase the mission’s resilience to hazardous events, both by directly responding to certain events (e.g., ones which unfold too quickly for the crew to catch, or which immobilize the crew) and by providing assistive services (e.g., fault diagnosis, contingency analysis, and mission replanning). However, implementing these cognitive agents presents significant challenges to the underlying software architecture. First, these agents will need to be able to take a significant amount of responsibility for mission operations while still operating under crew directives. Additionally, agents with different dedicated roles will need to share resources and hardware and may have differing goals and instructions from human operators that need to be managed and coordinated. Such agents will, thus, need to be able to take these actions autonomously while enabling (1) effective crew (or vehicle occupant) control of the vehicle even when the agent is operating autonomously (meaning, the agents should not be acting in unexpected ways and should report when the situation has changed enough to justify a change in operations), (2) direct crew control of the task when manual intervention is needed, and (3) autonomous and manual coordination/deconfliction of agent goals and tasks. Second, for NASA space missions, long-duration spaceflight is likely to uncover new challenges during the mission that require some level of adaptation. Whether this is because of known low-probability hazardous events or because of "unknown unknown" situations that were not planned for, cognitive agents will need to have a capacity for "graceful extensibility." This concept is not unique to space missions—Earth-based vehicles will also need to be able to respond to similar types of events in-time given the highly variable and heterogenous environments they will likely encounter when operated at scale. As a result, the architecture of the cognitive agent will need to be able to learn (both from taught examples and from the environment) and reconfigure itself (in collaboration with the crew) to perform new tasks. Finally, these capabilities need to be implemented with the high level of assurance required by mission operations, meaning that learned and autonomous behavior must be transparent, predictable, and verifiable using traditional software assurance techniques.

This subtopic solicits intelligent autonomous agent cognitive architectures that are open, modular, make decisions under uncertainty, interact closely with humans, incorporate diverse input/data sources, and learn such that the performance of the system is assured and improves over time. This subtopic will enable small businesses to develop the underlying learning/knowledge representation, methods for enabling the required behavior (e.g., operations and interactions), and necessary software architectures required to implement these technologies within the scope of cognitive agents that assist operators in managing vehicle operations. 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 vehicle 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. It should be noted that fulfilling this requirement would additionally make the cognitive agent suitable for a wide variety of Earth applications where a high level of assurance is needed (e.g., autonomous vehicles and aircraft).

An effective cognitive architecture would be capable of integrating a wide variety of knowledge sources to perform a wide variety of roles depending on mission requirements. For example, an effective prognostics and health management (PHM) agent would need to be able to take sensor data, interpret this data to diagnose the current state of the system using learned artificial intelligence (AI) models, digital twin simulations and data, and user input, and project out potential contingencies to plan optimal maintenance and/or fault avoidance operations under uncertainty. These operations would need to be modifiable in operations, for example, if a hazardous event occurs, there are changes to the mission, or there is a learnable change in behavior that reduces arising projection errors. This agent would need to be able to conduct operations autonomously for low-level inspection and maintenance operations while enabling safe human intervention throughout the process. It would finally need to communicate with crews for planning and performance of maintenance operations, to report/escalate potential hazardous contingencies, and for modification of operations (e.g., learning). This communication could include producing human-interpretable visual dashboards, communicating directly via speech, and direct manipulation of hardware (e.g., to teach/learn certain operations). Agents like this (with functionality appropriate to the given task) would be needed to perform a variety of roles in the spacecraft, including low-level tasks like state estimation, hardware control, and subsystem management and high-level tasks like mission planning and scheduling. Agents with independent responsibilities will furthermore need to be managed and coordinated to enable functional and resilient overall operations.

Well-constructed proposals will focus on developing a prototype cognitive agent(s) in the context of a limited test. This agent will need to embody a cognitive architecture that can be readily applied to a wide variety of roles and tasks throughout a mission that embodies the desired capabilities of autonomous and semi-autonomous operations, modifiable and/or learned behaviors, data/model fusion for decision-making under uncertainty, advanced user interaction, and assurance/transparency. This architecture could then be able to be extended to a wider scope in a more advanced mission in future phases of the project. This project and the agent architecture will need to be thoroughly documented and demonstrated to enable the understanding (e.g., capabilities and limitations) of this technology.

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, the expectation is to develop (1) a preliminary cognitive architecture with trades study/requirements analysis supporting the selection of the architecture in a desired mission (e.g., Human Exploration of Mars Design Reference Mission: https://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf), (2) early feasibility prototypes of architecture features and conceptual description (e.g., in SysML) for a cognitive agent(s) in that mission, and (3) a detailed implementation plan for full architecture with technical risks identified and managed.

For Phase II, the implementation plan will be executed, resulting in a functional prototype of the agent capable of performing the desired roles/tasks for the mission chosen that passes the preliminary tests required to meet mission requirements. Ideally, this functional prototype will be suitable for a flight demonstration in a relevant operational context (e.g., the International Space Station (ISS)). At this phase, it will also be necessary to provide comprehensive documentation of cognitive architecture and final prototype of the agent(s), including architectural/process/interaction diagrams (e.g., SysML), reporting regarding the implementation and design process, and the flowdown of prototype tests (with results included) from high-level requirements. It is also desired that the software developed (both the agent prototype and the underlying architecture modules/library) will be releasable as open-source software that can be improved, modified, and adapted to new missions.

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 Exploration Systems Development Mission Directorate (ESDMD) and Space Operations Mission Directorate (SOMD) 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:

Zhou, J., Zhou, Y., Wang, B., & Zang, J. (2019). Human–cyber–physical systems (HCPSs) in the context of new generation intelligent manufacturing. *Engineering*, *5*(4), 624636.
Woods, D. D. (2018). The theory of graceful extensibility: basic rules that govern adaptive systems. *Environment Systems and Decisions*, *38*(4), 433457.
Thomaz, A. L., & Breazeal, C. (2008). Teachable robots: Understanding human teaching behavior to build more effective robot learners. *Artificial Intelligence*, *172*(67), 716-737.
Kotseruba, I., & Tsotsos, J. K. (2020). 40 years of cognitive architectures: core cognitive abilities and practical applications. *Artificial Intelligence Review*, *53*(1), 1794.
Tang, L., Kacprzynski, G. J., Goebel, K., Saxena, A., Saha, B., & Vachtsevanos, G. (2008, October). Prognostics enhanced automated contingency management for advanced autonomous systems. In *2008 international conference on prognostics and health management* (pp. 19).

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 operation 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 (namely, 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 S17.04, Application of Artificial Intelligence for Science Modeling and Instrumentation; or S17.02, Integrated Campaign and System 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 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 user 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 onground 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:

- 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
- 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
- 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
- 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

Z5.08: Integrated Mission Planning and Execution for Autonomous Robotic Systems (SBIR)

Lead Center: LaRC
Participating Center(s): ARC, JSC

Scope Title: Codesign and Development of Autonomous Systems for Persistent Operations

Scope Description:

Space operations are on the cusp of a revolutionary new operational paradigm that leverages modular systems and recurring robotic visits to “persistent platforms” enabling platform assembly, maintenance, repair, and enhancement. Persistent platforms require persistent operations, and persistent operations require a paradigm shift in how we approach system design, development, and operations. Persistent platforms include, but are not limited to, telecommunication platforms; Earth-observing science platforms; deep space telescopes; and planetary surface systems that support missions such as human outposts, science stations, and in-situ resource utilization systems. These persistent platforms will be autonomously and robotically constructed, maintained, enhanced, and reconfigured in situ as needed to prepare for and support human occupation, maintain critical infrastructure, upgrade with new technology, adapt to changing mission needs, etc.

Beyond the platforms themselves, integrated human-machine and autonomous machine-machine systems for mission planning and execution will be critical to NASA's success in building a lunar economy and a persistent presence on Mars. To achieve this, we must develop innovative function-allocation strategies and solutions that move us away from the traditional human-centric approaches to mission management (with machines as decision-support tools) and toward approaches that empower machines to make decisions. This could be instantiated as teams with humans and machines as equal partners as well as machine-only teams capable of collaborating and making decisions with and without human input. Co-design of the robotics, autonomy, and human-machine function allocation will be critical to achieving intuitive and efficient processes. For example, retrofitting a function-allocation approach onto an autonomous robot built without the system in mind will likely produce a suboptimal product. History has proven that bolting the human operator or teammate onto a system built without roles and responsibilities in mind often fails in the field because invalid assumptions have been made about human interaction, crew preferences, exposed/hidden information, and real-world operations.

To achieve the required performance at a system level, subsystems must be co-designed with a mission(s) in mind and evolve cooperatively during the development process to achieve an optimized system. Robotics systems that retroactively add autonomy will not be optimal systems. Autonomous systems built without a robot and/or mission in mind will not achieve peak performance. This optimization includes the human as manager, operator, inhabitant, etc., functioning as part of a human-machine team with consideration given to function allocation across multiple-asset systems that may change over the lifetime of a mission or across mission phases. For example, the function allocation required for dormant operations of a habitat versus crew occupancy will utilize the same systems but likely not the same roles and responsibilities across team members. Further, teaming is a paradigm shift away from traditional decision-support tools (DSTs) that assist human decision making to machine systems that are capable of and empowered to make decisions (within constraints) in the absence of human intervention or with human supervision.

This subtopic seeks integrated robot/autonomy/human solutions for mission planning, mission execution, and function allocation for systems ranging from full autonomy with oversight to supervised autonomy to human-in-the-loop teaming. Human-machine teaming elevates the machine from a decision-support tool for humans to use while making decisions to a member of the team who is empowered to make decisions, capable of communicating rationale and situation awareness (SA) with other team members (whether human or machine), and participating in collaborative decision making and operations.

Proposal elements of interest include, but are not limited to:

- Autonomous systems for dexterous robots.
- Mission-planning tools.
- Modeling and simulation environments for gaming out mission scenarios and function allocation.
    - ModSim for design, development, test, evaluation
    - Digital Twin
- Human-machine teaming and/or modalities of human-machines interfaces (HMIs).

within the context of a design reference mission (DRM) such as construction and/or operation of a large space telescope, lunar infrastructure, and lunar habitats/safe havens, where "construction" is a broad term that includes assembly, repair, maintenance, cable routing, cable mating/demating, etc.

Expected TRL or TRL Range at completion of the Project: 1 to 4

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
- Hardware
- Software

Desired Deliverables Description:

A minimally successful Phase I proposal should deliver a feasibility study of the proposed subsystem, including modularity assessment and expected interoperability with external systems, where the subsystem could be:

- Defined ConOps
- Mission planning tools
- Mission/asset prognostic capabilities
- Autonomous robotic systems capable of operating under multiple human-machine function allocation assignments
- Innovative approaches to human-machine teaming and/or modalities

and must include evidence of codesign/development with related subsystems around a specific concept of operations. Phase I deliverables that include a demonstration are preferred.

A Phase II deliverable should include a working prototype (hardware and software) and associated system-level feasibility study focused on a specific design reference mission. End-to-end demonstrations via software- and/or hardware-in-the-loop simulation environments are preferred.

State of the Art and Critical Gaps:

The state of the art (SOA) for mission planning and operations is human-centric with machine DSTs for scheduling and monitoring. The current paradigm enables the addition of the DSTs into the traditional planning and operation model but was not designed and has not evolved with delegation of responsibility and decision-making authority away from the human.

There is no SOA or standard operating procedure for human-machine teaming (HMT) and mission planning. There are currently abstract concepts that are a challenge to instantiate as a system.

Relevance / Science Traceability:

This scope represents an enabling approach to technology development for persistent reliable operations for in-space and on-surface autonomous systems. Examples include robotic in-space servicing, assembly, and manufacturing (ISAM), on-orbit Gateway (science utilization, logistics management, payload handling, maintenance, etc.), as well as robotic manipulation in support of lunar surface infrastructure assembly and robotic in-space assembly and outfitting.

Autonomous manipulation, inspection, and utilization, supported by the perception technologies in scope, directly support NASA’s Moon-to-Mars objectives to “(LI-4) Demonstrate technologies supporting cislunar orbital/surface depots […] and support systems needed for continuous human/robotic presence,” and “(OP-9) Demonstrate the capability of integrated robotic systems to support and augment the work of crewmembers on the lunar surface, and in orbit around the Moon."

References:

- Doggett et al., "Persistent Assets in Zero-G and on Planetary Surfaces: Enabled by Modular Technology and Robotic Operations," AIAA SPACE Forum, 2018. https://arc.aiaa.org/doi/pdf/10.2514/6.2018-5305
- "Digital Twins and Living Models at NASA," ASME Digital Twin Summit, Keynote Address, 2021. https://ntrs.nasa.gov/api/citations/20210023699/downloads/ASME%20Digital%20Twin%20Summit%20Keynote_final.pdf
- "Serious Gaming for Building a Basis of Certification for Trust and Trustworthiness of Autonomous Systems," AIAA Aviation Forum, 2018. https://arc.aiaa.org/doi/pdf/10.2514/6.2018-3844
- Kelley et al., "A Persistent Simulation Environment for Autonomous Systems," AIAA Aviation Forum, 2018. https://arc.aiaa.org/doi/pdf/10.2514/6.2018-4015
- "OSAM: Autonomy and Dexterous Robots," NASEM DMMI Workshop, 2021. https://ntrs.nasa.gov/api/citations/20210016860/downloads/NASEM%20Workshop%20June2021%20Allen0608.pdf

Focus Area 4 Robotic Systems for Space Exploration

This focus area includes the development of robotic systems and technologies (hardware and software) that will enable and enhance future space exploration, science, and service 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 assistants working alongside and supporting humans, as caretakers of assets left behind, and as remote agents servicing and assembling critical space instruments and infrastructure.
As science and exploration activities reach further into the solar system and humans continue to work and live-in space, establishing a sustainable presence on the moon and progressing on to Mars, there will be an increased reliance on intelligent and versatile robots capable of performing a variety of tasks in remote settings under dynamic mission conditions. Technologies are needed to improve robotic mobility across extreme surface terrains, on and around small bodies, and in challenging environmental conditions. This includes hazard detection, sensing/perception, robotic navigation, grappling/anchoring, actuation, novel locomotion paradigms, and innovative technologies to enhance situational awareness and user interfaces for the semi-autonomous command and control of remote robotic systems. Robotic manipulation likewise provides a critical capability for servicing and assembling equipment in space, for sample collection and handling, science utilization in the absence of the crew, and as a means to free crew from mundane logistics management tasks or augment crew performance to increase efficiency and maximize useful work in situ. Effective affordance recognition and scene understanding, grasp planning, robotic end-effectors, force control, task primitives/task parameterization, approaches to human-robot interaction for supervised autonomy, and robust, fail-operational designs are all relevant technologies needed to accomplish robotic manipulation tasks internal to space vehicles and habitats, on the lunar surface, while interacting with orbital assets, and on distant planetary bodies. New technologies are desired to enable or enhance robotic docking and refueling operations, lunar surface site preparation, and the mobile dexterous manipulation required to handle tools, interfaces, and materials not specifically designed for robots in support of establishing, maintaining, and utilizing science and exploration infrastructure.

Advances beyond our current robotic capabilities can be realized through new component technologies, the development and integration of novel robotic systems, ground testing of potential solutions, advances in software and simulation tools, and flight demonstration of new robots and robotic task performance. Hardware and software, both onboard remote robots and contributing to improved human-robot interaction and supervisory control by remote operators, will improve safety and increase the complexity of tasks robots can efficiently and effectively perform in support of NASA's Moon to Mars objectives, the broader space economy, and an array of terrestrial applications with comparable technology needs. Relevant overlap exists with other focus areas targeting advances in autonomy and hardware suited for the extreme environments of space destinations, as technologies are sought to enable productive, sustainable robotic science and exploration in remote, and evermore challenging, reaches of the solar 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:
The NASA Planetary Science Decadal Survey for the 2023-2032 decade identifies missions to solar system bodies, including to comets, asteroids, Ceres, Enceladus, Titan, Venus, Mars, and Earth's Moon, which require new mobility, manipulation, and sampling technologies. Mobility systems will provide access to more challenging and scientifically important terrains, sampling systems will acquire samples for scientific analysis, and manipulation will provide deployment of the sampling systems and handling of the samples. Small businesses can provide some of the necessary technologies.

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 Mars, Venus, Ceres, Enceladus, Europa, Titan, comets, asteroids, and Earth's Moon.

Mobility technologies are needed to enable access to steep, subsurface, and rough terrain for planetary bodies where gravity dominates, such as Earth's Moon and Mars. Wheeled, legged, and aerial solutions are of interest. Technologies to enable mobility on small bodies and access to subsurface oceans (e.g., via conduits or drilling) 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 the 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. 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:

- Subsurface ocean access such as via a deep-drill system.
- Surface, near-subsurface, and 2- to 10-m-depth 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. Technical feasibility and value should be demonstrated.
- Phase II: prototype with test results. A full capability unit of at least TRL 4 should be delivered.

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 missions to Mars and asteroids. Nonflight systems have been developed for sampling on comets, Venus, Enceladus, Titan, 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. Very lightweight, compact, low power avionics components are needed for surface mobility systems of all kinds and for aerial mobility systems on bodies with atmospheres, including inertial measurement units (IMUs), processors, radios, and altimeters. High-power batteries with good specific energy are needed for aerial mobility systems.

Relevance / Science Traceability:

This 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. 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. The NASA Decadal Survey for the 2023-2032 decade identifies various future missions that require these technologies including missions to Ceres, comets, asteroids, Enceladus, Venus, Mars, and Earth's Moon.

References:

- Mars Exploration—Program and Missions: https://mars.nasa.gov/programmissions/
- Solar System Exploration: https://solarsystem.nasa.gov/
- Ocean Worlds: https://www.nasa.gov/specials/ocean-worlds/
- Ocean Worlds article: https://science.nasa.gov/news-articles/ocean-worlds

Z5.06: Servicing and Assembly Applications (SBIR)

Lead Center: GSFC
Participating Center(s): KSC, LaRC, MSFC

Subtopic Introduction:
Technology development efforts are required to enable in-space servicing, assembly, and manufacturing (ISAM) for commercial satellites and robotic and human exploration. ISAM 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, as well as the inspection and possible remediation of unprepared and uncontrolled targets such as debris. This subtopic addresses key servicing and assembly gaps in the Space Technology Mission Directorate (STMD) roadmap.

Scope Title: Modular Autonomous Robotic Docking and Mating Interfaces

Scope Description:
NASA requests novel conceptual designs for an autonomous direct-dock system for small satellites that enables advanced science and exploration missions and addresses STMD roadmap gaps. There is a need to reduce the system size, weight, and power requirements of existing docking and grapple technologies so they can be applicable for small satellites. The current state of the art includes CubeSat docking systems (e.g., the CubeSat Proximity Operations Demonstration (CPOD) mission includes autonomous docking in low Earth orbit (LEO)). Servicing applications require expanded capabilities to larger small satellites* (e.g., Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) class) and in multiple orbital domains, including LEO, geosynchronous Earth orbit (GEO), and beyond.
*Note: "Larger small satellites" are intended to be ESPA-class small satellites and similar-sized small satellites. The state of the art is referenced for CubeSats that are typically from 1U (10 cm x 10 cm x 10 cm) up to 12U (20 cm x 20 cm x 30 cm). ESPA-class small satellites are less than 160 kg, while ESPA-Grande small satellites are less than 320 kg.

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 04.1 Sensing and Perception

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.
- Modeling to demonstrate feasibility.
- Conceptual design, trade studies, and description of proposed solution.
- Demonstrations of subsystems or key technologies.
- Pathfinder technology demonstrations.
- Brassboard docking interface.
- Concept for low-cost flight demonstration.

Phase II deliverables include:

- Demonstration using the brassboard docking interface.
- Environmental testing of key components.

State of the Art and Critical Gaps:

The current state of the art includes CubeSat docking systems (e.g., the CPOD mission includes autonomous docking in LEO). Servicing applications require expanded capabilities for small satellites larger than CubeSats (e.g., ESPA class) and in multiple orbital domains, including LEO, GEO, Lagrange points, and beyond.

In addition to providing an enabling capability for innovative planetary science mission concepts, this scope also addresses two relevant STMD gaps:

1. Small satellites that can perform inspection of higher value assets, assist with sample returns, and optimize resupply logistics.
2. The need for vehicle/module mating systems. Autonomous small-satellite docking can potentially reduce crew time for orbital operations.

Relevance / Science Traceability:

NASA is studying mission concepts that require dispensing multiple science spacecraft and having them return to the host spacecraft for relocation to another science location.

References:

On-Orbit Satellite Servicing Study Project Report. October 2010.
https://sspd.gsfc.nasa.gov/images/NASA_Satellite%20Servicing_Project_Report_0511.pdf
CubeSat Proximity Operations Demonstration (CPOD).
https://www.nasa.gov/directorates/spacetech/small_spacecraft/cpod_project.html

Scope Title: Refueling and Storable Fluid Transfer

Scope Description:

Near-continuous, liquid-free microgravity venting is essential for the efficient and timely servicing of satellites (existing critical-asset and heritage satellites as well as newly deployed satellites) with propellant management device (PMD)-style propellant tanks that are not the positive displacement variety. A prototype design that is ready for microgravity testing with simulant fluids is of interest. The current state of the art for microgravity liquid-gas separation is surface tension screens or vanes that reside in propellant tanks to manage the propellant, along with short-duration, liquid-free venting following settling burns. These existing devices ensure liquid outflow in microgravity; however, this proposal is to ensure only pneumatic gas (and propellant vapor) outflow during venting required before refill. System-level solutions are sought involving, but not limited to, leverage from strategic internal tank design, revised concept of operations (ConOps), and add-on vent-line phase-separation devices.

Development solutions may be extensible from bipropellant (MMH/NTO) to multiple two-phase commodities in-space replenishment efforts on other storables (including green propellants) and cryogenics.
The transfer of xenon gas up to and including its supercritical and/or cryogenic phase is required for future space missions. A prototype design able to meet the launch and spaceflight environment is of interest to enable highly mass-efficient and timely xenon fluid transfers up to hundreds of kilograms. The current state of the art for efficient and timely on-orbit transfer of xenon fluid in large quantities is nonexistent. Previous attempts have been made to design and build hardware for mechanically assisted subsystem-level transfer, but to date, none have been successful for high cycle/highly reliable use in a microgravity environment. Lessons learned can be leveraged from these past efforts to make improvements for efficiency, reliability, and power needs for an advanced prototype for testing.

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.X Other Propulsion Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Deliverables include a ground-based demonstration of a liquid-free tank while venting without reliance on gravity. Prototypes should be designed for integration into a microgravity experiment on an aircraft or suborbital rocket.
Phase I deliverables include:

- Background research and feasibility studies.
- Modeling to demonstrate feasibility.
- Conceptual design, trade studies, and description of proposed solution.
- Demonstrations of subsystems or key technologies.
- Pathfinder technology demonstrations.
- Prototype tank-venting device.
- Xenon transfer up to and within supercritical pressures using design, fabrication, and testing of prototype unit with Xe [government furnished equipment (GFE)] at typical spacecraft pressures. (Note: Target goals of >90% mass transferred from supply tank at pressures up to 3,000 psi at minimum of 10 kg/hr scalable to 500 kg/hr with high reliability and less than 500 W maximum power draw.)

Phase II deliverables include:

- Advancement of the design to a flight engineering development unit.
- Demonstration using the tank-venting prototype on a microgravity flight.
- Environmental testing of key components.
- Further advancement of the unit for the spaceflight and launch environments (vibration, shock, thermal vacuum, electromagnetic interference and emissions, etc.).
- Demonstration using the xenon compressor in a thermal vacuum chamber.

State of the Art and Critical Gaps:

The existing state of the art for microgravity liquid-gas separation consists of surface tension screens or vanes that reside in propellant tanks to manage the propellant, along with short-duration, liquid-free venting.

There are currently no known compressors to perform an on-orbit transfer of xenon. Technologies to transfer xenon in space include (but are not limited to) cryogenic transfer, compressors/pumps, and thermal transfer. There are also potential system-level solutions with integrated subsystem-level heat exchangers, etc. Advances need to be made to significantly reduce mass, improve mass transfer efficiency (with reasonable required power and timeline), and address design changes necessary to allow these components and systems to operate in microgravity. Each method has challenges, such as achieving high efficiency with the thermodynamic/thermal pumping approach and supercritical fluid transfer with a compressor/pump.

Relevance / Science Traceability:
Microgravity venting is relevant to missions such as On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1), OSAM-2, International Space Station (ISS), sample return missions, Gateway, Artemis, and Human Landing System (HLS), along with other cislunar programs. Extendable use of technologies for green propellant systems will enhance infusion on new NASA and military satellites and for in situ resource utilization (ISRU)-related programs. Xenon is the current propellant of choice for electric propulsion, and future science and deep space missions require the ability to perform a xenon transfer in space, including sample return missions, Gateway, Artemis, and HLS, along with other cislunar platforms and Mars spacecraft.

References:
NASA’s Exploration & In-Space Services (NExIS). Propellant Transfer Technologies.
https://nexis.gsfc.nasa.gov/propellant_transfer_technologies.html
Coll, G.T., et al. Satellite Servicing Projects Division Restore-L Propellant Transfer Subsystem Progress 2020. AIAA-2020-3795. AIAA Propulsion and Energy Forum. August 24, 2020.

Scope Title: Ground Simulation of Servicing and Assembly Applications

Scope Description:
NASA is currently using commercial robot manipulators in hardware-in-the-loop ground testbeds for simulating on-orbit operations. In many simulation scenarios, the ground robots interact with very stiff environments (typically metal surfaces), which can impose large forces or cause instability when actively compliant control is being used. Space robots, however, are typically not nearly as stiff as ground robots, which tends to mitigate these effects.

The goal of this solicitation is to develop a mechanical spring-damper device that can be mounted aft of the robot end-effector to reduce the effective stiffness of the ground robot. The purpose of this device is thus twofold: (1) enable the ground robot to replicate the stiffness and damping properties of the flight robot at the point of interaction, and (2) help stabilize an actively compliant controller by adding damping to mitigate the effects of time delay and reducing the environmental stiffness seen by the force sensor. The stiffness and damping properties of the device should be tunable to accommodate a large range of impedance parameters to simulate flight robots and/or stabilize an active compliance control loop.

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.X Other Robotic Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I deliverables include:

- Background research and feasibility studies.
- Modeling to demonstrate feasibility.
- Conceptual design, trade studies, and description of proposed solution.
- Construction of a prototype.

Phase II deliverables include:

- Demonstrations of concept on industrial robot or other motion platform.
- Analysis on data collected during the demonstration.

State of the Art and Critical Gaps:
Many industries are failing to take advantage of active compliance control in robotic assembly tasks because it is difficult to tune and stabilize the controller. The main reason for this deficiency is that the high stiffness of the contact surfaces in combination with time delays in the controller cause significant phase lags that lead to instability. However, using compliance control can significantly increase the speed at which tasks are performed (typically tenfold) through reduction of the contact forces during assembly. In traditional position-controlled robots, these forces can only be reduced by slowing down the task (because the forces build up much more quickly) or by building in passive compliance in the tool. However, passive compliance does not work well alone because it is traditionally limited to direction only, and any misalignments can cause significant forces in the other directions. Moreover, passive compliance is traditionally achieved with spring flexures and dampers that can only be tuned for one task at a time.

Relevance / Science Traceability:
The concepts developed will enable more accurate and less expensive system simulations of ISAM missions, Artemis missions, and asteroid- and comet-sampling missions.

References:

On-Orbit Satellite Servicing Study Project Report. October 2010.
https://sspd.gsfc.nasa.gov/images/NASA_Satellite%20Servicing_Project_Report_0511.pdf
Brannan, J.C., Carignan, C.R., and Roberts, B.J. Hybrid Strategy for Evaluating On-orbit Servicing, Assembly, and Manufacturing Technologies. AIAA 2020-4194. ASCEND 2020, virtual, 16-18 November 2020.

Z5.07: Autonomous Robotic Manipulation, Utilization, and Maintenance (SBIR)

Lead Center: ARC
Participating Center(s): JSC, LaRC

Subtopic Introduction:
NASA’s Moon-to-Mars objectives highlight the need to develop and demonstrate robotic and autonomous systems capable of supporting sustained operations on the lunar surface, in lunar orbit, and eventually on Mars. To achieve the goals of maximum science return and an expanded and sustainable exploration infrastructure, robotic and autonomous systems must be capable of efficient and effective interaction with their in-space environment.

Utilization and maintenance of equipment or experiments during extended periods of uncrewed operation is needed to significantly augment mission work capacity, and autonomous robotic manipulation provides the means to remotely handle payloads, interact with existing equipment interfaces, and address a variety of both routine and contingency operations typically reserved for crew.

Technologies are specifically sought that will improve the accuracy, operational cadence, and performance capability of in-space robotic manipulation, provide greater independence from direct ground control or crew intervention during utilization and maintenance tasks, and increase robot and/or remote operator situational awareness, detection, recognition, and understanding for more reliable task performance. Advancements in these areas will have a direct impact on maturing intravehicular robotics (IVR) for NASA's Gateway and future lunar surface or Martian habitats, while also being extensible to extravehicular activity (EVA) surface infrastructure assembly and outfitting, in-space servicing activities, and a broad range of commercial applications, both in space and terrestrial, where robotic manipulation in challenging and/or remote conditions is required.

Scope Title: Sensing and Perception Software for Autonomous Manipulation and Utilization Tasks

Scope Description:

Accurate sensing and perception is critical for achieving the autonomous manipulation and task performance capabilities required for future lunar missions (both on Gateway and on the lunar surface). Limited situational awareness, time delay, data latencies, etc., prevent direct, real-time, human-in-the-loop control from the ground at efficient operational cadences and necessitate greater on-board autonomy for remote robots in situ. Like those developed for terrestrial applications, perception algorithms and approaches for in-space manipulation require improvements in a variety of technical areas, but with the added challenge of being compatible with current-generation space-rated computing, sensors, etc. Solutions must also be suitable for use within the intravehicular activity (IVA)/EVA environment and relevant mission operation constraints.

Technology areas of interest include, but are not limited to:

- Affordance recognition.
- Object/obstacle detection and segmentation.
- Object classification and/or registration.
- Pose estimation.
- Semantic SLAM (simultaneous localization and mapping).
- Grasp detection and planning.

Proposals to improve performance and advance current capabilities in areas of interest are encouraged, but technologies must also present a viable path to deployment on board space robots using current-generation computers and sensing suitable for the environment. Improving the speed and efficiency of sensor data processing and perception algorithm performance is desired, and novel techniques to translate state-of-the-art (or better) terrestrial performance to flight robotic manipulation is specifically sought.

Technologies must be applicable to IVR, lunar surface, or other in-space activities, such as:

- Assembly and maintenance (e.g., mating/demating power, data, and fluid connections; opening/closing panels; installation, stowage, and handling of cables and fluid lines; manipulation of softgoods).
- Science utilization (e.g., moving samples between cold storage and instruments; experiment monitoring and caretaking; small tool use; manipulation of buttons, switches, levers, etc.).
- Habitat mobility (e.g., hatch opening/closing, handrail and seat track grasping).
- Logistics management (e.g., payload handling, packing/unpacking bags, kitting items).

Dual-use technologies with broad applicability to both space and terrestrial applications are encouraged, but a clear infusion path to NASA missions must be demonstrated. To facilitate infusion, proposals are encouraged, but not required, to:

- Target near-term integration and testing on relevant NASA robots (e.g., International Space Station (ISS) Astrobee Facility, Valkyrie) or in coordination with ongoing NASA development efforts.
- 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 robotic development efforts to reduce future integration effort (e.g., Robot Operating System (ROS)/ROS2/SpaceROS).
- Demonstrate technology advances in the context of relevant manipulation or utilization task performance.

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

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.1 Sensing and Perception

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.
- Conceptual design, trade studies, and description of proposed solution.
- In some instances, an initial proof-of-concept implementation and/or testing (using either hardware or simulation).

Phase II deliverables include:

- Software source code, user manual/instructions, documentation.
- Test and/or performance data.
- Demonstration of software prototype on robot hardware.

State of the Art and Critical Gaps:

Current state-of-the-art approaches rely on computing performance far greater than current space-rated systems, external equipment or sensors not suitable for the IVR or in-space environments, significant cloud computing resources, or large external data sets. Increased accuracy and speed are needed for improved reliability during task performance and to expand the range of manipulation and utilization tasks possible with autonomous robots. Perception suitable for fine dexterous manipulation is limited in the field. Improved processing efficiency and a reduced reliance on external resources is needed to facilitate deployment on board space robotic systems and mitigate the lack of direct user interaction during remote operations.

Relevance / Science Traceability:

This scope represents an enabling technology for IVR operations on Gateway (science utilization, logistics management, payload handling, maintenance, etc.) and, more generally, for remote robotic manipulation in support of lunar surface infrastructure assembly and robotic in-space servicing.

Autonomous manipulation, inspection, and utilization supported by the perception technologies in scope directly support NASA's Moon-to-Mars objectives to "(LI-4) Demonstrate technologies supporting cislunar orbital/surface depots […] and support systems needed for continuous human/robotic presence," and "(OP-9) Demonstrate the capability of integrated robotic systems to support and augment the work of crewmembers on the lunar surface, and in orbit around the Moon."

References:

- "The Robot Operating System (ROS)." https://www.ros.org/
- "What is Astrobee?" https://www.nasa.gov/astrobee
- https://www.nasa.gov/feature/nasa-outlines-lunar-surface-sustainability-concept
- J. Crusan, et al. 2018. "Deep space gateway concept: Extending human presence into cislunar space." In Proceedings of IEEE Aerospace Conference, Big Sky, MT.
- "NASA's Gateway." https://www.nasa.gov/gateway
- M. Deans, et al. 2019. "Integrated System for Autonomous and Adaptive Caretaking (ISAAC)." Presentation, Gateway Intra-Vehicular Robotics Working Group Face to Face, Houston, TX; NASA Technical Reports Server. https://ntrs.nasa.gov/search.jsp?R=20190029054
- 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
- "NASA's Plans for Commercial LEO Development." https://ieeexplore.ieee.org/document/9172512
- 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.

Scope Title: Improved Robot Hardware for In-Space Manipulation

Scope Description:

The goals of maximizing science return and establishing a sustainable exploration infrastructure, highlighted in NASA's Moon-to-Mars objectives, require extensive robotic operations in lunar orbit and on the lunar surface. Much of this work is needed during uncrewed periods of operation; precursor missions; and initial deployment, assembly, and outfitting of equipment. Effective assembly and maintenance of in-space assets and sustained utilization of equipment, instruments, and experiments require high-performance robotic manipulation to interact with existing interfaces, tools, and components. Fine manipulation to perform dexterous tasks traditionally reserved for the human hands of crew is a particular challenge in the space environment and would significantly improve mission capability if further advanced.

IVR on board Gateway is one immediate application for improved robot manipulation hardware, but novel designs and new technology in this area have wide applicability to in-space servicing, assembly, and manufacturing (ISAM) and surface asset/infrastructure outfitting as well.

Novel hardware designs with improved manipulation performance are specifically sought for a range of IVR, lunar surface, and in-space servicing tasks, including:

- Assembly and maintenance (e.g., mating/demating power, data, and fluid connections; opening/closing panels; installation, stowage, and handling of cables and fluid lines; manipulation of softgoods).
- Science utilization (e.g., moving samples between cold storage and instruments; experiment monitoring and caretaking; small tool use; manipulation of buttons, switches, levers, etc.).

- Habitat mobility (e.g., hatch opening/closing, handrail and seat track grasping).
- Logistics management (e.g., payload handling, packing/unpacking bags, kitting items).

Technology areas of interest include, but are not limited to:

- End effector design (with specific emphasis on adaptability and fine grasp dexterity).
- Compact, low-mass robotic actuation and manipulators with human-scale force and manipulation capability.
- Embedded force and tactile sensing for manipulation.
- Fault tolerance, redundancy, or fail-operational designs.
- Reliability, robustness, and repeatability.

All technologies must provide a demonstrable advance over current state-of-the-art solutions and present a viable path toward use in the IVA or EVA environment. Dual-use technologies with broad applicability to both space and terrestrial applications are encouraged, as are both system- and component-level technology proposals, but a clear infusion path to NASA mission applications must be demonstrated. To facilitate infusion, proposals are encouraged, but not required, to:

- Target near-term integration and testing on relevant NASA robots (e.g., ISS Astrobee facility, Valkyrie) or in coordination with ongoing NASA development efforts.
- 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 robotic development efforts to reduce future integration effort (e.g., ROS/ROS2/SpaceROS).
- Demonstrate technology advances in the context of relevant manipulation or utilization task performance.

Expected TRL or TRL Range at completion of the Project: 4 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
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.
- Conceptual design, trade studies, and description of proposed solution.
- Initial concept of operation and demonstrated progress toward a significant improvement over state-of-the-art robotic solutions, rather than just an incremental enhancement.

Phase II deliverables include:

- Hardware prototype with supporting software, design information, and documentation.
- Test and/or performance data.

- Demonstration of robot hardware performing a relevant task.

State of the Art and Critical Gaps:
State-of-the-art manipulation hardware is largely seen in industry-targeted “cooperative robots” for factory-floor applications and early Technology Readiness Level (TRL) dexterous robots. Improving on these systems and transitioning to flight applications is desired. Existing flight systems are limited in dexterity and are significantly larger than fine manipulation tasks require.

Critical gaps exist in the demonstrated performance of key use cases, particularly fine manipulation tasks such as mating/demating connectors designed for human-hand manipulation. Low-size, low-mass solutions are needed that can nevertheless withstand human-scale forces. Compact embedded sensing integrated into robot manipulators (arm and/or end effectors) is needed to reduce robot size and eliminate the need for external support equipment during manipulation tasks.

Relevance / Science Traceability:
This scope represents an enabling technology for IVR operations on Gateway (science utilization, logistics management, payload handling, maintenance, etc.) and, more generally, for remote robotic manipulation in support of lunar surface infrastructure assembly and robotic in-space servicing.
Autonomous manipulation, inspection, and utilization supported by the novel hardware technologies targeted directly support NASA’s Moon-to-Mars objectives to “(LI-4) Demonstrate technologies supporting cislunar orbital/surface depots […] and support systems needed for continuous human/robotic presence,” and “(OP-9) Demonstrate the capability of integrated robotic systems to support and augment the work of crewmembers on the lunar surface, and in orbit around the Moon.”

References:

- “The Robot Operating System (ROS).” https://www.ros.org/
- “What is Astrobee?” https://www.nasa.gov/astrobee
- https://www.nasa.gov/feature/nasa-outlines-lunar-surface-sustainability-concept
- J. Crusan, et al. 2018. "Deep space gateway concept: Extending human presence into cislunar space." In Proceedings of IEEE Aerospace Conference, Big Sky, MT.
- “NASA’s Gateway.” https://www.nasa.gov/gateway
- M. Deans, et al. 2019. "Integrated System for Autonomous and Adaptive Caretaking (ISAAC)." Presentation, Gateway Intra-Vehicular Robotics Working Group Face to Face, Houston, TX; NASA Technical Reports Server. https://ntrs.nasa.gov/search.jsp?R=20190029054
- 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
- “NASA’s Plans for Commercial LEO Development” https://ieeexplore.ieee.org/document/9172512
- 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.

Scope Title: Supervised Autonomy for Cislunar Space and Lunar Surface Robotics

Scope Description:
Robotic operations in cislunar space and on the lunar surface require different operational paradigms than currently used in low Earth orbit (where real-time human-in-the-loop control by crew or the ground is often reasonable) or on Mars (where the lack of human crew, limited interaction dynamics, and a relatively static environment allow for slow, preplanned operations). Supporting NASA’s Moon-to-Mars science and exploration objectives necessitates both greater onboard autonomy for cislunar and lunar surface robots, and more efficient

control modalities, interfaces, and task-planning/execution integration for remote operators. Faster, human-scale operational cadences must be achieved; robotic tasks on board Gateway, throughout cislunar space, or in support of lunar surface operations will require significantly more manipulation/interaction with equipment and the environment; and the complexity of these tasks will be higher to effectively utilize science equipment in the absence of crew or to service, maintain, or assemble surface and orbital assets.

Advances in supervisory control, shared control, autonomy for remote operations, and tools or technologies that efficiently balance the strengths of an in-situ robot and a remote operator during real-time task planning and execution are desired.

Technology areas of interest include, but are not limited to:

- Task primitives/task parameterization.
- User interfaces for efficient supervisory control.
- Control techniques and onboard autonomy to accommodate intermediate time delays, data latencies, and unreliable/intermittent communication.
- Fault/failure detection, mitigation, and response during remote robotic tasks.
- Improved autonomy for planning, scheduling, and execution.
- Coordinated mobility and manipulation control.

All technologies must provide a demonstrable advance over current state-of-the-art solutions and have immediate applicability to the performance of robotic tasks relevant to the NASA IVR, lunar surface, or cislunar environment, such as:

- Assembly and maintenance (e.g., mating/demating power, data, and fluid connections; opening/closing panels; installation, stowage, and handling of cables and fluid lines; manipulation of softgoods).
- Science utilization (e.g., moving samples between cold storage and instruments; experiment monitoring and caretaking; small tool use; manipulation of buttons, switches, levers, etc.).
- Habitat mobility (e.g., hatch opening/closing, handrail and seat track grasping).
- Surface mobility (e.g., high-progress-rate navigation, sample collection, excavation).
- Logistics management (e.g., payload handling, packing/unpacking bags, kitting items).

Dual-use technologies with broad applicability to both space and terrestrial applications are encouraged, but where applicable, technologies for deployment on remote robot hardware should be appropriate to the hardware/computing limitations imposed by the cislunar and/or lunar surface IVA/EVA environment. An emphasis on interoperability, modularity, and compatibility with multiple robots and existing control architectures/frameworks is strongly encouraged to facilitate infusion and the development of fully integrated human-machine supervisory control solutions. To this end, proposals are encouraged, but not required, to:

- Target near-term integration and testing on relevant NASA robots (e.g., ISS Astrobee Facility, Valkyrie) or in coordination with ongoing NASA development efforts.
- 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 robotic development efforts to reduce future integration effort (e.g., ROS/ROS2/SpaceROS).
- Demonstrate technology advances in the context of relevant remote manipulation or utilization task performance.

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

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.4 Human-Robot Interaction

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.
- Conceptual design, trade studies, and description of proposed solution.
- In some instances, an initial proof-of-concept implementation and/or testing (using either hardware or simulation).

Phase II deliverables include:

- Software source code, user manual/instructions, documentation.
- Test and/or performance data.
- Demonstration with robot hardware.

State of the Art and Critical Gaps:

Current state of the art includes the control of recent robotic demonstrations on board ISS (e.g., Astrobee, Robonaut 2) as well as numerous terrestrial applications that demonstrate the control of remote robotic assets (military, undersea, etc.). Advancements are needed to improve remote operator situational awareness and understanding of robot actions, provide more efficient means of high-level task commanding, and leverage onboard autonomy for real-time task performance and coordination between operator and robot over intermediate time delays and intermittent/unreliable communication.

Relevance / Science Traceability:

This scope represents an enabling technology for IVR operations on Gateway (science utilization, logistics management, payload handling, maintenance, etc.) and, more generally, for remote robotic operations in cislunar space and on the lunar surface.

Integrated human-robot systems leveraging novel supervisory control technology for remote operations; improvements in onboard robot autonomy and shared control paradigms; and established approaches to interoperability, modularity, and coordination will directly support NASA's Moon-to-Mars objectives to "(TH-9/TH-10) Develop integrated human and robotic systems with inter-relationships that enable maximum science return from the lunar/Mars surface and from lunar/Mars orbit," and "(OP-10) Demonstrate the capability to remotely operate robotic systems that are used to support crew members on the Lunar or Martian surface, from the Earth or from orbiting platforms." Advancing these objectives has additional relevance to achieving the wide array of autonomous infrastructure activities further envisioned in agency objectives.

References:

- "The Robot Operating System (ROS)." https://www.ros.org/
- "What is Astrobee?" https://www.nasa.gov/astrobee
- https://www.nasa.gov/feature/nasa-outlines-lunar-surface-sustainability-concept
- J. Crusan, et al. 2018. "Deep space gateway concept: Extending human presence into cislunar space." In Proceedings of IEEE Aerospace Conference, Big Sky, MT.
- "NASA's Gateway." https://www.nasa.gov/gateway

- M. Deans, et al. 2019. "Integrated System for Autonomous and Adaptive Caretaking (ISAAC)." Presentation, Gateway Intra-Vehicular Robotics Working Group Face to Face, Houston, TX; NASA Technical Reports Server. https://ntrs.nasa.gov/search.jsp?R=20190029054
- 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
- "NASA's Plans for Commercial LEO Development." https://ieeexplore.ieee.org/document/9172512
- 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.

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 communications systems to have higher peak throughput along with lower cost, mass, and power per bit transmitted. Missions to the Moon, Mars, and beyond will require reliable and secure communications systems operating in the radio frequency bands and optical wavelengths to reduce mission operations burden and support for 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 that can provide a significant improvement over the current state of the art, including ultra-fast, robust optical communications systems; positioning, timing, guidance, navigation, and control techniques; and space-based applications of 3GPP technologies, waveforms, and modeling for future Lunar surface communications infrastructure.

H9.01: Long-Range Optical Telecommunications (SBIR)

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

Scope Title: Free-Space Optical Communications Technologies

Scope Description:
This Free-space Long Range Optical Communications subtopic seeks innovative technologies for advancing free-space optical communications by pushing future data volume returns to and from space missions in multiple domains. Modulation and signaling techniques for long range optical communications should serve multiple functions that include the laser beams serving as (i) high-rate data carriers, (ii) high precision range and range-rate monitoring, and (iii) time-transfer.
Specific metrics are return data rates >100 Gb/s (cislunar, i.e., geosynchronous equatorial orbit (GEO) or lunar orbit to ground), >10 Gb/s (Earth-Sun L1 and L2), >1 Gb/s per astronomical units squared (AU2) (deep space), and >1 Gb/s (planetary lander to orbiter and/or interspacecraft). Ground-to-space forward data rates >25 Mb/s to farthest Mars ranges. High-precision centimeter to subcentimeter ranging, **and picosecond-level time transfer.**

Systems to satisfy the goals above require agile; cost-effective; low size, weight, and power (SWaP); and space-qualified optical transceivers with auxiliary assemblies for laser beam pointing control and thermal control. The ability to easily integrate the transceivers to diverse space platforms is highly desired. Interoperability by conforming to emerging signaling standards is also sought for the communications signaling.

NASA-validated optical communications architectures include ground transceivers that transmit and receive laser signals to and from space. Cost-effective technologies for ground assets that can point to and collect signal efficiently, as well as instrumentation for these ground transceivers including robust lasers transmitters and receivers, with considerations for mitigating atmospheric turbulence are required. This subtopic is broadly divided between Flight and Ground technologies for Free Space Optical Communications (FSOC). Innovation priorities are listed in order below:

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.

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 rate.
3. Partial- or full-correcting aberrations of laser signals traversing Earth's turbulent atmosphere.
4. Coherent receivers for multi-Gb/s data rates for space-to-ground optical links.

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 thermo-mechanical designs to withstand planetary launch loads and spaceflight thermal environments, 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.

- Acquisition, tracking, and pointing architectures that can operate with dim laser beacons (irradiance of a 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%).
- Vibration isolation/suppression systems that can be integrated to the optical transceiver in order to reject high-frequency base disturbance by at least 50 dB.
- 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.
- Assume integrated spacecraft microvibration angular disturbance of 150 µrad (<0.1 to ~500 Hz).
- Integrated launch lock and latching mechanism.

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.
- >10 to 100 Gb/s at a nominal link range of 1,000 to 40,000 km for space-to-Earth optical links.

- 10 to 100 Gb/s space-to-space crosslinks.
- Disruptive low-SWaP technologies for space or planetary/lunar surface over extended mission duration.

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.
- Build-in redundancy and other fail-safe measures.
- High rate 10 to 100 Gb/s for cislunar.
- 1 Gb/s for deep space.
- Integrated modem functions conforming to emerging optical communications Consultative Committee for Space Data Systems (CCSDS) standards.
- High-photon-efficiency lasers for planetary distances with high peak-to-average power for regular or augmented M-ary pulse position modulation (PPM) with M = 4, 8, 16, 32, 64, 128, and 256 operating at near-infrared (NIR) wavelengths, preferably 1,550 nm, with average powers from 5 to 50 W.
- Subnanosecond pulse.
- Low-pulse jitter (<25 ps).
- Long lifetime and reliability operating in space environment (>5 years and as long as 20 years).
- High modulation extinction ratio (>30 dB).
- High polarization extinction ratio (>20 dB).
- 1- to 10-GHz linewidth.
- Integrated modem functions.
- >10% wall-plug efficiency, direct current (DC)-to-optical, including support electronics with description of approach for stated efficiency of space-qualifiable lasers. Multiwatt to 20 W Erbium Doped Fiber Amplifier (EDFA), or alternatives, with high-gain bandwidth (>30 nm, 0.5-dB flatness) concepts will be considered.
- Operational thermal range 0 - 50 °C.
- Storage -15 to 65 °C.
- Radiation tolerance greater than 100 krad is required (including resilience to photodarkening).

RECEIVERS/SENSORS:
Space-qualified 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 effect (total dose >100 krad), displacement damage and single-event effects.

NOVEL TECHNOLOGIES AND ACCESSORIES:

- Center wavelength (CWL) 1,064 or 1,550 nm.
- Space-qualified, 0.1 to 1.3 nm, noise equivalent bandwidth with ~90% throughput, large spectral range out-of-band blocking (~40 dB).

- 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.

- Low-loss, high-power multiplexing devices that can handle up to 20 W of optical power per channel and tens to 100 W of optical power output.
- 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 Deep Space Optical Communications (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/s incident rate.
- Time resolution <50 ps, 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/s.

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 state of the art (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 70°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 timeframe. The Laser Communication Relay Demonstration (LCRD) is an Earth-to-geostationary satellite relay demonstration that launched 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 returns to Earth.
In 2022, the DSOC Project technology demonstration will be hosted by the Psyche Mission spacecraft extending FSOC links to AU distances.

These missions are being funded by NASA's Space Technology Mission Directorate (STMD) Technology Demonstrations Missions (TDM) program and Exploration Systems Development Mission Directorate (ESDMD) and Space Operations Mission Directorate (SOMD) Space Communications Navigation (SCaN) program.
Of the 6 technologies recently identified by NASA for sending humans to Mars, laser communications were identified

(https://www.nasa.gov/directorates/spacetech/6_Technologies_NASA_is_Advancing_to_Send_Humans_to_Mars)

References:
Laser Communications Relay Demonstration (LCRD) using two ground nodes and GEO space asset https://www.nasa.gov/mission_pages/tdm/lcrd/index.html
Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T) from ISS-to-GEO and ISS-to-Ground https://www.nasa.gov/directorates/heo/scan/opticalcommunications/illuma-t
Optical to Orion (O2O) optical communications DTO from on Artemis II with crewed Orion https://www.nasa.gov/feature/goddard/2017/nasa-laser-communications-to-provide-orion-faster-connections
Deep Space Optical Communications (DSOC), first demonstration of optical communications from planetary distances https://www.nasa.gov/mission_pages/tdm/dsoc/index.html
Small Satellite Conference, 2019, NASA’s Terabyte Infrared Delivery (TBIRD) Program: Large-Volume Data Transfer from LEO https://digitalcommons.usu.edu/smallsat/2019/all2019/107/

H9.03: Flight Dynamics and Navigation Technologies (SBIR)

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

Subtopic Introduction:
NASA is planning and proposing increasingly ambitious missions such as crewed and robotic missions in cislunar space, multiple small body (comet/asteroid) rendezvous/flyby missions, outer planet moon tours, Lagrange point missions, and small body sample return using low thrust propulsion (including solar sails). Trajectory design for these complex missions can take weeks or months to generate a single reference trajectory. This subtopic seeks new techniques and tools to speed up and improve the trajectory design and optimization process to allow mission designers to more fully explore trade spaces and more quickly respond to changes in the mission.

Future NASA missions require precision landing, rendezvous, formation flying, cooperative robotics, proximity operations (e.g., servicing and assembly), noncooperative object capture, and coordinated platform operations in Earth orbit, cislunar space, libration orbits, and deep space. These missions require a high degree of autonomy. This subtopic seeks advancements in autonomous navigation and maneuvering technologies for applications in Earth orbit, lunar, cislunar, libration, and deep space to reduce dependence on ground-based tracking, orbit determination, and maneuver planning.

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 human spaceflight and robotic missions in the near-Earth and cislunar environment. The NASA Conjunction Assessment Risk Analysis (CARA) team identifies close approaches (conjunctions) between NASA satellites and other space objects, determines the risk posed by those events, and plans and executes risk mitigation strategies, including collision avoidance maneuvers to protect space assets and humans in Earth orbit. The ability to perform CARA more accurately and rapidly will improve space safety for all near-Earth operations, improve operational support by providing more accurate and longer-term collision predictions, and reduce propellant usage for collision avoidance maneuvers. This subtopic seeks innovative technologies to improve the CARA process.

Scope Title: Advanced Techniques for Trajectory Design and Optimization

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

- Low-thrust trajectories in a multibody dynamical environment.
- Multiple small-body (moons, asteroids, and comets) exploration.
- Solar sail trajectories.
- Anytime abort (return to Earth) for crewed spaceflight missions (e.g., from the lunar surface, or a near rectilinear halo orbit).

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, crew safety, and/or science observation requirements.

Trajectory design for complex space 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 explore trade spaces more fully and more quickly respond to changes in the mission. Thus, NASA seeks innovative techniques that allow rapid exploration of mission design trade spaces, address high-dimensionality optimization problems (i.e., multimoon/multibody tours; low thrust), and/or provide initial guesses that can be used to improve convergence of complex trajectories in existing tool suite.

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can integrate with those packages, such as the General Mission Analysis Tool (GMAT); Collocation Stand Alone Library and Toolkit (CSALT); Evolutionary Mission Trajectory Generator (EMTG); Mission Analysis, Operations, and Navigation (MONTE); and Optimal Trajectories by Implicit Simulation (OTIS), or other available software tools are highly 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.

Disclaimer: Technology Available (TAV) subtopics may include an offer to license NASA Intellectual Property (NASA IP) on a nonexclusive, royalty-free basis, for research use under the SBIR award. When included in a TAV subtopic as an available technology, use of the available NASA IP is strictly voluntary. Whether or not a firm uses available NASA IP within their proposal effort will not in any way be a factor in the selection for award.

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 to NASA, as well as show a plan towards Phase II integration.

Phase II new technology development efforts shall deliver components at Technology Readiness Levels (TRLs) 5 to 6 to NASA, with mature algorithms and software components complete and preliminary integration and testing in an operational environment.

State of the Art and Critical Gaps:

Trajectory optimization techniques that account for, or even minimize, spacecraft and trajectory uncertainties are not widely available in current trajectory design software. The incorporation of these uncertainties into optimization frameworks that also include constraints imposed by spacecraft, operational, and science requirements would result in more robust trajectory designs. Moreover, trajectory design for complex missions or in sensitive dynamical regimes is frequently a human in-the-loop process that relies upon the intuition of experienced engineers. While this approach can suffice for the design of a single reference trajectory, it is highly inefficient for processes that necessitate the generation of thousands of trajectories, e.g., the exploration of a trade space or a missed thrust analysis. Processes that reduce the person-hours required to generate optimal trajectories within these complex trade spaces are needed.

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 (DAVINCI).
- Venus Emissivity Radio science, InSAR, Topography, and Spectroscopy (VERITAS).
- SmallSat and CubeSat class missions, such as Lunar IceCube.

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. Evolutionary Mission Trajectory Generator (EMTG): https://software.nasa.gov/software/GSC-16824-1, https://github.com/nasa/EMTG
4. Mission Analysis, Operations, and Navigation (MONTE): https://montepy.jpl.nasa.gov/

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

Scope Description:
Future human and robotic lunar and Mars missions require landing within a 50-m radius of the desired surface location to land near features of interest or other vehicles. Also, future exploration and On-orbit Servicing, Assembly and Manufacturing (OSAM) missions require rendezvous, formation flying, proximity operations, noncooperative object capture, and coordinated spacecraft operations in Earth orbit, cislunar space, libration orbits, and deep space. Furthermore, the next generation of human spaceflight missions in cislunar space (e.g., Artemis, Human Landing Systems (HLS), and Gateway) will require very complex trajectories with a wide range of possible abort and contingency scenarios that must be accounted for. These missions all require a high degree of autonomy.

The subtopic seeks advancements in autonomous, onboard trajectory design, spacecraft navigation and guidance algorithms and software for application in Earth orbit, lunar, cislunar, libration, and deep space to reduce dependence on ground-based tracking, and orbit determination, including:

- Advanced, computationally tractable algorithms and software 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 algorithms that leverage active lidar-based imaging, or methods with limited or no reliance on a priori maps.
- Computer 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 relative and proximity navigation (relative position, velocity and attitude, and/or pose) algorithms and software, which support cooperative and collaborative space operations.
- Autonomous onboard mission design and trajectory planning for crewed missions. In a loss-of-comm scenario in cislunar space, potentially complex multi-burn transfer trajectory solutions will be required in order to return to Earth without inputs from ground controllers. This may include onboard trajectory optimization, analytical or semi-analytical methods to seed optimization or guidance algorithms, as well as machine learning (ML) algorithms to produce results from a complex abort space.
- High accuracy (1-meter level), local positioning concepts for surface operations (i.e., astronauts and rovers on the moon) within a local area of up to 10 km.

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can integrate with those packages, such as the core Flight System (cFS), AutoNav, or other available NASA hardware and software tools are highly 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.
Disclaimer: Technology Available (TAV) subtopics may include an offer to license NASA Intellectual Property (NASA IP) on a nonexclusive, royalty-free basis, for research use under the SBIR award. When included in a TAV subtopic as an available technology, use of the available NASA IP is strictly voluntary. Whether or not a firm uses available NASA IP within their proposal effort will not in any way be a factor in the selection for award.

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, determine expected system performance and assess computational resource requirements, with preliminary software being delivered to NASA, 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 to NASA, 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 has only limited 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, HLS).
- 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. core Flight System (cFS): https://cfs.gsfc.nasa.gov/
2. On-orbit Servicing, Assembly, and Manufacturing (OSAM): https://www.nasa.gov/mission_pages/tdm/osam-2.html
3. LunaNet: https://esc.gsfc.nasa.gov/news/_LunaNetConcept

4. Bhaskaran, S., “Autonomous Navigation for Deep Space Missions,” Proceedings of the SpaceOps 2012 Conference, AIAA 20212-1267135, Stockholm, Sweden, June 11-15, 2012.

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 from collision with other objects 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.

In addition, there are also an increasing number of spacecraft orbiting other solar system bodies, such as the Moon and Mars. The corresponding risk assessment process to CARA for satellites in deep space is called MADCAP (Multimission Automated Deepspace Conjunction Assessment Process). These spacecrafts are not tracked by the Space Surveillance Network, and all trajectory data for them must be provided by their respective navigation teams, which compute orbits based on tracking data obtained from a suitable deep space antenna operated by NASA’s Deep Space Network and from some foreign space agencies.

Because neither CARA nor MADCAP produces ephemeris data for the NASA-protected assets or the catalogued objects, the orbit determination aspect of the problem is not of interest in this subtopic. 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):

- Alternative risk assessment techniques and parameters. The Probability of Collision (Pc) is the standard metric for assessing collision likelihood. Its use has substantial advantages over the previous practice of using standoff 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). Special consideration will be directed to approaches that explicitly avoid extreme conservatism but instead enable 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.
- Innovative approaches to characterizing the uncertainties in the hard-body radius and object covariances (see Reference 4) that account for all 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. Although NASA is open to entirely different constructs and approaches, CARA does not control the orbit determination process and cannot change the state estimation/propagation and uncertainty representation paradigm.

- New or improved techniques or algorithms that use information available in a Conjunction Data Message (CDM) and historical information of a given space object to predict 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.
- 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.
- Novel, efficient methods for locating the minimum distance and location of the closest approach between objects with reduced run times and/or increased accuracy. Due to limitations in the availability of formal trajectory uncertainty covariances for spacecraft in orbit at Mars and the Moon, MADCAP currently analyzes conjunctions by comparing minimum orbit distances, among other attributes. For spacecraft with noncoplanar orbits, the minimum orbit distance is located at the orbit crossing locations, which are relatively simple to find. However, the search for minimum orbit distances is less straightforward when the orbits are coplanar. MADCAP currently utilizes a brute force algorithm to find the minimum orbit distance locations. Solutions that assume elliptical orbits are acceptable, but those which allow for hyperbolic orbits are preferred. An efficient method that applies universally to noncoplanar orbits could also be beneficial if quick and accurate, as it would eliminate the need to check for coplanarity and switch algorithms.
- Conjunction event visualizations are an effective method of improving understanding of conjunction geometry. To date, these visualizations have been set up manually when conjunctions of interest arise. It would be beneficial to be able to automatically produce an image showing the visualization of a close approach (state information in various coordinate/reference frames, covariance, variable hard-body radius information, approach angles, and other pertinent information using data from CDMs) when high-risk conjunctions are reported. These images would be sent out with email warnings of the high-risk event.

Disclaimer: Technology Available (TAV) subtopics may include an offer to license NASA Intellectual Property (NASA IP) on a nonexclusive, royalty-free basis, for research use under the SBIR award. When included in a TAV subtopic as an available technology, use of the available NASA IP is strictly voluntary. Whether or not a firm uses available NASA IP within their proposal effort will not in any way be a factor in the selection for award.
See section 1.6 for additional details on TAV requirements.

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 to NASA, 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 to NASA, with mature algorithms and software components complete and preliminary integration and testing in a quasi-operational environment.

State of the Art and Critical Gaps:
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. Thus, CARA and MADCAP have 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 conjunction assessment (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, lunar, and other solar system body environments. The ability to perform CARA more accurately will improve space safety for all operations involving orbiting spacecraft, 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: 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, Martin, Ryan, and Ferson, Scott, "Satellite conjunction analysis and the false confidence theorem." Proceedings of the Royal Society A 475, no. 2227 (2019): 20180565.
4. Frigm, Ryan C., Hejduk,Matthew D., Johnson, Lauren C., and Plakalovic, Dragan, "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://www.nasa.gov/conjunction-assessment
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: NID_7120_132_.pdf (nasa.gov)
12. NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook: OCE_50.pdf (nasa.gov)
13. Consultative Committee for Space Data Systems (CCSDS) Recommended Standard for Conjunction Data Messages: https://public.ccsds.org/Pubs/508x0b1e2c2.pdf

14. Tarzi, Zahi, Berry, David, and Roncoli, Ralph “ An Updated Process for Automated Deepspace Conjunction Assessment,” Paper AAS 14-373, 25th International Symposium on Space Flight Dynamics, Munich, Germany, October 2015.

H9.08: Lunar 3GPP Technologies (SBIR)

Lead Center: **GRC**
Participating Center(s): **JSC**

Scope Title: Lunar 3GPP Capability Development

Scope Description:
Terrestrially, substantial investments have been made in the Third Generation Partnership Project (3GPP) standards and technology over the past several decades of 3G/4G/5G development and operation. NASA is seeking to leverage this extensive development for the deployment of cost-effective and highly capable networking systems within the lunar communications architecture. However, operating in the lunar environment can be drastically different than operating terrestrially. This subtopic is being proposed to encourage development that is needed to translate terrestrial 3GPP technologies into a format suitable for the lunar environment, whether in terms of hardware (radiation hardening), software (lunar analysis tools), modeling (lunar regolith propagation and scattering), etc. This technology is urgently needed to close gaps in the lunar communications architecture and support the mission objectives of the Artemis program.

NASA’s Space Communications and Navigation (SCaN) program seeks innovative approaches to leverage terrestrial cellular technologies, standards, and architectures to establish and grow an adaptable and interoperable lunar communications infrastructure capable of supporting a wide range of future lunar mission users through lunar surface assets as well as orbiting relay constellations. The Lunar Third Generation Partnership Project (3GPP) Applications subtopic specifically focuses on 3GPP-compatible hardware that can operate in space and on the lunar surface, channel modeling pertinent to operation of 3GPP networks on the lunar surface, advances in 3GPP waveforms beneficial to deployment of lunar networks, and demonstration of capabilities for Non-Terrestrial Networks (NTN) applicable to use from lunar orbit to lunar surface.

NASA’s Artemis program is committed to landing and establishing a sustained presence for American astronauts on the Moon in collaboration with our commercial partners. In support of this goal, a flexible, interoperable communications network that can grow as demand and number of lunar mission users establish a presence on the lunar surface is critical. Currently, NASA is already supporting demonstrations of 4G LTE (Long Term Evolution) hardware and protocol performance on the lunar surface in 2023. In the 2025 timeframe, the first crewed landing of Artemis III will look to conduct additional demonstrations of 5G communications systems on the lunar surface. In preparation of these and other future activities, the study and development of lunar surface/space-based applications of 3GPP technologies, waveforms, and modeling will lay the foundation for the future lunar surface communications infrastructure. Examples of specific research and/or technology development areas of interest include:

- Development of 3GPP-compliant hardware for long-term survivability in the lunar environment (surface and orbit), including radiation and thermal characteristics across a lunar day/night cycle.
- Path-to-standardization development/modification of 3GPP standards/waveforms to address the unique lunar surface environment (e.g., high multipath) and/or space-based environment (e.g., high Doppler, high latency).
- Interoperability between lunar surface architecture and orbiting relay architecture, including delay tolerant networking (DTN) to bridge the gap between ad hoc surface networks and highly scheduled

Earth-relay networks. DTN functionality may be demonstrated as compatibility/operational use with the DTN layer of other services, as opposed to independent implementation of DTN.
- Development of unique capabilities supporting lunar exploration that can operate within the 3GPP framework (e.g., precision Position, Navigation, and Timing (PNT) services, sidelink capability, etc.).
- Development of channel models to support analysis of 3GPP performance in lunar environments.
- Development of coverage planning and capacity analysis tools that take into account the unique properties of the lunar environment (e.g., lunar radius, regolith RF transparency, lunar topography, lunar geology, propagation through dust clouds, accumulation of dust layer on devices, etc.).
- Sidelink architectures for mission-critical suit-to-suit communication in disconnected environments, including 5G ProSe/V2X and multi-protocol (e.g., 5G + Wi-Fi) solutions.

Proposals to this subtopic should consider application to a lunar communications architecture consisting of surface assets (e.g., astronauts, science stations, robotic rovers, vehicles, 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 and 3GPP waveforms capable of withstanding relatively high Doppler rates (when considering NTN links). 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. If a proposal suggests or implies modification of 3GPP standards, the proposer should demonstrate a familiarity/history of participation in the relevant standard-making bodies and successful contributions to those organizations. The intent of this subtopic is to leverage existing terrestrial technologies and standards only the minimum customization necessary for space/lunar usage, while acknowledging that there do exist fundamental differences that need to be addressed (e.g. lunar surface propagation modeling).

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 05.3 Internetworking

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

Desired Deliverables Description:
Phase I will study technical feasibility, infusion potential for lunar operations, and 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 (Technology Readiness Levels (TRLs) 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/waveform/model development with delivery of specific product for NASA targeting future demonstration missions. 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 capability or hardware component(s) and evaluate performance in the lunar architecture 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 and channel models must be implemented in software and should be ready to be run on an appropriate general-purpose processor.

Opportunities and plans should be identified for technology commercialization. Software applications and platform/infrastructure deliverables shall be compliant with the latest NASA standards. 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:
NASA's Draft LunaNet Interoperability Specification has baselined 3GPP release 16 or later for short-to-medium range wireless networking with mobility and roaming.
The technology need for the lunar communication architecture includes:

- SWaP-efficient 3GPP hardware deployable as hosted payloads on lunar missions (habitats, rovers), surface assets (CLPS landers), or orbital assets.
- Connectivity between surface and orbital assets for trunk links, continuous coverage of the lunar South Pole and far side, as well as potential direct-to-handheld orbital 5G links.
- Effective characterization of 3GPP network performance in the lunar environment through channel modeling and emulation.
- Efficient use of lunar communication spectrum while avoiding the generation of interference (e.g. sensitive radio astronomy science concerned with very low out of band emissions).

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

- Space qualification of terrestrial 3GPP hardware and standards such as radiation hardening and survivability at extreme temperatures (-180 °C to +130 °C on the lunar surface, RF front end only).
- Implementation of 3GPP-capable systems on SWaP-constrained platforms.
- Operation of 3GPP networks in GPS denied environments.
- Direct-to-handheld (DTH) connectivity including tolerance for high Doppler and high latency from lunar orbit.
- Device-to-device connectivity when one or more devices cannot see a 5G tower.
- Precision PNT over the surface link to augment availability and precision of overhead navigation assets.

Relevance/Science Traceability:
Leveraging the vast investment in terrestrial 3GPP technologies over the past several decades is a critical opportunity for NASA's lunar communications architecture to deploy highly capable, reliable technologies at reasonable cost, but the feasibility of operation in the lunar environment must be demonstrated, and due consideration must be given to the unique challenges of operating in the lunar environment. As activity in the lunar vicinity increases through NASA's Artemis program as well as through international and commercial partnerships, deployment of scalable and efficient networks is essential to mitigate complexity and reduce operational cost.

References:
Several related reference documents include:

- 2020 NASA Technology Taxonomy: https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy.pdf

- LunaNet Interoperability Specification: https://esc.gsfc.nasa.gov/static-files/Draft%20LunaNet%20Interoperability%20Specification%20Final.pdf
- International Communications System Interoperability Standards (ICSIS): https://nasasitebuilder.nasawestprime.com/idss2/wp-content/uploads/sites/45/2020/10/communication_reva_final_9-2020.pdf
- IOAG Future Lunar Communications Architecture Report: https://www.ioag.org/Public%20Documents/Lunar%20communications%20architecture%20study%20report%20FINAL%20v1.3.pdf
- Space Frequency Coordination Group Recommendation SFCG 32-2R3: https://www.sfcgonline.org/Recommendations/REC%20SFCG%2032-2R4%20(Freqs%20for%20Lunar%20Region).pdf
- CCSDS 883.0-B-1: https://public.ccsds.org/Pubs/883x0b1.pdf

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

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

Subtopic Introduction:
This subtopic has two scopes. Scope 1 is for Guidance, Navigation, and Control (GNC) and seeks sensors and actuators that are mission-enabling technologies with significant size, weight and power, cost, and performance (SWaP-CP) improvements over the state-of-the-art commercial off-the-shelf (COTS) capabilities. Scope 2 is focused on Star Tracker Technologies for CubeSats; in particular, a star tracker that can provide accurate attitude information to a rapidly spinning CubeSat hosting an Earth-observing instrument.

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, 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-arcsec-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 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 technologies 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. 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.

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 attitude 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 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.

The relevant technology taxonomy items include:

- TX04.1.1 Sensing for Robotic Systems
- TX04.1.4 Object, Event, and Activity Recognition
- TX04.5.1 Relative Navigation Sensors
- TX04.5.4 Capture Sensors
- TX05.1.4 Pointing, Acquisition, and Tracking (PAT)
- TX05.1.6 Optimetrics
- TX05.1.7 Innovative Signal Modulations
- TX05.4.1 Timekeeping and Time Distribution
- TX05.4.2 Revolutionary Position, Navigation, and Timing Technologies
- TX05.5.3 Hybrid Radio and Optical Technologies
- TX05.X Other Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
- TX09.4.7 Guidance, Navigation and Control (GN&C) for EDL
- TX17.1.1 Guidance Algorithms
- TX17.1.2 Targeting Algorithms
- TX17.2.3 Navigation Sensors
- TX17.2.4 Relative Navigation Aids
- TX17.2.5 Rendezvous, Proximity Operations, and Capture Sensor Processing and Processors
- TX17.3.1 Onboard Maneuvering/ Pointing/ Stabilization/Flight Control Algorithms
- TX17.3.1 Onboard Maneuvering/Pointing/Stabilization/ Flight Control Algorithms
- TX17.3.3 Ground-based Maneuvering/ Pointing/ Stabilization/Flight Control Algorithms
- TX17.3.4 Control Force/ Torque Actuators
- TX17.3.5 GN&C actuators for 6DOF Spacecraft Control During Rendezvous, Proximity Operations, and Capture
- TX17.4.1 Onboard Attitude/ Attitude Rate Estimation Algorithms
- TX17.4.1 Onboard Attitude/Attitude Rate Estimation Algorithms
- TX17.4.2 Ground- Based Attitude Determination/ Reconstruction Algorithm Development
- TX17.4.3 Attitude Estimation Sensors
- TX17.5.2 GN&C Fault Management/Fault Tolerance/Autonomy
- TX17.5.3 GN&C Verification and Validation Tools and Techniques
- TX17.5.9 Onboard and Ground-Based Terrain and Object Simulation, Mapping, and Modeling Software
- TX17.X Other Guidance, Navigation, and Control

Consequently, improvements supporting this GNC subtopic have broader impacts, increasing the return on investment for this individual topic.

References:

- 2020 NASA Technology Taxonomy: https://go.nasa.gov/3hGhFJf
- 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:
Prototype hardware/software, documented evidence of delivered TRL (test report, data, etc.), summary analysis, and 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 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) under the Phase II contract is preferred.

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:

- 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.
- McBryde, C.R. and Lightsey, E.G.: "A star tracker design for CubeSats," 2012 IEEE Aerospace Conference, pp. 1-14, 2012, doi: 10.1109/AERO.2012.6187242.
- 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.
- 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

NASA's Science Mission Directorate (SMD), https://science.nasa.gov encompasses research in the areas of Astrophysics, Earth Science, Heliophysics, Planetary Science, and Biological/Physical Sciences. The National Academies of Sciences, Engineering, and Medicine 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://nap.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 a 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 the 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 2023 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 the 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 an 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 the 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 enable new measurements. Proposals are sought for the 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 toward a Phase II prototype demonstration. The following subtopics are concomitant with these objectives and are organized by technology.

H3.10: Microbial Monitoring of Spacecraft Environments: Automated Sample Preparation for Sequencing-Based Monitoring (SBIR)

Lead Center: JSC
Participating Center(s): JPL, KSC

Scope Title: Microbial Monitoring of Spacecraft Environments: Automated Sample Preparation for Sequencing-Based Monitoring

Scope Description:
Microbial monitoring of the spaceflight environment, including surfaces, water, and air, is required by the medical operations community and enables crew health risk assessments. To date, this monitoring has relied on culture-based analysis in which the samples must be returned to Earth for identification. This data is used to assess risk to the vehicle and crew health, as well as to evaluate the effectiveness of the engineering controls in place and define any required remediation activities. While this method has served the International Space Station (ISS) well, it results in a bias towards the detection of culturable organisms, an inherent delay between sample collection and ground-based analysis, and an increase in the number of potential pathogens on the spacecraft. Moreover, sample return will not be possible on exploration missions. As such, a near real-time monitoring system capable of in situ analysis is absolutely critical. Significant strides toward in situ microbial monitoring have been made through the implementation of nanopore sequencing onboard the ISS. Sequencing was first demonstrated onboard the ISS in 2016 using Oxford Nanopore Technologies MinION. Following this demonstration, miniPCR (polymerase chain reaction), a small thermal cycler, was paired with the MinION, and a complete sample-to-answer method was validated. Following validation in subsequent payload experiments, this analysis method was transitioned to medical operations hardware and is currently being evaluated by Crew Health Care Systems to replace culture-based monitoring methods that require sample return; the current NASA microbial monitoring requirements have evolved to allow for the inclusion of this technology. Moreover, these updated requirements are in place for future programs, and this current manual sequencing-based method has been baselined for Gateway.

The current sequencing-based method is manual, involves substantial crew time, and involves numerous consumables and piece parts. NASA is soliciting an automated system yielding a sequence-ready sample. With the movement of the field toward metagenomic assessments, the increase in portability of these platforms, NASA's acceptance of this molecular-based analysis and the evolution of requirements to include this technology, and the baselining of this molecular method as the monitor for future programs, this is a key time to seek an automated solution for sample preparation to enable sequencing. Innovations needed are:

DNA Extraction
Based on data from the ISS, spacecraft surfaces are relatively clean microbially, and swabs from these surfaces are considered to be low biomass. Optimal and efficient extraction from varied sample sources is needed, including swabs, wipes, and filters.

DNA Purification
Removal of cellular and source sample debris. This is critical for downstream processing.

DNA Amplification
While nontargeted metagenomics is the ultimate goal, the ability to amplify DNA as needed is ideal. For example, fungal identification is required, and it can be problematic to obtain sequencing reads from low levels of spores. The proposer does not need to define PCR targets but, rather, to describe the capability of the platform to perform this reaction. Another purification will likely be required following amplification.

Library Preparation
All sequencers require that DNA be put into a format that can be detected. As nanopore sequencing has been selected for future programs, providing libraries compatible with nanopore sequencing chemistry is required.

Requirements

- Provide DNA from low biomass environmental samples from surface swabs, surface wipes, and water/air filters.
- Provide purified, nanopore sequence-ready DNA.
- At Phase I, describe the ability to include an amplification reaction.
- Overall platform should need the minimal mass, volume, and power as required.
- Provide complete description of consumables required for toxicology assessment.
    - Provide the needed containment for the consumables per NASA Safety.
- All consumables should be able to be produced in a temperature-stable format with a shelf life minimum of at least 3 years.
- The overall platform should be stable at ambient conditions for at least 3 years with consumables replaced as required.
- The overall platform should be able to process multiple samples at once.
    - A minimum of 16 samples should either be processed simultaneously or sorted and processed sequentially.
- The overall platform should have a high ease of use and require minimal hands-on crew time (less than 1 hr, not including sample collection time).
    - Current manual prep and sequencing require ~5 hr of hands-on crew time, a 50% reduction to no more than 2.5 hr is desired.

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

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

At the completion of Phase I, it is anticipated that a report detailing the proof of concept of a fully automated system will be provided. While a full prototype is not expected, laboratory test data detailing DNA extraction, purification, and library preparation should be delivered. Reporting should also discuss the ability to multiplex samples and reuse of the system. Additional data provided at the end of Phase I includes, but is not limited to, detailed schematics of the platform, test data from designs, test data of individual components (if included), and a plan for movement to Phase II. During development, attention should be directed toward mass, volume, power requirements, stowage conditions, ease of use, required consumables, toxicity of reagents, shelf stability of reagents, and level of biomass required for successful results (with low biomass samples expected from spacecraft environments).

At the completion of Phase I, expected deliverables will include:

- Proof of concept for an automated sample-to-sequence-ready DNA system.
- Laboratory demonstration of DNA extraction and purification from multiple sample sources.
- Report describing the capability of an optional amplification reaction.
- Laboratory demonstration of a library preparation compatible with nanopore sequencing.

Phase II

At the completion of Phase II, a full-scale prototype of the finished platform should be delivered to NASA. Documentation to accompany the prototype should include technical data sheets detailing the materials and consumables used, detailed instructions for operations, and design drawings. A final report should also be included that documents all development efforts, troubleshooting, and optimization that resulted in the final system. In addition, performance test data should be included detailing input source samples, DNA concentrations and purity achieved, and the total amount of prepared libraries generated. It is expected that some sequencing data will also be provided and discussed.

At the completion of Phase II, expected deliverables include:

- A full-scale prototype of the finished platform.
- A prototype demonstration of an automated solution for DNA extraction, purification, and library preparation from multiple sample sources.
- A prototype demonstration of nanopore sequencing from the resulting prepped DNA.
- Technical data sheets detailing materials and consumables.
    - Containment needed based on NASA Safety recommendations.
    - Demonstrated temperature-stable consumables for at least 3 years.
- Performance descriptions regarding storage at ambient temperature for up to 3 years (hardware, not consumables).
- A 50% reduction in hands-on crew time compared to the current method (current method ~5 hr).
    - Desired no more than 2.5 hr of hands-on time from sample collection to the initiation of sequencing.

The proposers should clearly state the Technology Readiness Level (TRL) at which the research begins and what is expected at the end of Phase I and Phase II. Reference the TRL definitions here: [Microsoft Word - TRL Definitions.doc (nasa.gov)]

State of the Art and Critical Gaps:

The state of the art in microbial identification, a NASA requirement needed for crew health assessments, is DNA sequencing, which is also the gold standard. NASA has been using DNA sequencing to identify returned cultures since 2006. The development of small, portable sequencers has provided the ability to place the monitor at the point of sample collection. NASA has achieved this, but the sample preparation required to support the generation of sequence-ready DNA involves multiple piece parts and consumables and requires a significant amount of hands-on time.

The gap is the lack of available commercial-off-the-shelf (COTS) automated solutions for DNA extraction from low biomass samples through library preparation in support of nanopore sequencing.

The development of a fully automated solution would extend far beyond microbial motioning and would be of great value to the planetary protection community and space biology researchers within the spaceflight industry. Beyond spaceflight, this technology would make substantial contributions to health care settings.

Relevance / Science Traceability:

This scope is included under the Space Operations Mission Directorate (SOMD) (previously the Human Exploration and Operations Mission Directorate (HEOMD)).

This work is needed to support Gateway and lunar microbial monitoring operations. While the focus of this work is directed toward the medical operations community within SOMD, including NASA's international partners, it is extendable to all stakeholders with the goal of microbial analysis. These groups include, but are not limited to: OSMA, Planetary Protection Office, SMD-Planetary Sciences Division/Planetary Protection Research Program, the Human Research Program, AES Exploration Capabilities, space industry, academia, other government agencies, and SMD-Biological and Physical Sciences Division.

References:

1. Castro-Wallace, S. L., Chiu, C. Y., John, K. K., Stahl, S. E., Rubins, K. H., McIntyre, A. B. R., Dworkin, J. P., Lupisella, M. L., Smith, D.J., Botkin, D. J., Stephenson, T. A., Juul, S., Turner, D. J., Izquierdo, F., Federman, S., Stryke, D., Somasekar, S., Alexander, N., Yu, G., Mason, C. E., and Burton, A. S. (2017) Nanopore DNA Sequencing and Genome Assembly on the International Space Station. *Scientific Reports*. 7:18022. Nanopore DNA Sequencing and Genome Assembly on the International Space Station | Scientific Reports (nature.com)
2. Burton, A. S., Stahl, S. E., John, K. J., Jain, M., Juul, S., Turner, D. J., Harrington, E. D., Stoddart, D., Paten, B., Akeson, M., and Castro-Wallace, S. L. (2020) Off Earth Identification of Bacterial Populations Using 16S rDNA Nanopore Sequencing. *Genes.* 11(1), 76. Genes | Free Full-Text | Off Earth Identification of Bacterial Populations Using 16S rDNA Nanopore Sequencing (mdpi.com)
3. Stahl-Rommel, S., Jain, M., Nguyen H. N., Arnold, R.R., Aunon-Chancellor, S. M., Sharp, G. M., Castro, C., John, K. K., Juul, S., Turner, D. J., Stoddart, D., Paten, B., Akeson, M., Burton, A. S., and Castro-Wallace, S. L. (2021) Real-Time Culture-Independent Microbial Profiling Aboard the International Space Station Using Nanopore Sequencing. *Genes*. 12(1), 106. Genes | Free Full-Text | Real-Time Culture-Independent Microbial Profiling Onboard the International Space Station Using Nanopore Sequencing (mdpi.com)
4. NASA-STD-3001 - Requirements: https://www.nasa.gov/offices/ochmo/human_spaceflight/standards101
    1. New requirements have not been made publicly available but can be provided upon selection.

H4.08: Anti-Fog Solutions for Spacesuit Helmet (SBIR)

Lead Center: **JSC**

Participating Center(s): **N/A**

Scope Title: Anti-Fog Solutions for Spacesuit Helmet

Scope Description:
For the current Extravehicular Mobility Unit (EMU) spacesuit, an astronaut applies an anti-fog solution to the interior of the helmet bubble before each extravehicular activity (EVA). However, the anti-fog solution has been reported to cause eye discomfort during at least seven EMU EVAs when the anti-fog solution contacted the crewmember's eyes. During STS-100, astronaut Chris Hadfield reported that eye irritation temporarily blinded him during his spacewalk. In addition, the wipe-on anti-fog solution is a consumable that needs to be accounted for and a supply launched for missions. To solve this, the Pressure Garment Subsystem (PGS) team wants the next-generation helmet pressure bubbles to use a permanent anti-fog technology for a solution. Having a permanent anti-fog solution for spacesuit helmets would eliminate eye irritation and the need for additional consumables.

During the Constellation spacesuit development program, NASA conducted a trade study on four different permanent anti-fog solutions. The evaluation tested coated samples with the four permanent anti-fog candidates based on Transmission, Haze, Adhesion and Abrasion Resistance, Craze Resistance, Cold Box, Steam, and Human Breath Response tests.
Despite our efforts on Exploration EMU (xEMU) to develop a suitable permanent anti-fog coating on the helmet, the PGS team has had issues with inconsistent application in manufacturing, as well as robustness. It was easily damaged or worn away after only 40 or more hours of manned pressurized time (MPT). It was difficult even during careful cleaning using distilled or deionized (DI) water and a soft, lint-free wipe. In addition, the material used in the xEMU anti-fog coating is being discontinued. There is renewed interest in further investigation into a permanent anti-fog solution such as a coating or other technology for exploration suit helmet bubbles that the xEMU team is interested in pursuing.

Requirements

- The anti-fog must be applied to a general-purpose polycarbonate bubble.
- Geometry is TBD. However, the xEMU bubble is a hemi-ellipsoid 10- by 13-in. polycarbonate bubble and the anti-fog would need to be applied across the curvature.
- If applicable, the vendor must be able to consistently meet recommended anti-fog coating thickness.
    - Note: Historically, the required thickness is 6-12 microns, but this will depend on the anti-fog solution chosen.
- Must be tolerant to breathing air and 100% oxygen operations environment and able to be manually cleaned.
- Testing includes the following:
    - Steam cycle (simulated breathing). The suggested cycle regiment would be for at least 104 °F temperature steam cycled for 216,000 cycles at 18 cycles per minute.
        - 104 °F is the high average of exhaled breath temperature.
        - 216,000 cycles is calculated from 18 breaths per minute, 8-hr EVAs, and 25 EVA certification.
        - Success criteria: No fogging occurring on samples and no evidence of delamination after the test.
    - Adhesion per ASTM 3359.
    - Cleaning Test
        - Using distilled and DI water and wipe testing for 100 cycles.
- Must be tolerant to a low-pressure environment (4.3 psia) and meet NASA off-gassing requirements for a confined space.
- Must be tolerant of pressurization cycles that introduce minor variations of helmet surface area.

- Maintain optical clarity of the helmet assembly without reducing transmission to less than 70% through visible light wavelengths.
- Performance of eliminating condensation while a test subject is in the suit in a relevant thermal vacuum environment for space.
- Must pass White Sands Test Facility (WSTF) off-gas testing, specification TBD.
- Nice to have: Resistant to isopropyl alcohol (IPA) at any concentration, stericide, or a 50% water/50% dish soap mixture

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:

- Research
- Prototype

Desired Deliverables Description:
Phase I

- Completed test plan/report on the following for flat samples:
  - Steam cycle (simulated breathing). The suggested cycle regiment would be for at least 104 °F temperature steam cycled for 216,000 cycles at 18 cycles per minute.
    - 104 °F is the high average of exhaled breath temperature.
    - 216,000 cycles is calculated from 18 breaths per minute, 8-hr EVAs, and 25 EVA certification.
    - Success criteria: No fogging occurring on samples and no evidence of delamination after the test.
  - Adhesion per ASTM 3359.
  - Cleaning Test
    - Using distilled and DI water and wipe testing for 100 cycles.
- Consistently able to meet anti-fog thickness requirement from manufacturer along the entire geometry on the helmet assembly.
- At least five flat samples (no smaller than 1 by 1 in.) of coated polycarbonate.
- Monthly status meetings with NASA on progress.

Phase II

- Delivered prototype of helmet pressure bubble or equivalent size and shape bubble made of polycarbonate material, coated with permanent anti-fog solution.
- Completed test plan/report on curve samples or prototype helmet for the following:
  - Steam cycle (simulated breathing). The suggested cycle regiment would be for at least 104 °F temperature steam cycled for 216,000 cycles at 18 cycles per minute.
    - 104 °F is the high average of exhaled breath temperature.
    - 216,000 cycles is calculated from 18 breaths per minute, 8-hr EVAs, and 25 EVA certification.
    - Success criteria: No fogging occurring on samples and no evidence of delamination after the test.
  - Adhesion per ASTM 3359.
  - Cleaning Test

        - Using distilled and DI water and wipe testing for 100 cycles.
- NASA WSTF off-gas testing.

State of the Art and Critical Gaps:
For the current Extravehicular Mobility Unit (EMU) spacesuit, an astronaut applies an anti-fog solution to the interior of the helmet bubble before each EVA. However, the anti-fog solution has been reported to cause eye discomfort during at least seven EMU EVAs when the anti-fog solution contacted the crewmember's eyes. During STS-100, astronaut Chris Hadfield reported the eye irritation temporarily blinded him during his spacewalk. In addition, the wipe-on anti-fog solution is a consumable that needs to be accounted for and a supply launched for missions.

To solve this, the Exploration EMU (xEMU) pressure bubble wants to use a permanent anti-fog coating or other technology that prevents fogging. The EMU program did some work investigating a permanent anti-fog solution, HTAF-308. It failed during qualification due to delamination and flaking after manned testing so was never implemented. During the Constellation spacesuit development program, NASA conducted a trade study on four different permanent anti-fog solutions. The evaluation tested coated samples with the four permanent anti-fog candidates based on Transmission, Haze, Adhesion and Abrasion Resistance, Craze Resistance, Cold Box, Steam, and Human Breath Response tests. The results of that trade study selected HTAF-601 as the primary option.

The HTAF-601 permanent anti-fog solution was tested throughout the xEMU Design, Verification, and Test (DVT) human-in-the-loop (HITL) events. However, major issues have arisen with further HITL testing with the coating. Cleaning the helmet has been a challenge to avoid damaging the permanent anti-fog coating. NASA has completed a set of different methods for cleaning the anti-fog to try to document a preferred method. It was found IPA cannot be used to clean the interior of the helmet because it will strip and delaminate the permanent anti-fog coating. Even with using a very gentle cleaning method of flushing with distilled or DI water and dabbing at facial oils, the permanent anti-fog starts to delaminate consistently after 50 hr of MPT. Finally, the HTAF-601 coating is being discontinued by the vendor.

This subtopic will focus on companies looking at permanent anti-fog solutions that specifically address the issues that the Exploration Pressure Garment System (xPGS) team found with DVT. The hope is an innovative anti-fog solution can be found that is more appropriate and durable for the spacesuit environment. Success for a Phase II completion would be the company's anti-fog solution applied to a flight-like helmet shape of hemi-ellipsoid bubble that has completed sample steam and cleaning cycle testing. This technology could be infused in the current EMU spacesuit or future advanced suits selected by the new program, "Extravehicular Activity and Human Surface Mobility Program Office."

Other commercial industries have successfully implemented permanent anti-fog solutions. Ski goggles, motorcycle visors, and fighter pilot helmets are all examples of this technology being implemented. However, most of these solutions are for goggles only, and do not have the requirements of breath cycles. This SBIR will expand the application of this technology.

Relevance / Science Traceability:
This technology would be applicable to all spacesuit architectures used by the agency. Also, 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 the Johnson Space Center (JSC), solutions will have a direct infusion path as the xEMU is matured to meet the design and performance goals.

References:
Davis, K. and Kukla, T., "NASA Advanced Space Suit xEMU Development Report – Helmet and Extravehicular Visor Assembly (EVVA)" ICES-2022-260, 51st International Conference on Environmental Systems, St. Paul, MN, July 2022.

Focus Area 7 Human Research and Health Maintenance

The NASA Human Research Program (HRP) drives advances in scientific and technological research to enable human space exploration. It is a human-focused Program dedicated to providing solutions and mitigation strategies beyond low-earth orbit by reducing the risks to human health & performance through focused translational, applied and operational research. HRP's primary deliverables include:

- Human health, performance, and habitability standards
- Countermeasures and other risk mitigation solutions
- Advanced habitability and medical support technologies

Recently, HRP has developed a strategy to deliver critical components for an evolvable Crew Health and Performance System by 2032. This will be central to how HRP characterizes spaceflight risks and produces mitigation strategies that enable optimal crew health and performance during exploration missions. HRP will demonstrate and mature this system in ground analogs, in LEO, and on and around the moon to support a 2039 Mars mission. The Human Research Roadmap (https://humanresearchroadmap.nasa.gov) is a web-based version of an HRP Integrated Research Plan (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 addresses 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. Furthermore, HRP has invested in a set of cross-risk initiatives, including -omics research, systems biology, and precision health. HRP subtopics are aligned with Element research and solicit technologies identified in their respective strategic plans.

H12.05: Autonomous Medical Operations (SBIR)

Lead Center: **JSC**
Participating Center(s): **ARC, GRC**

Scope Title: Autonomous Medical Operations

Scope Description:
Current medical operations on the International Space Station (ISS) rely on real-time communication with NASA's Mission Control Center (MCC), leveraging telemedicine technologies to monitor and enable the optimization of Crew Health and Performance (CHP) measures. Near real-time communications allow MCC staff (Flight Surgeons, Flight Controllers, etc.) to intervene when a given medical scenario exceeds the crew's knowledge, skills, or abilities. This MCC subject matter expertise pool extends crew capabilities, allowing them to respond to larger and more complex sets of medically relevant events as they arise. Further, well before launch, crewmembers are trained to operate essential medical assets onboard the ISS and employ detailed, MCC-led procedures to respond to various planned and unplanned events. Importantly, all crewmembers receive pre-mission training on medically

centric procedures in preparation for assigned spaceflight. Despite selecting a specific astronaut who receives additional medical training and is the designated “Crew Medical Officer,” onboard medical capabilities are understandably limited by experience, logistics, and communications. Consequently, crewmembers are not fully vested with the resources to adequately address the breadth of medical situations that will require more robust medical (and non-medical) decision support and may arise in exploration-class spaceflight operations.

In contrast to ISS missions where MCC can work with a crewmember to “troubleshoot” medical anomalies in real-time, exploration-class missions (and their more burdensome requirements for increasing autonomy) will necessarily evolve and come to dominate NASA’s efforts. Mars missions, understandably, will not have real-time communications with MCC, nor will they have a rapid return capability. Round trip communications between the surface of Mars and Earth is approximately 40 minutes, and the return trip for the spacecraft and crew will be months, which significantly complicates NASA's current medical operations paradigm. Communication bandwidth considerations may also limit data transmission between the crew and MCC, even in high acuity medical situations. More specifically, a variety of existing ISS medical operations require the spaceflight team to "Contact MCC" or "Notify Surgeon" for additional instructions, a capability significantly delayed, reduced, or unavailable for early and future Mars surface operations. In the more near term, Artemis missions in lunar orbit and on the surface of the Moon will also require a commensurate increase in remote operations. Artemis crews, faced with communications latencies that will make instantaneous procedural guidance impossible, medical evacuation times of up to 2 weeks because of the near rectilinear halo orbit, and limitations on crew training for medical operations, will need to address and resolve medical problem sets independently farther and farther afield, specifically in the domains of clinical decision support, medical decision making, and diagnostic/procedural execution. Independent medical decision-making activities can be achieved through autonomous crew decision support technologies combined with integrated systems that permit assessment, treatment, stabilization, or the resolution of problems in progressively Earth-independent fashion. Therefore, it is likely that some in-flight events will exceed the crew's and MCC's ability to medically respond to preserve CHP during exploration-class spaceflight missions.

Unmanageable in-flight medical circumstances would otherwise require the astronauts to resort to providing inadequate or relatively ineffective medical care or would make a rapid, unplanned return to Earth (medical evacuation) necessary to seek definitive medical care for their affected crewmember. If mission planners, engineers, scientists, and policymakers do not explore, define, develop, select, test, and integrate autonomous medical support systems into future spaceflight systems, these scenarios become more likely.

NASA requires highly functional and easy-to-use novel autonomous medical support technologies that will reduce resource footprint, tools, and training while enabling greater autonomy and self-reliance for the crew. These technologies will allow astronauts to operate in a progressively Earth-independent manner by fomenting the integration and leveraging of highly transferable technologies to buy down risk. Enhanced clinical decision support tools focused on exploration-class spaceflight operations will nominally enable MCC, at baseline, to accurately monitor and even predict potentially adverse conditions when communications are robust while enhancing and facilitating crew decision support technologies and autonomous crew decision-making capability when MCC-Crew communication is suboptimal or absent.

Optimally, integrated solutions should add minimal mass, volume, power, and crew time, or even, where possible, result in savings of these resources. Examples of technology developments can include but are not limited to: advanced just-in-time training modalities; enhanced procedure execution technologies (augmented reality); autonomous physiologic monitoring and trend prediction, integrated clinical decision making support technologies, tools, and systems; automated in situ diagnostic and image interpretation capabilities; multipurpose medical supplies, devices, and technologies (e.g., 3D printing, etc.); and surface operations medical autonomy systems (e.g., casualty assessment/extraction/in situ evacuation, etc.).

This subtopic will advance NASA’s long-term priority for maturation of Earth-independent medical operations, but will also support near-term medical capabilities for the Artemis program, specifically in high-risk, critical path solutions for Artemis Phase I, by boosting "best in class" commercial-off-the-shelf (COTS) or near-term translational technologic solutions to the NASA-specific exploration-class spaceflight problem sets and requirements that will augment operational clinical decision support, medical decision making and diagnostic/procedural execution. Clear deliverables to these ends entail innovations to: (1) maximize crew autonomy and self-reliance across a wide range of medical operations, (2) demonstrate how technology could be leveraged to prevent adverse medical conditions and provide prolonged in situ medical capabilities, (3) extend the amount of time needed before (or eliminate) MCC intervention is required, (4) minimize or reduce the occurrence of medically oriented operational scenarios that could negatively impact mission success, and (5) simultaneously reduce resource costs in terms of up and down mass, power, and volume through novel application of combination technologies, material solutions, or "cross-over" or "cross-domain" multiuse systems that optimize resource allocation/dedication. The subtopic will not only address the near-term needs of Artemis, but also provide a solid platform for maturation of technologies to support Artemis sustaining missions as well as deep space Earth-independent medical operations.

Expected TRL or TRL Range at completion of the Project: 5 to 7

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:
Desired Deliverables Description (provide deliverable description for both Phase I & Phase II)
Autonomous medical systems technologies that minimize mass, volume, and material waste, that increase crew ability to make sound and timely decisions independent of terrestrial mission control across a wide range of medical operational scenarios and optimize crew health and performance on long-duration spaceflight operations.

Desired Deliverables Description

Phase I Deliverable—Candidate autonomous medical support technology prototypes. Documentation of analytical/experimental results validating predictions of key parameters, critical function and/or characteristic proof of concept. Examples may include component and/or breadboard validation in a relevant laboratory environment and documented test performance demonstrating agreement with analytical predictions.
Phase II Deliverable—System prototypes successfully demonstrated in analog and space environments. Documentation of test performance demonstrating agreement with analytical predictions as well as clarifying definition of scaling requirements. Examples may include system/sub-system model or prototype demonstration in an operational environment.

State of the Art and Critical Gaps:
Current space-relevant autonomous systems comprise software, sensors, and other various technologies applied predominantly to spacecraft operational systems, habitats, and propellant loading systems. Two NASA testbeds evaluate autonomous systems technology: The 2^nd Generation Deep Space Habitat (Johnson Space Center, Houston, TX) and the Cryogenic Test Bed Laboratory (Kennedy Space Center, FL). Additionally, the ISS is essentially remotely and autonomously controlled by a large team of experts located at the NASA MCC (Houston, TX). The commercial industry is experiencing a significant paradigm shift regarding its adoption of autonomous systems enabled by multisensory industrial scale "Internet of Things" tracking, low-emission public transport utilization, factory production line optimization, sustainable agricultural practice implementations, and self-governing power

grid solutions. Machine learning, artificial intelligence, and digital transformation are currently laying the groundwork to create new employment opportunities across the public sector that will be enhanced or wholly facilitated by autonomous systems. Recent and upcoming advances secondary to the high speeds and low latency of 5G cellular and space-based internet systems (e.g., Starlink™) will supplement deployment and dissemination of the seeds of a future system of systems comprising interacting robots, sensors, and humans in the workforce. Future missions to the lunar surface and beyond to Mars will have significant delays in communication. Despite speed-of-light communication capabilities, future astronauts will experience delays of up to 22 minutes each way—requiring the development of synergistic and cross-cutting autonomous system technologies that assist astronauts in critical, timely decision making supported by integrated sensors, systems management tools, and "human in the loop" devices and software systems that automatically alert, detect, and assist in the diagnosis of ailing crewmembers as well as to alert the crew to potentially dangerous environmental conditions onboard their spacecraft.

Relevance / Science Traceability:

This subtopic seeks technology development that benefits the Exploration Medical Capability (ExMC) Element of the NASA Human Research Program (HRP) as well as the Exploration Medical Integrated Product Team (XMIPT), part of the Environmental Control and Life Support System (ECLSS)-CHP Systems Capability Leadership Team. Autonomous medical systems technologies are needed to address the following assigned risks mappings:

"Risk of Adverse Health Outcomes and Decrements in Performance Due to Medical Conditions that occur in Mission, as well as Long Term Health Outcomes Due to Mission Exposures" (ExMC)

“Risk of Adverse Outcome Due to Inadequate Human Systems Integration Architecture” (Human Factors and Behavioral Performance [HFBP])

Supports the following identified HRP Gaps:

Medical-701: We need to increase in-flight medical capabilities and identify new capabilities that (a) maximize benefit and (b) reduce “costs” on the human system/mission/vehicle resources.

HSIA-501: We need to determine how Human Systems Integration (HSI) will be used to develop dynamic and adaptive mission procedures and processes, to mitigate individual and team performance decrements during increasingly Earth-independent, future exploration missions (including in-mission and at landing).

And assigned Task Book entries:

-Assisted Medical Procedures (Status: Completed; Responsible HRP Element: ExMC)

-Medical Training Methods for Exploration Missions (Status: Completed; Responsible HRP Element: ExMC)

-Medical Proficiency Training (Status: Completed; Responsible HRP Element: Space Human Factors and Habitability; Collaborating Organization: ExMC)

-Adaptive Stress Training for Hazardous Conditions (Status: Active; Responsible Element: HFBP)

-ExMC Support of Medical Scenarios for the Autonomous Mission Operation (AMO) Test (Status: Completed; Responsible HRP Element: ExMC)

This topic also supports the following entries on the Exploration Medical IPT roadmap:

1. Medical Imaging, Diagnostics, and Treatment Technology
2. Operational Medical Decision Support and Informatics
3. CHP-Integrated Data Architecture

References:

- Ackerman MJ, Filart R, Burgess LP, et al. (2010) Developing next-generation telehealth tools and technologies: patients, systems, and data perspectives. Telemed J E-Health Off J Am Telemed Assoc 16:93–95. doi: 10.1089/tmj.2009.0153 https://www.liebertpub.com/doi/abs/10.1089/tmj.2009.0153
- Antonsen E, Hanson A, Shah R, et al. (2016) Conceptual Drivers for an Exploration Medical System. 67th International Astronautical Congress, Guadalajara, Mexico. https://ntrs.nasa.gov/citations/20160010839

- Ball J, Evans C (2001) Safe Passage: Astronaut Care for Exploration Missions. National Academies Press, Washington, DC. https://books.google.com/books?hl=en&lr=&id=LfybAgAAQBAJ&oi=fnd&pg=PT24&dq=Safe+Passage:+Astronaut+Care+for+Exploration+Missions&ots=jO4P0eJOuV&sig=2KKr7ZBIRTU65Q-UQ2qQedGJY90
- Billica RD, Simmons SC, Mathes KL, et al. (1996) Perception of the medical risk of spaceflight. Aviat Space Environ Med 67:467–473. https://europepmc.org/article/med/8725475
- Blue R, Bridge L, Chough N, et al. (2014) Identification of Medical Training Methods for Exploration missions. National Aeronautics and Space Administration. https://ntrs.nasa.gov/citations/20130013532
- Cummings, M. L. (2017) Informing autonomous system design through the lens of skill-, rule-, and knowledge-based behaviors. Journal of cognitive engineering and decision making, 12(1), 58-61. https://doi.org/10.1177/1555343417736461
- Defense Science Board. (2016) Defense science board summer study of autonomy. Washington, DC: Under Secretary of Defense. https://apps.dtic.mil/sti/citations/AD1017790
- Endsley, M. R. (2017) From here to autonomy: Lessons learned from human-automation research. Human factors, 59(1), 5-27. https://doi.org/10.1177/0018720816681350
- Hamilton D, Smart K, Melton S, et al. (2008) Autonomous medical care for exploration class space missions. J Trauma 64:S354-363. doi: 10.1097/TA.0b013e31816c005d https://journals.lww.com/jtrauma/fulltext/2008/04001/Autonomous_Medical_Care_for_Exploration_Class.8.aspx
- Johnson, M., Bradshaw, J., Feltovich, P., Jonker, C., van Riemsdijk, B., & Sierhuis, M. (2011) The fundamental principles of coactive design: Interdependence must shape autonomy. In M. de Vos, N. Fornara, J. Pitt, & G. Vouros (Eds.), Coordination, organizations, institutions, and norms in agent systems VI, 6541, pp. 172-191. The Institute for Human & Machine Cognition. https://www.researchgate.net/publication/221455987_The_Fundamental_Principle_of_Coactive_Design_Interdependence_Must_Shape_Autonomy, https://www.ihmc.us/
- Schaefer, K. E., Chen, J. Y. C., Szalma, J. L., & Hancock, P. A. (2016) A meta-analysis of factors influencing the development of trust in automation: Implications for understanding autonomy in future systems. Human factors, 58(3), 377-400. https://doi.org/10.1177/0018720816634228.
- Wu, S.-C., & Vera, A. H. (2019) Supporting crew autonomy in deep space exploration: preliminary onboard capability requirements and proposed research questions. Technical report of the autonomous crew operations technical interchange meeting. NASA technical memorandum, NASA/TM—2019–220345. https://humansystems.arc.nasa.gov/publications/NASA_TM-2019_220345.pdf

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 the 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:

- Regolith Transfer
- Non-Water Volatile Capture and Utilization
- Mineral Beneficiation
- Metal Production
- Regolith Inlet/Outlet Valves

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

Subtopic Introduction:
In April 2020, NASA submitted the Plan for Sustained Lunar Exploration and Development to the National Space Council. The report defines several goals for the Artemis Program and states that in-situ resource utilization (ISRU) "will enable the production of fuel, water, and/or oxygen from local materials, enabling sustainable surface operations with decreasing supply needs from Earth."

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 the supporting technologies that may enable or enhance the ability to extract oxygen from lunar regolith.
Hopper and Regolith Transfer: Hopper must be able to hold 100 kg of relevant lunar simulant and demonstrate the ability to flow into a regolith transfer device. Regolith transfer device must demonstrate the ability to lift simulant to target that is at least 3 m above the ground and at least 3 m horizontal from the hopper at a rate of 5 kg/hr. Concepts should be scalable to a full-scale transfer rate of 50 kg/hr with a vertical lift of 10 m. Concepts should also consider longevity (at least 180 days of operation per year) and identify any potential wear issues.

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 and tested in a vacuum where applicable.

State of the Art and Critical Gaps:
Some oxygen-from-regolith methods have been demonstrated at relevant scales and are progressing toward Technology Readiness Level (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:
The Artemis III Science Definition Report states that "the Artemis III mission will provide important new information relevant to leveraging the Moon's resources towards a sustainable human presence on the surface."

References:

- Lomax, B. A., Conti, M., Khan, N., Bennett, N. S., Ganin, A. Y., & Symes, M. D. (2020). Proving the viability of an electrochemical process for the simultaneous extraction of oxygen and production of metal alloys from lunar regolith. *Planetary and Space Science*, *180*, 104748.
- Schwandt, C., Hamilton, J. A., Fray, D. J., & Crawford, I. A. (2012). The production of oxygen and metal from lunar regolith. *Planetary and Space Science*, *74*(1), 49-56.
- Fox, E. T. (2019). Ionic liquid and in situ resource utilization. https://ntrs.nasa.gov/citations/20190027398
- Cardiff, E. H., Pomeroy, B. R., Banks, I. S., & Benz, A. (2007, January). Vacuum pyrolysis and related ISRU techniques. In *AIP Conference Proceedings* (Vol. 880, No. 1, pp. 846-853). American Institute of Physics. https://ntrs.nasa.gov/citations/20070014929
- Gustafson, R. J., White, B. C., & Fidler, M. J. (2009). Oxygen production via carbothermal reduction of lunar regolith. *SAE International Journal of Aerospace, 4* (2009-01-2442), 311-316.
- Gustafson, R. J., White, B. C., Fidler, M. J., & Muscatello, A. C. (2010). The 2010 field demonstration of the solar carbothermal reduction of regolith to produce oxygen. https://ntrs.nasa.gov/citations/20110005526
- Gustafson, R., White, B., & Fidler, M. (2011, January). 2010 field demonstration of the solar carbothermal regolith reduction process to produce oxygen. In *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition* (p. 434).
- Muscatello, T. (2017). Oxygen extraction from minerals. https://ntrs.nasa.gov/citations/20170001458
- Paley, M. S., Karr, L. J., & Curreri, P. (2009). Oxygen production from lunar regolith using ionic liquids. https://ntrs.nasa.gov/citations/20090017882
- Sibille, L., Sadoway, D. R., Sirk, A., Tripathy, P., Melendez, O., Standish, E., ... & Poizeau, S. (2009). Production of oxygen from lunar regolith using molten oxide electrolysis. https://ntrs.nasa.gov/citations/20090018064

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. NASA is interested in developing technologies that can be used to excavate water ice in a vacuum and deliver it to a sealable container with minimal losses due to sublimation. NASA is also interested in technologies that can capture and utilize other volatiles that may be located in PSRs.

Icy Regolith Excavation: Proposed concepts should be able to excavate frozen regolith simulant with a water ice content between 1% and 5% by mass that is 0.5 m below the surface while minimizing a temperature increase in the excavated material. Phase II efforts should demonstrate the technique with an icy lunar simulant mixture at a target production rate of 35 kg regolith/hr with 1% water ice and 7 kg regolith/hr with 5% water ice. Phase II designs should consider demonstration in a relevant environment representative of a lunar polar shadowed region.

Non-Water Volatile Capture and Utilization: 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 (e.g., production of polymers).

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.

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.

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 Artemis III Science Definition Report states that “the Artemis III mission will provide important new information relevant to leveraging the Moon’s resources towards a sustainable human presence on the surface.”

References:

- Colaprete, A., Schultz, P., Heldmann, J., Wooden, D., Shirley, M., Ennico, K., ... & Goldstein, D. (2010). Detection of water in the LCROSS ejecta plume. *Science, 330*(6003), 463-468.
- Gladstone, G. R., Hurley, D. M., Retherford, K. D., Feldman, P. D., Pryor, W. R., Chaufray, J. Y., ... & Stern, S. A. (2010). LRO-LAMP observations of the LCROSS impact plume. *Science*, *330*(6003), 472-476.

- Hibbitts, C. A., Grieves, G. A., Poston, M. J., Dyar, M. D., Alexandrov, A. B., Johnson, M. A., & Orlando, T. M. (2011). Thermal stability of water and hydroxyl on the surface of the Moon from temperature-programmed desorption measurements of lunar analog materials. *Icarus, 213*(1), 64-72.
- Poston, M. J., Grieves, G. A., Aleksandrov, A. B., Hibbitts, C. A., Darby Dyar, M., & Orlando, T. M. (2013). Water interactions with micronized lunar surrogates JSC-1A and albite under ultra-high vacuum with application to lunar observations. *Journal of Geophysical Research: Planets, 118*(1), 105-115.
- Mortimer, J., Lécuyer, C., Fourel, F., & Carpenter, J. (2018). D/H fractionation during sublimation of water ice at low temperatures into a vacuum. *Planetary and Space Science*, *158*, 25-33.

Scope Title: Mineral Beneficiation and Metal and Silicon Production

Scope Description:
Beneficiation allows for improved efficiency of ISRU processes that involve heating regolith in order 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.

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 and Silicon Production: Proposed concepts should define a target metal other than iron (e.g., aluminum) to be extracted from lunar regolith. Proposed concepts must include a method to move regolith through the reaction zone. Proposed concepts should be capable of passing abrasive granular material through the reaction zone for at least 1,000 cycles and determine the leak rate after 1,000 cycles. Near-pure silicon and metals or metal alloys are acceptable. Form and 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.

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.

References:

- Trigwell, S., Captain, J., Weis, K., & Quinn, J. (2012). Electrostatic beneficiation of lunar regolith: Applications in in situ resource utilization. *Journal of Aerospace Engineering, 26*(1), 30-36. https://ntrs.nasa.gov/api/citations/20110016173/downloads/20110016173.pdf
- Quinn, J. W., Captain, J. G., Weis, K., Santiago-Maldonado, E., & Trigwell, S. (2013). Evaluation of tribocharged electrostatic beneficiation of lunar simulant in lunar gravity. *Journal of Aerospace Engineering*, *26*(1), 37-42. https://ntrs.nasa.gov/api/citations/20110016172/downloads/20110016172.pdf
- Schwandt, C., Hamilton, J. A., Fray, D. J., & Crawford, I. A. (2012). The production of oxygen and metal from lunar regolith. *Planetary and Space Science*, *74*(1), 49-56.

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 has 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 a 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 the 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 the 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 an 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 the 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 the 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 toward 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:
This NASA SBIR subtopic seeks to advance laser/lidar technologies to overcome critical observational gaps in Earth and planetary science. 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, 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 measurement types:

- Backscatter: Measures the profile of beam backscatter and attenuation from aerosols and clouds in the atmosphere to retrieve the optical and microphysical properties of suspended particulates.
- Laser spectral absorption: Measures the profile of laser absorption by trace gases from atmospheric (aerosol/cloud) or surface backscatter and volatiles on surfaces of airless planetary bodies at multiple laser wavelengths to the retrieve concentration of gas within the measurement volume.
- Altimetry: An accurate measure of distance to hard targets in the atmosphere and ocean.
- Doppler: Measures wavelength changes in the return beam to retrieve velocity, direction of velocity vector, and turbulence.

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, technologies and components should be applicable to subsystem or system-level lidar technology solutions, as opposed to stand-alone components such as lasers or photodetectors 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 operation on a wide range of compact (SmallSat, CubeSat, or Unmanned Aerial Vehicle size) packages. Reduction in the complexity and environmental sensitivity of laser architectures is sought, while still meeting performance metrics for the measured geophysical observable. Novel thermal management systems for laser, optical, and electronic subsystems are also 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 (SWaP) of lidar instruments.
- Compact, efficient, tunable, 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), 420 to 490 nm (ocean sensing), 532 nm (aerosols), 820 and 935 nm (water vapor lines), 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), and 3000 to 4000 nm (hydrocarbon lines and ice measurement). 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 >200 pm on a shot-by-shot basis while maintaining high spectral purity (>1,000:1). Direct generation of laser light in the 820 nm spectral band without use of nonlinear optics (e.g., parametric conversion or harmonic conversion) is sought after for space-based water vapor DIAL (differential absorption lidar) applications. Technology solutions employing cryogenic lasers are encouraged to help improve efficiency and enable use of new laser materials. 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 DIAL (<10 pm 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. Integrated receivers for Doppler wind measurement at 1550 or 1650 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 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 SWaP to fit into a CubeSat package or smaller. New high-resolution 3D lidar with appropriate SWaP for stratospheric platforms for wild fire fuel modeling. 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, low-SWaP 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:

- NASA missions are aligned with the National Research Council's decadal surveys, with the latest survey on earth science published in 2018, "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space": https://www.nationalacademies.org/our-work/decadal-survey-for-earth-science-and-applications-from-space
- For planetary science, NASA missions are aligned with the National Academies' 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
- 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

Subtopic Introduction:

Advancements and continued development of active microwave sensors, such as radars or active receivers for remote sensing, applied to Earth and planetary science with the goal of future mission infusion is the target of this subtopic. Key advances in four main topic areas are deemed of high importance to support advancements needed in future missions for NASA in the next decade.

1. Surface Deformation and Change science is a continuing Decadal Survey topic, and follow-ons to the science desired for NISAR (NASA-ISRO Synthetic Aperture Radar) are already in planning. Cloud, water, and precipitation measurements increase capability of measurements to smaller particles and enable much more compact instruments. Advancements in components are needed to support these advanced measurements.
2. Low-frequency-band electronics and antennas are of great interests 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. Studies of the subsurface of other icy worlds is of great interest to a planetary science, as is tomography of small bodies such as comets and asteroids. Lastly, such low-frequency bands are also of interest to radio astronomy. Advances in deployable, steerable aperture and antenna technologies are needed to advance these techniques.
3. 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.
4. Quantum radio and radar receivers such as Rydberg or atom-based radio sensors are poised to improve remote-sensing capabilities for Earth and planetary science applications. Key component advances in radiofrequency (RF) optics and stabilization systems are needed to support multiple upcoming applications including those in Surface Topography and Vegetation (STV).

To advance the four topic areas above, three key scope areas are identified covering components, deployable/steerable technology, or low-power transceivers:

- Component Advancements for Microwave Remote Sensing
- Deployable and/or Steerable Aperture Technologies
- Low-Power W-Band Transceiver

Scope Title: Component Advancements for Microwave Remote Sensing

Scope Description:

This subtopic supports technologies to aid NASA in its microwave sensing missions. Component advancements are desired to improve capabilities of active microwave remote sensing instruments, including improvements for classical radar/radio components—solid-state power amplifier (SSPA) technology, low-loss high-isolation switching, high-linearity low-noise amplifiers, and quantum radar/radio components—Rydberg laser stabilization systems to access target RF transitions in S-band and K-band, and monolithic integrated RF-optics sensor head for atom-based Rydberg detectors:

Classical radar/radio components:

- 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. High-isolation switches are also desired within this frequency 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.

- Low-noise amplifiers at V-band (64-70 GHz) and W-band (94 GHz) are desired with increased linearity. While very low noise figures (2.5 dB) are available at these frequencies, input-referred P1dB is typically below -20 dBm. Amplifiers are desired with increased P1dB over the state of the art, while maintaining or improving noise figure.

Quantum radar/radio components or subsystems to support STV:

- Optimized frequency-stabilization subsystems for a compact Rydberg laser package with a coupler laser wavelength tunable to access target RF transitions at S-band and K-band with absolute frequency stability at the 100-kHz level or better (goal: 10kHz) for operation under typical vibration conditions in suborbital flight.
- Integrated sensor head in a monolithic construction that is a thermally controlled vapor cell with dual RF couplings for atom-mixer optical front-end applications. Mechanically-stable fiber-to-free-space optics/opto-mechanics.

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
- Software

Desired Deliverables Description:

Phase I: Provide research, analysis, and software to advance scope concept as a final report.

Phase II: Design and simulation with prototype.

State of the Art and Critical Gaps:

Advances in Surface Deformation and Change are strongly desired for Earth remote sensing, 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 postrelaxation. 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.

Advances in quantum radars/receivers are strongly desired. Quantum sensing (QS) has the ability to transform space-based science, particularly by substantially increasing the spatial and temporal resolution of remote sensing measurements needed to understand Earth’s climate variability. Quantum detectors configured in, or as a primary part of, novel remote sensing technologies, could assist SMD’s science needs by harnessing QS-derived technology and a variety of advanced component technologies. This could potentially enable unprecedented science measurements in established areas ranging from geodetic observation of aquifers on Earth to lunar seismometry, and in new mission concepts including experimental searches for signatures of dark energy, achieving spatio-temporal super-resolution, super-broad-band or dynamic sensing, and testing the connection between general relativity and quantum mechanics. An example of a technical challenge for the remote sensing of Earth's surface topography and vegetation is that differences in precipitation, vegetation zones (canopy, near surface, or root), ice, and basal properties set distinctly different measurement requirements. For example, in radar remote sensing, observations of these key variables require the use of multiple bands covering the entire radio window (VHF to Ka-band: 50 MHz – 40 GHz) with different configurations sensitive to amplitude, phase or polarization of signals to enable vertical profiling with high accuracy, high spatio-temporal resolution, and with tomography capability.

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. Surface, Topography, and Vegetation (STV) is a Decadal Survey topic that will have significant impact in the following decade and that require new and nonconventional technologies. STV touches multiple science goals from solid earth, ecosystems, climate, hydrology, and weather, and is challenging to fit within the cost cap.

References:

- NISAR follow-on for Surface Deformation and Change: https://science.nasa.gov/earth-science/decadal-sdc
- NASA: "Radar in a CubeSat (RainCube)," https://www.jpl.nasa.gov/cubesat/missions/raincube.php
- National Academies Press: "Global Atmospheric Composition Mission," https://www.nap.edu/read/11952/chapter/9(link is external)
- NASA: "Global Precipitation Measurement Mission," https://www.nasa.gov/mission_pages/GPM/overview/index.html
- NASA Surface Topography and Vegetation Incubation Study: https://science.nasa.gov/earth-science/decadal-stv

Scope Title: Deployable and/or Steerable Aperture 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.

Technologies enabling low-mass steerable technologies, especially for L- or S-bands, including—but not limited to—antenna or radiofrequency (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:
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 (Orbiting Low Frequency Antenna for Radio Astronomy): https://research.utwente.nl/files/5412596/OLFAR.pdf.
V-band deployable antennas are mission enabling for pressure sounding from space.

References:
For low frequency deployable, see similar missions (on much larger platforms):

- REASON: https://www.jpl.nasa.gov/missions/europa-clipper/
- MARSIS: https://mars.nasa.gov/express/mission/sc_science_marsis01.html

For high frequency deployable, see similar, but lower frequency mission:

- RainCube: https://www.jpl.nasa.gov/cubesat/missions/raincube.php

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:

- ACE: https://solarsystem.nasa.gov/missions/ace/in-depth/
- 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**

Subtopic Introduction:
This subtopic addresses current challenges in passive microwave remote sensing. Technology advancement needs are collected into three scopes, including:

- Components or Methods to Improve the Sensitivity, Calibration, or Resolution of Microwave/Millimeter-Wave Radiometers.
- Advanced Digital Electronic or Photonic Systems for Microwave Remote Sensing.
- Advanced Deployable Antenna Apertures at Frequencies up to Millimeter-Wave.

Small businesses are encouraged to propose concepts that fall within these scopes, or to propose novel technologies that are applicable to NASA passive microwave remote sensing.

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 (e.g., total power, pseudo-correlation, polarimetric) 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.
- Noise sources up to 1 THz.
- Broad-band (multi-octave) packaged low-noise amplifiers covering up to 70 GHz.

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.
Gaps include technologies to reduce 1/f noise with submillimeter amplifier-based receivers, particularly using internal calibration sources such as noise sources or pseudo-correlation architectures. Other gaps include highly linear receiver front ends capable of being calibrated in the presence of radio-frequency interference (RFI) that may change the operating point of prefilter components.

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:

- Ulaby, Fawwaz; and Long, David: *Microwave radar and radiometric remote sensing*, Artech House, 2015.
- Wilson, W.J.; Tanner, A.B.; Pellerano, F.A.; and Horgan, K.A.: "Ultra stable microwave radiometers for future sea surface salinity missions," Jet Propulsion Laboratory, National Aeronautics and Space Administration, 2005.
- Racette, P. and Lang, R.H.: "Radiometer design analysis based upon measurement uncertainty," *Radio science*, 40(05), pp. 1-22, 2005.
- Cooke, C.M. et al.: "A 670 GHz integrated InP HEMT direct-detection receiver for the tropospheric water and cloud ice instrument," *IEEE Transactions on Terahertz Science and Technology*, 11(5), pp. 566-576, 2021.

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) components or systems to implement spectrometers, beamforming 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 beamforming, 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 radiofrequency and digital-processing methods.

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 spectrometers (or other applications in the Scope Description) for an ASIC or other component that can be incorporated into multiple NASA microwave remote-sensing instruments are desired:

- 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.

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:

- Ulaby, Fawwaz; and Long, David: *Microwave radar and radiometric remote sensing*, Artech House, 2015.

- Chovan, Jozef; and Uherek, Frantisek: "Photonic Integrated Circuits for Communication Systems," *Radioengineering*, vol. 27, issue 2, pp. 357-363, June 2018.
- Pulipati, S. 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.
- 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.
- 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: Advanced 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, particularly 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. Typical bandwidths required for these antennas may be 10% or more for microwave radiometers.

NASA also requires low-loss broad-band deployable or compact antenna feeds with bandwidths of two octaves or more. Frequencies of interest start at 500 MHz. Loss should be as low as possible (less than 1%) to minimize radiometric uncertainty caused by changes in the antenna physical temperature. The possibility of thermal control and/or monitoring of the antenna is desired to further 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.

Typical radiometer frequencies without deployable antenna technologies include (but are not limited to) 50-57 GHz, 88 GHz, 112-120 GHz, and 176-190 GHz. Radar remote sensing would also benefit from deployable antenna technologies at 65-70 GHz, 94 GHz, and 167-175 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. NASA requires low-loss deployable antenna apertures at frequencies up to 200 GHz or beyond. NASA also requires low-loss broad-band deployable or compact antenna feeds with bandwidths of two octaves or more; these frequencies of interest start at 500 MHz.

References:

- Passive remote sensing such as performed by the Global Precipitation Mission (GPM) Microwave Imager (GMI): https://gpm.nasa.gov/missions/GPM/GMI
- 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, MSFC**

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):

- Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation 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/
- Pathways to Discovery in Astronomy and Astrophysics for the 2020s (Astro2020): "https://nap.nationalacademies.org/catalog/26141/pathways-to-discovery-in-astronomy-and-astrophysics-for-the-2020s,

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 2023 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 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 or 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 to 1,200 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, operated at cryogenic as well as room temperature.
    - 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. A 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. Direct-current (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.

References:

- Meixner, M. et al.: "Overview of the Origins Space telescope: science drivers to observatory requirements," *Proc. SPIE* 10698, 2018, https://asd.gsfc.nasa.gov/firs/docs/
- Leisawitz, D. et al.: "The Origins Space telescope: mission concept overview," *Proc. SPIE* 10698, 2018, https://asd.gsfc.nasa.gov/firs/docs/
- Allan, L. N.; East, N. J.; Mooney, J.T.; Sandin, C.: "Materials for large far-IR telescope mirrors," *Proc. SPIE* 10698, Paper 10698-58, 2018.
- DiPirro, M. et al.: "The Origins Space telescope cryogenic-thermal architecture," *Proc. SPIE* 10698, Paper 10698-44, 2018, https://asd.gsfc.nasa.gov/firs/docs/
- Sakon, I., et al.: "The mid-infrared imager/spectrometer/coronagraph instrument (MISC) for the Origins Space Telescope," *Proc. SPIE* 10698, Paper 10698-42, 2018, https://asd.gsfc.nasa.gov/firs/docs/
- Staguhn, J. G., et al.: "Origins Space Telescope: the far infrared imager and polarimeter FIP," *Proc. SPIE* 10698, Paper 10698-45, 2018, https://asd.gsfc.nasa.gov/firs/docs/
- Risacher, C. et al.: "The upGREAT 1.9 THz multi-pixel high resolution spectrometer for the SOFIA Observatory," *A&A* 595, A34, 2016.
- Goldsmith, P.: "Sub-Millimeter Heterodyne Focal-Plane Arrays for High-Resolution Astronomical Spectroscopy," *The Radio Science Bulletin*, 362, 53, 2017.

- "Performance of Backshort-Under-Grid Kilopixel TES arrays for HAWC+," DOI 10.1007/s10909-016-1509-9.
- "Characterization of Kilopixel TES detector arrays for PIPER," http://adsabs.harvard.edu/abs/2018AAS...23115219D
- "A Time Domain SQUID Multiplexing System for Large Format TES Arrays," https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=31361
- Mellberg, A. et al.: “InP HEMT-based, Cryogenic, Wideband LNAs for 4-8 GHz operating at very low DC-Power,” https://ieeexplore.ieee.org/document/1014467
- Montazeri, S. et al.: “A Sub-milliwatt 4-8 GHz SiGe Cryogenic Low Noise Amplifier," https://ieeexplore.ieee.org/document/8058937
- Montazeri, S. et al.: “Ultra-Low-Power Cryogenic SiGe Low-Noise Amplifiers: Theory and Demonstration,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 1, 2016.
- Schleeh, J. et al.: “Ultralow-Power Cryogenic InP HEMT with Minimum Noise Temperature of 1 K at 6 GHz,” *IEEE Electron Device Letters*, Vol. 33, No. 5, 2012.
- ACCP study: "Science and Applications Traceability Matrix," at https://science.nasa.gov/science-red/s3fs-public/atoms/files/ACCP_SATM_Rel_E_TAGGED.pdf
- Teixeira, J. et al.: "*Toward a Global Planetary Boundary Layer Observing System: The NASA PBL Incubation Study Team Report.*"
- Surface Topography and Vegetation Structure Study Team report: https://science.nasa.gov/science-red/s3fs-public/atoms/files/STV_Study_Report_20210622lowres.pdf

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 Oceans

Scope Description:

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 Research Opportunities in Space and Earth Sciences (ROSES) solicitation. Data from such sensors also inform process studies to improve our scientific understanding of the Earth System. In situ sensor systems (airborne, 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, unmanned aircraft systems (UAS), or balloons; 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.

Specific desired sensors or mated platform/sensors include:

- A hyperspectral in-water radiometry system (HIWRS), ideally with linear polarization measurement capability, completely covering the UV-Vis-NIR (ultraviolet-visible-near-infrared) wavelength range between 320 and 890 nm with a minimum resolution of 5 nm and 1-nm sampling desired (minimum spectral sampling of 2.5 nm). The instrument system shall measure upwelling and downwelling radiances and have a separate solar irradiance reference sensor with equivalent spectral and polarization capabilities. Spectral radiometric uncertainty should be lower than 4% in the 400 to 580 nm spectral region and approximately 5% for the 580 to 720 nm region, combining uncertainty contributions from instrument absolute calibration, characterization (including at least spectral calibration, nonlinearity, stray light perturbation and polarization sensitivity, temperature dependence, and, if applicable, geometrical and in-water response), environmental perturbation, and data processing (with National Institute for Standards and Technology (NIST) traceability). The HIWRS must be ocean submersible to 200 m and ideally will be deployable as an ocean vertical profiling system that provides high vertical resolution near the sea surface on the order of 5 cm (preferred for top 1 m) to 20 cm. Integrated tilt, temperature, and water-depth sensors are essential for the in-water profiling system.
- In situ measurements of ocean particulate backscatter, depolarization, beam attenuation, and diffuse attenuation coefficients relevant for combined ocean-atmosphere active remote sensing (355, 473, 486, 532, 1064 nm wavelengths and 170° to 180° scattering angle with ≤1° angular resolution). Instrument must be ocean submersible to 300 m or deeper.
- In situ polarized hyperspectral UV-Vis volume scattering function (VSF) instrument (ocean submersible to 300 m) covering the angular range close to 0° and, more importantly, as far as 180° (with ≤2° angular resolution). Instrument should have ability to measure (at least) horizontal and vertical aspects of linear polarization. Degree of resolution in angles and wavelength can be decreased for instrument portability and robustness (such as for autonomous unmanned vehicle (AUV) deployments).
- A well-calibrated airborne hyperspectral imager with spectral sensitivity in the UV to Vis (340 to 900 nm; preferably 320 to 1,080 nm) with spectral sampling of at least 2.5 nm, spectral resolution of at least 5 nm, and a wide dynamic range and sensitivity spanning from ocean radiances to cloud radiances for use in comparison to the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Ocean Color Instrument and other sensors.
- 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.

The S1.08 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. 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, TEMPO (Tropospheric Emissions: Monitoring of Pollution), OCO-2 (Orbiting Carbon Observatory 2), GLIMR (Geosynchronous Littoral Imaging and Monitoring Radiometer), SBG (Surface Biology and Geology), and ACCP (Aerosols, Cloud, Convection and Precipitation)—see links below). The solicited measurements will be highly relevant future NASA campaigns with objectives and observing strategies similar to past campaigns; for example, NAAMES (North Atlantic Aerosols and Marine Ecosystems Study), EXPORTS (EXport Processes in the Ocean from RemoTe Sensing), CAMP2EX (Cloud, Aerosol and Monsoon Processes-Philippines Experiment), FIREX-AQ (Fire Influence on Regional to Global Environments Experiment-Air Quality), KORUS-AQ (Korea-United States Air Quality), and DISCOVER-AQ (Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality).

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/Sensors

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 the NASA 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 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 (Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment), NAAMES, EXPORTS, CAMP2EX, FIREX-AQ, KORUS-AQ, and DISCOVER-AQ; see links in References).

Obtaining quality measurements during ship-board field and airborne flight campaigns for support of active satellite missions and for obtaining observations to support next-generation missions remains highly important for NASA Ocean Science. Quality field instruments for particle backscatter at high scattering angles (>170°), multiple scattering angles, and high fidelity remains elusive, with most of these only measuring specific components of the scattering matrix. New in situ optical instruments are needed with higher spectral resolution to support the upcoming PACE mission field support activities. Finally, there are few instruments that can provide comprehensive measurements of the polarization characteristics of the ocean, with most capturing selective aspects. For subsurface radiance measurements, a critical gap is that no commercially available profiling package has become available that can obtain hyperspectral measurements of the ocean upwelling and downwelling within the upper 1 m of the ocean with high vertical resolution necessary for in-water profiling.

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 sensor systems is both near-term (<5 yr) and midterm (5 to 10 yr).
Relevant Programs and Program Officers include:

- NASA Earth Science Division (ESD) Ocean Biology and Biogeochemistry Program
- NASA ESD Tropospheric Composition Program
- NASA ESD Radiation Sciences Program
- NASA ESD Weather and Atmospheric Dynamics Program
- NASA ESD Earth Surface and Interior Program
- NASA ESD Airborne Science Program

References:
Relevant current and past satellite missions and field campaigns include:

- PACE Satellite Mission, scheduled to launch in 2022, that focuses on observations of ocean biology, aerosols, and clouds: https://pace.gsfc.nasa.gov/
- EXPORTS field campaign, targeting the export and fate of upper ocean net primary production using satellite observations and surface-based measurements: https://oceanexports.org
- 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
- Decadal Survey Recommended ACCP Mission (now named Atmos), focusing on aerosols, clouds, convection, and precipitation: https://science.nasa.gov/earth-science/decadal-surveys
- TEMPO Satellite Mission, focusing on geostationary observations of air quality over North America: http://tempo.si.edu/overview.html
- CAMP2Ex airborne field campaign, focusing on tropical meteorology and aerosol science: https://espo.nasa.gov/camp2ex
- 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/
- 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
- 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/
- NAAMES Earth Venture Suborbital field campaign targeting the North Atlantic phytoplankton bloom cycle and impacts on atmospheric aerosols, trace gases, and clouds: https://science.larc.nasa.gov/NAAMES/
- ACTIVATE Earth Venture Suborbital field campaign targeting atmospheric aerosols, trace gases, and clouds over the Western Atlantic: https://activate.larc.nasa.gov/
- AToM airborne field campaign mapping the global distribution of aerosols and trace gases from pole to pole: https://espo.nasa.gov/atom/content/ATom
- 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.
- Decadal Survey Planetary Boundary Layer (PBL) Incubation Study: https://science.nasa.gov/earth-science/decadal-pbl
- 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 primarily in astrophysics, heliophysics, and planetary science, and also to Earth 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 Earth Science Decadal Survey missions. Additive manufacturing of interconnect technology development requested here is a science enabling technology for the next strategic-class astrophysics mission infrared/optical/ultraviolet (IROUV) that has been recommended by the 2020 Astrophysics Decadal Survey. Proposals should reference current NASA missions and mission concepts where relevant. Specific technology areas are:

- Large-format, high-resolution focal plane arrays: Desired features include 8k x 8k, three-side buttable; pixel size: <~7 µm; read noise: ~1 e^- rms; dark signal ~1×10^{-4} e^-/pixel/s; operating temperature >150 K; radiation hard.
- Large-format, low-dark-rate, high-efficiency, photon-counting, solar-blind, far- and near-UV detectors: Desired features include at least 100x100 mm^2 formats with <25 µm resolution elements, flat-field uniformity <10% across face, low-power-consumption-anode readout electronics, immunity to gain sag, high photon-counting rates (> 10^7 counts/s), low dark (<<1 count/cm^2/s); quantum efficiency (QE) >30% between 100 and 200 nm; solar blind; radiation hard.
- High-dynamic-range, high-efficiency detectors in UV/O/NIR, narrowband (UV only), and broadband (UV to NIR (near IR)).
- 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 and for O_3, NO_2, SO_2, H_2S, and ash detection. Refer to National Research Council's Earth Science Decadal Survey (2018).
- 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:
  - Extreme-UV (EUV) photon counting, a linear mode gain >10×10^6 at a breakdown reverse voltage between 80 and 100 V.
  - Detection capability of better than 6 photons/pixel/s 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.
- Solar x-ray detectors with small independent pixels (10,000 count/s/pixel) over an energy range from <5 to 300 keV.
- Supporting technologies that would help enable the x-ray Surveyor mission that requires 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.

- Novel concepts for improving superconducting magnetic shielding such as superconducting inks or additive manufacturing are of interest for detector focal planes with challenging shielding geometries and other requirements.
- 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 IR transmission of 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.
- Detectors with fast readout that can support high count rates and large incident flux from the EUV and x-rays for heliophysics applications, especially solar-flare measurements.
- Supporting technologies for packaging of UV detector focal planes with suitable device interfaces (such as microshutter arrays) including additive manufacturing of electronics (AME) of conductive materials to create high-density, well-isolated interconnects in fine feature sizes (down to 50 µm wide on planar substrates that include up to a 1.5-mm sidewall). In NASA 2022 Astrophysics Strategic Technology Gaps, see gap "High Throughput, Large-Format Object Selection Technologies for Multi-Object and Integral Field Spectroscopy."

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:

- 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.
- 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:

- NASA Cosmic Origins (COR): https://cor.gsfc.nasa.gov/
- NASA Planetary Missions Program Office: https://www.nasa.gov/planetarymissions/index.html
- NASA Explorers and Heliophysics Projects Division (EHPD): https://ehpd.gsfc.nasa.gov/
- NASA Astrophysics Technology Gap list: https://apd440.gsfc.nasa.gov/tech_gaps.html; https://apd440.gsfc.nasa.gov/tech_gap-descriptions.html#tieronetop
- NASA Heliophysics Strategic Mission Programs: https://science.nasa.gov/heliophysics/2024_decadal_survey/heliophysics-strategic-mission-programs
- Planetary Science and Astrobiology Decadal Survey 2023-2032: "Origins, Worlds, and Life," https://www.nationalacademies.org/our-work/planetary-science-and-astrobiology-decadal-survey-2023-2032
- "Pathways to Discovery in Astronomy and Astrophysics for the 2020s," https://nap.nationalacademies.org/catalog/26141/pathways-to-discovery-in-astronomy-and-astrophysics-for-the-2020s
- Earth Science Decadal Survey: "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space (2018)," https://nap.nationalacademies.org/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth

S13.05: In-Situ Instruments and Instrument Components for Planetary Science (SBIR)

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

Scope Title: In Situ Instruments and Instrument Components for Planetary Science

Scope Description:
This subtopic solicits development of instruments and instrument components suitable for deployment on in situ planetary missions. To narrow the critical gaps between the current state of art and the technology needed for the ever-increasing science and exploration requirements, in situ technologies are being sought to increase instrument resolution and sensitivity and/or reduce mass, power, and volume as well as increase data rates without loss of scientific capability. Of particular interest are technologies to support future missions described in the National Research Council Planetary Decadal Survey report "Origin, Worlds, and Life: A Decadal Strategy for Planetary

Science and Astrobiology 2023-2032" (hereafter referred to as the Planetary Decadal Survey). 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. Proposers should provide a comparison metric for assessing proposed improvements compared to existing flight instrument capabilities.
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.

The proposed 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.
Specifically, this year this subtopic solicits instruments and instrument components that provide significant advances in the following areas:

- Technologies relevant to detection and/or identification of organic molecules (including biomolecules), salts, and/or minerals at Mars, ocean worlds, and other bodies. Examples include high-resolution gas or liquid chromatographs, miniaturized mass spectrometers and their drive electronics (e.g., radio-frequency (RF) tanks) and front-end/back-end advancements (e.g., electrospray ionization sources, lasers, ion mobility sources/separators, RF guides/funnels, pumps), isotope analyzers, dust detectors, organic analysis instruments with chiral discrimination, x-ray spectrometers, laser-induced breakdown spectroscopy, electrochemical methods, nanopore technologies, etc.) These developments should be geared towards analyzing and handling very small sample sizes (microgram to milligram) and/or low column densities/abundances.
- Imagers and spectrometers and the associated components that provide high performance in low-light environments (visible and near-infrared (NIR) imaging spectrometers, thermal imagers, etc.)
- Instruments capable of monitoring the bulk chemical composition and physical characteristics of gas samples and ice particles such as the plume (density, velocity, variation with time, etc.).
- Seismometers, mass analyzers, heat flow probes, and trace gas detectors with improved robustness and high-g-force survivability that are applicable to impactor deployment to planetary surfaces.
- Sensors, instruments, components, and technologies for operation in extreme-environment conditions (e.g., temperature, pressure, radiation) such as Venus and Europa.
- Technologies for quantifying lunar water and measuring the D/H ratio in lunar water and other solar system destinations.
- Flight qualifiable low-SWaP (size, weight, and power) laser systems applicable to quantum accelerometers using cold-Cs-based atom interferometers. Of particular interest is an integrated 850-nm laser system complete with control and electronics that produce >150 mW of total usable laser power with <20 W of DC power consumption in a <2-liter package. The laser systems should meet typical requirements of Raman-based light-pulse atom interferometers (linewidth 100 kHz, long-term frequency stability, two controllable laser frequency outputs of 10 GHz apart, ~µs switching time, -60 dB extinction, amplitude control (arbitrary waveform capable preferred), frequency tuning >2 GHz, and others. Offerors should consult papers in open literature of typical atom interferometer laser control requirements).
- Technologies that allow sample collection during high-speed (>1-km/sec) passes through plumes and can maximize total sample mass collected while passing through tenuous plumes. This includes 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, such as cold double-walled isolators for sample manipulation at -80 ºC and Biohazard Safety Level (BSL)-4 conditions. This fly-through sampling focus is distinct from S13.01, which solicits sample collection technologies from surface platforms.

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

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. 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 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 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, volume, and data rate.

Relevance / Science Traceability:

In situ instruments and technologies are essential bases to achieve the 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:

- National Academies' Planetary Decadal Survey report "Origin, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032": https://nap.nationalacademies.org/catalog/26522/origins-worlds-and-life-a-decadal-strategy-for-planetary-science
- NASA Roadmap for Ocean Worlds Exploration: http://www.lpi.usra.edu/opag/ROW
- In situ instruments and technologies for NASA's ocean worlds exploration goals: https://www.nasa.gov/specials/ocean-worlds/
- NASA technology solicitation ROSES 2022, "C.12 Planetary Instrument Concepts for the Advancement of Solar System Observations"(PICASSO) call: https://nspires.nasaprs.com/external/solicitations/summary.do?solId={C29CDA56-E518-672A-23C6-8BEB8639E5AC}&path=&method=init
- NASA technology solicitation ROSES 2022, "C.13 Maturation of Instruments for Solar System Exploration (MatISSE) call: https://nspires.nasaprs.com/external/solicitations/summary.do?solId={E241ECD4-E5F4-CE18-22C2-303C02B5EA73}&path=&method=init
- NASA technology solicitation ROSES 2022/ C.19 Development and Advancement of Lunar Instrumentation (DALI) call: https://nspires.nasaprs.com/external/solicitations/summary.do?solId={CCF1C796-C426-2A96-0664-91648897CCA8}&path=&method=init
- Needed instrument technologies as listed on the website of NSAS’s Planetary Exploration Science Technology Office (PESTO): https://www1.grc.nasa.gov/space/pesto/instrument-technologies-future/

S14.02: In-Situ Particles and Fields and Remote-Sensing Enabling Technologies for Heliophysics Instruments (SBIR)

Lead Center: GSFC
Participating Center(s): MSFC

Subtopic Introduction:
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. This subtopic also solicits the development of advanced remote-sensing instrument technologies and components suitable for heliophysics missions for both solar and geospace science applications.
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 these 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.

Scope Title: Enabling Technologies for Remote-Sensing Heliophysics Instruments

Scope Description:
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:
Auroral, Airglow, and Geospace Instrumentation:

- Technologies or components enabling auroral, airglow, and geospacer at far and extreme ultraviolet (FUV/EUV) and soft x-ray wavelengths.
    - Technologies to reduce size, weight, and power beyond the current state of the art.
    - Technologies to reject background beyond the current state of the art.
    - Technologies to improve live time, spatial resolution, or spectral resolution beyond the current state of the art.
- 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.

Ionosphere and Magnetosphere Instrumentation:

- Passive sensing of ionospheric and magnetospheric plasma density structure using transmitters of opportunity (e.g., global navigation satellite system (GNSS) or ground-based transmissions).
- Electromagnetic sounding of ionospheric or magnetospheric plasma density structure at radio-frequencies from kilohertz to >10 MHz.
    - Solar x-ray, ultraviolet, and visible light instrumentation.
- Technologies or components that advance capabilities for solar imaging at far and extreme ultraviolet (FUV/EUV) and soft x-ray wavelengths.
    - Technologies to reduce size, weight, and power beyond the current state of the art.
    - Technologies to improve background rejection beyond the current state of the art.
    - Technologies to improve live time, spatial resolution, or spectral resolution beyond the current state of the art.
- 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., charge-coupled device (CCD) and complementary metal-oxide semiconductor (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 of 0.1 to 2 keV.
- Technologies to reduce the size, complexity, mass, or power of solar coronagraphs to enable better inclusion on extra-Sun-Earth-line missions (e.g., L4, L5, high solar inclination, solar farside, etc.). For example, extendable high, precision booms that include occulters and baffles.
- Technologies, including metamaterials and microelectromechanical systems (MEMS) that enable polarization, wavelength, or spatial discrimination without macroscale moving parts.

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 S12.06 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:

- Prototype
- Hardware

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:

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.

References:

- For example missions, see "NASA Science Missions," https://science.nasa.gov/missions-page?field_division_tid=5&field_phase_tid=All
- 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
- For details of NASA's Heliophysics roadmap, see the "NASA Heliophysics Science and Technology Roadmap for 2014-2033," https://explorers.larc.nasa.gov/HPSMEX/MO/pdf_files/2014_HelioRoadmap_Final_Reduced_0.pdf
- 2013 Heliophysics Decadal Survey: https://www.nationalacademies.org/our-work/a-decadal-strategy-for-solar-and-space-physics-heliophysics

Scope Title: Enabling Technologies for In Situ Particle and Fields Heliophysics Instruments

Scope Description:
In situ technologies for particles and fields instruments are being sought to achieve improved performance over existing capabilities that are amenable to CubeSats and SmallSats. Specifically, this subtopic solicits instrument development that provides significant advances in the following areas:

- Technologies for the development of high-voltage control elements (e.g., optocouplers or transistors) for use with high-voltage power supplies to linearly apply a specified high voltage to an electrode. These components need to be highly reliable; radiation hardened (100 krad TID); stable over wide temperature ranges (-35 ºC to >70 ºC); and capable of operating at voltages of >6 kV with >100 mA continuous current, >1 A pulse current, and low leakage current (<<100 nA).
- Technologies for the development of magnetic core material suitable for incorporation into science-grade flux-gate magnetometers that can achieve reliable 0.1 nT resolutions and 100 Hz sampling.
- Technologies for the development of 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 (down to 0.1 mV/m) and plasma waves. Mass target: 2 kg or less.

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.

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/Sensors

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:

Most charged-particle instruments have the need to apply high-voltage to electrodes or grids in order to select the energy-per-charge of ions and electrons in space. The availability of high-voltage optocouplers (HVOCs) suitable for spaceflight are severely limited, and the number of reliable vendors since the Covid-19 pandemic has significantly decreased. MOSFET high-voltage technology (SiC) is currently limited to stand-off distances of a few kilovolts but may present an alternative solution to HVOCs in stepping circuits.

Suitable magnetic core material for incorporation into science-grade flux-gate magnetometers has become extremely limited. New vendors of core materials are critical for the continuation of high-quality magnetic field measurements.

The ability to deploy electric field sensors on CubeSat or SmallSats is limited yet is of critical need for the ever-increasing number of Heliophysics 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 these 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, Discovery Missions, and New Frontiers Missions.

References:

- National Research Council: "Solar and Space Physics: A Science for a Technological Society," http://nap.edu/13060
- Example missions (e.g., NASA Magnetospheric Multiscale (MMS) mission, Fast Plasma Investigation; Solar Probe; STEREO; and Geospace Dynamics Constellation): http://science.nasa.gov/missions

S15.02: In-Situ Sample Preparation and Analysis for Biological and Physical Sciences in a Microgravity Environment (SBIR)

Lead Center: GRC

Participating Center(s): ARC, KSC, MSFC

Scope Description
Background: The Biological and Physical Sciences Division within in NASA’s Science Mission Directorate sponsors long-duration microgravity research aboard the International Space Station (ISS). Experimental samples traditionally have been prepared in ground-based laboratories and launched to the ISS where experiments are conducted. Limited analyses of test samples can be conducted aboard the ISS, but most experiments require preserving, storing, and returning the samples to Earth, where detailed analyses are conducted. Consequently, the pace of scientific discovery has been sluggish due to the inability to quickly conduct the iterative process of research that includes the ability to either synthesize or adjust sample composition on-orbit based on real time diagnostic measurements.

Scope Title: Sample Preparation

Scope Description:
This subtopic seeks proposals that advance NASA's objective of leveraging the microgravity environment aboard the International Space Station (ISS) to maintain and strengthen the U.S. leadership in the area of biological and physical science research that is critical to our economic prosperity amid increasing global competition. Proposals should describe technologies capable of safely handling soft matter and/or biological materials in the microgravity environment for sample preparation and post-experiment analyses. Samples may consist of aqueous and polymer solutions that have non-Newtonian flow characteristics, volatile liquids, and particles over a wide range of sizes and properties. Preparation activities will include the ability to accurately measure and dispense reactants; rehydrate dry/lyophilized samples and specimens; mix; transfer; remove trapped bubbles; dry, desiccate, and seal samples; empty and cleanse containers.

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 08.3 In-Situ Instruments/Sensor

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

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:
Experimental samples traditionally have been prepared in ground-based laboratories and launched to the ISS where experiments are conducted. Limited analyses of test samples can be conducted aboard the ISS, but most experiments require preserving, storing, and returning the samples to Earth, where detailed analyses are conducted. The ability to safely prepare, manipulate, and analyze samples in crew environment is severely limited by handling fluids such that in a contained manner on-orbit is required to achieve the pace of ground-based samples.

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 product development and strengthen U.S. leadership in in-space manufacturing and production.

References:

- Chaikin, Paul, Noel Clark, and Sidney Nagel: *Grand Challenges in Soft Matter Science: Prospects for Microgravity Research,* No. E-19904, 2021.
- Burton, Aaron S., Sarah E. Stahl, Kristen K. John, Miten Jain, Sissel Juul, Daniel J. Turner, Eoghan D. Harrington et al.: "Off earth identification of bacterial populations using 16S rDNA nanopore sequencing," *Genes,* 11, 1, 2020, p. 76.
- Castro-Wallace, Sarah L., Charles Y. Chiu, Kristen K. John, Sarah E. Stahl, Kathleen H. Rubins, Alexa BR McIntyre, Jason P. Dworkin et al.: "Nanopore DNA sequencing and genome assembly on the International Space Station," *Scientific Reports*, 7, 1, 2017, pp. 1-12.
- Schneider, Walter, Jay Perry, James Broyan, Ariel Macatangay, Melissa McKinley, Caitlin Meyer, Andrew Owens, Nikzad Toomarian, and Robyn Gatens: "NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2019 to 2020 Overview," 2020 International Conference on Environmental Systems, 2020.

Scope Title: Sample Analysis

Scope Description:
This subtopic seeks proposals that advance NASA's objective of leveraging the microgravity environment aboard the International Space Station (ISS) to maintain and strengthen the U.S. leadership in the area of biological and physical science research that is critical to our economic prosperity amid increasing global competition. Proposals will be accepted for compact devices for measuring and transmitting data regarding cells, proteins, and metabolites in various specimen types, including blood, saliva, urine, and other body fluids. Exhaled breath (with an abundance of volatile molecules) may be especially attractive because it can be obtained from animals non-invasively and may hold important clues about mammalian physiology.

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

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:
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 International Space Station (ISS) during Phase II are especially valuable.

State of the Art and Critical Gaps:
Currently, most samples require preserving, storing, and returning the samples to Earth where detailed analyses are conducted. Not only does the process of returning the samples to Earth delay analysis and interpretation of the results, but it also adds risk that the samples may be compromised in some manner by the process.

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:

- Burton, Aaron S., Sarah E. Stahl, Kristen K. John, Miten Jain, Sissel Juul, Daniel J. Turner, Eoghan D. Harrington et al. "Off earth identification of bacterial populations using 16S rDNA nanopore sequencing," *Genes,* 11, 1, 2020, p. 76.
- Castro-Wallace, Sarah L., Charles Y. Chiu, Kristen K. John, Sarah E. Stahl, Kathleen H. Rubins, Alexa BR McIntyre, Jason P. Dworkin et al: "Nanopore DNA sequencing and genome assembly on the International Space Station." *Scientific Reports*, 7, 1, 2017, pp. 1-12.
- Schneider, Walter, Jay Perry, James Broyan, Ariel Macatangay, Melissa McKinley, Caitlin Meyer, Andrew Owens, Nikzad Toomarian, and Robyn Gatens: "NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2019 to 2020 Overview," 2020 International Conference on Environmental Systems, 2020.

S16.07: Cryogenic Systems for Sensors and Detectors (SBIR)

Lead Center: GSFC
Participating Center(s): JPL

Subtopic Introduction:
Cryogenic cooling systems are essential for the advancement of NASA's science goals. They enable telescopes and instruments in the submillimeter through near-infrared wavelength band, as well as ultra-sensitive detectors for submiilimeter through x-ray photons. Thus, cryogenics will play an important role in many of NASA's advanced missions in Astrophysics, Earth Science, and in the exploration of the solar system: particularly, the outer planets

and their moons. Advances in the development of miniature, low-power coolers will greatly enhance the science capability of SmallSats for Earth and Lunar observations, including swarm arrays of SmallSats for high-resolution remote sensing. Additionally, quantum mechanical behavior becomes more readily apparent at low temperatures, and many of the devices currently under development for manipulation of quantum states, such as quantum memory, operate at low temperature. Thus, cryogenics will likely be necessary for future on-orbit quantum communication and sensing systems.

More specifically, the subtopic seeks ideas for cooling systems covering a broad range of temperatures. At the higher temperature range (>20 K), the emphasis is on small, low-power devices. Such coolers would enable new capability, such as near- and mid-IR instruments on SmallSats and CubeSats for Earth and Lunar observations as well as on instruments for outer-planet missions, where power budgets are extremely constrained. In the low-temperature range (10 K > T > 4 K), advances in cryocoolers are needed primarily for astrophysics, for cooling of far- and mid-IR optics, and for cooling sensitive detectors. In the very low temperature range (T < 4K), advances in magnetic coolers enable the use of ultra-sensitive superconducting detectors. Although these detectors are primarily needed for astrophysics, there is growing interest in using them for quantum communication. This subtopic also seeks ideas to advance support technology for cryogenic cooling systems including (1) advanced heat-transport technologies to efficiently transfer cooling to remotely located detectors or cryocooler waste heat to radiators, including reliable solid-state conductors with variable thermal conductance to allow one cryocooler to efficiently cool two or more targets at significantly different temperatures with varying heat inputs, and (2) low-power dissipation actuators.

Scope Title: High-Efficiency Cryocoolers

Scope Description:

Low-temperature coolers: 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 includes a range of approximately 50 to 200 mW 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 several concepts currently under study for far-infrared and x-ray probe-class observatories recommended in the 2020 Astrophysics Decadal Survey. 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.

Miniature coolers:

NASA seeks miniature, high-efficiency 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.

Heterodyne techniques can achieve very high to extremely high spectral resolution for far-IR spectrometers. Advanced heterodyne receivers operating at 20 K, well above operating temperatures of other superconducting detectors, have been demonstrated. The mixer and low-noise amplifiers in these future advanced heterodyne sensors typically require 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 a SmallSat platform. The cryocooler input power must be compatible with available power in the

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 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: Desired deliverables include coolers and components, such as electronics, that are ready for functional and environmental testing.

State of the Art and Critical Gaps:
Low-temperature coolers:
Current spaceflight cryocoolers for this temperature range include hybrid coolers with a lower Joule-Thompson stage precooled by linear-piston-driven Stirling or pulse-tube upper stage at about 20 K. One such state-of-the-art cryocooler, the Mid-Infrared Instrument (MIRI) cooler on the James Webb Space Telescope (JWST), provides about 55 mW 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.

Miniature coolers:
Present state-of-the-art cryocoolers can achieve Carnot efficiency above 13% and specific mass lower than 0.75 kg/W of cooling at 77 K for cooling capacity under 1 W at 77 K.

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 (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 the far-infrared- and X-ray-probe-class observatories recommended by the 2020 Astrophysics Decadal Survey, as well, in the more distant future, far-infrared and x-ray flagships.

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:

- Examples of mission concepts for the far-IR probe include:
    - PRIMA (Probe Far-Infrared Mission for Astrophysics, which is based on the Galaxy Evolution Probe (GEP); see Moore et al.: "Thermal architecture of the galaxy evolution probe mission concept," *Proc. SPIE,* 10698, 1069858, 2018, doi.org/10.1117/12.2314237)
    - SPICE (Space Interferometer for Cosmic Evolution, which is based on the Space Infrared Interferometric Telescope (SPIRIT) concept; see DiPirro, M. et al.: "The SPIRIT thermal system," *Proc. SPIE*, 6687, 66870D, 2007, doi.org/10.1117/12.734140)
- Example of Astrophysics flagship mission concepts include:
    - Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/
    - LYNX: https://wwwastro.msfc.nasa.gov/lynx/docs/science/observatory.htm

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.
- Reliable solid-state conductors with variable thermal conductance ranging from 0.05 W/K to 0.005 W/K to allow one cryocooler to efficiently provide cooling for two or more targets operating at significantly different temperatures, maintaining them at their calibration temperatures even when their heat load ratios deviate significantly from design values. This technology would eliminate the need to iteratively alter the conductors to tune their conductance ratio during cryogenic instrument calibration stage, significantly reducing cryogenic infrared (IR) spectrometer integration and testing cost.

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. Although 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 of at least 20× less.

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, which complicates ground testing. Current conductors with a thermal switch can only operate in the ON or OFF mode, but not in a mode where its thermal conductance can be varied continuously with negligible (<50 mW) active control power in the temperature range of 120 to 180 K.

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:

- Brennan, P. et al.: AIAA paper 93-2735, https://doi.org/10.2514/6.1993-2735
- Prager, R.C.: AIAA paper 80-1484, https://doi.org/10.2514/6.1980-1484
- Alario, J. and Kosson, R.: AIAA paper 80-0212, https://doi.org/10.2514/6.1980-212

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) 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. Total volume must be >40 cm^3. For polycrystalline materials, this could be composed of smaller sections.
(2) 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.

(3) 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, noncontacting heat straps.

(4) 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.

(5) Suspensions with the strength and stiffness of Kevlar®, 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.

Missions that would benefit from this technology include several concepts presently under development for the far-infrared and X-ray probe-class missions recommended in the 2020 Astrophysics Decadal Survey, as well as future far-infrared and X-ray flagship missions.

References:
For a description of the state-of-the-art sub-Kelvin cooler in the Hitomi mission:

- 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:

- *Cryogenics,* 62, pp. 129-220, July 2014 special issue.

S16.08: Atomic Quantum Sensor and Clocks (SBIR)

Lead Center: JPL
Participating Center(s): GSFC

Subtopic Introduction:
Development and maturation towards space application and qualification of atomic systems that leverage their quantum properties such as:

- Optical atomic clocks:
    - Subsystem and components for high-performance and high-accuracy optical clocks.
    - Space-qualifiable small-size low-power clock lasers.
    - Technical approaches and methods for beyond-state-of-the-art compact and miniature clocks for space with the emphasis on the performance per size, power, and mass.
- Other atomic and artificial atomic sensors:
    - Rydberg atom sensors and artificial atom-based sensors such as nitrogen-vacancy (NV) center point-defect sensors, etc.
- Atom interferometers:
    - Space-qualifiable high-flux ultra-cold atom sources, related components.
    - Beyond-state-of-the-art photonic components at wavelengths for atomic species of interest, particularly those visible and ultraviolet (UV).
    - 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.

Scope Title: Optical Atomic 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 1x1018. 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.
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.
- Technical approaches and methods for beyond-state-of-the-art time transfer between orbiting and terrestrial clocks.

(2) 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: 1 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:

- 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:

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

Scope Title: Atomic Interferometry

Scope Description:
Recent developments of laser control and manipulation of atoms have led to new types of precision inertial force and gravity sensors based on atom interferometry. Atom interferometers exploit the quantum mechanical wave nature of atomic particles and quantum gases for sensitive interferometric measurements. Ground-based laboratory experiments and instruments have already demonstrated beyond the state-of-the-art performances of accelerometer, gyroscope, and gravity measurements. The microgravity environment in space provides opportunities for further drastic improvements in sensitivity and precision. Such inertial sensors will have great potential to provide new capabilities for NASA Earth and planetary gravity measurements, for spacecraft inertial navigation and guidance and for gravitational wave detection and test of properties of gravity in space. Currently the most mature development of atom interferometers as measurement instruments are those based on light-pulsed atom interferometers with freefall cold atoms. There remain a number of technical challenges to infuse this technology in space applications.
Some of the identified key challenges are (but not limited to):

- 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 quantum sensor 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.
  - Integrated micro-optical assemblies for quantum sensor applications.
- 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.

Expected TRL or TRL Range at completion of the Project: 1 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
- Hardware
- Software

Desired Deliverables Description:

Desired deliverables for this scope include an analysis and simulation tool of a cold atom system in trapped and free-fall states relevant to an atom interferometer in space. Other types of deliverables are lasers or laser systems of narrow linewidth (~10 kHz) , high tunability, and/or higher power (> 1 W) for clock and cooling transitions of atomic species of interest. Examples of Phase I deliverables will include results of a feasibility study, analysis, and preliminary laboratory demonstration, as described in a final report. The Phase II deliverables will be prototype or demonstration hardware; summary of performance analysis; and applicable supporting documentation, data, and/or test reports.

State of the Art and Critical Gaps:

Flight-qualifiable laser or laser system transitions that would be suitable for cooling or trapping atomic species of interest. The wavelengths for these lasers are outside of the telecom wavelengths (in particular, 852 nm to enable

Cs cold atom systems). Many technology gaps exist in the development of these lasers for NASA space Atom Interferometer Gravity Gradiometer (AIGG) 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 atom interferometer applications.

Relevance/Science Traceability:
The technology advancement from this subtopic will lead to the realization of an orbiting AIGG, which would significantly advance the capability to measure the Earth’s time variable gravity (TVG). Performance simulations have shown that an orbiting AIGG will result in a factor of 8 improvement in the recovery of the Earth’s TVG compared to GRACE Follow-On. Also, the Mass Change Designated Observable (MCDO) mission study team has identified an advanced gravity gradiometer based on atomic interferometry as a critical future technology for significant advancement in TVG observations. The MCDO study has included simulation performance studies of a notional space-based AIGG, as well as supporting an Instrument Design Lab study and a Mission Design Lab study for an AIGG Technology Demonstration Mission (TDM). The AIGG testbed is being developed at the Goddard Space Flight Center.

References:
2017 NASA Strategic Technology Investment Plan: https://go.usa.gov/xU7sE
2015 NASA Technology Roadmaps: https://go.usa.gov/xU7sy

Focus Area 10 Advanced Telescope Technologies

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, 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 to collect 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**

Subtopic Introduction:

This subtopic includes three scopes that are crucial to the discovery, detection, and characterization of potentially habitable exoplanets. Extreme precision radial velocity is the only technique that can potentially discover these planets using ground-based telescopes, perhaps within the next decade as the technology is advanced and large telescopes come online. With the discovery of the exoplanets, imaging systems can be defined to characterize them. High-contrast "internal" coronagraphs are fed by the light of a large space telescope. They rely on extremely stable wavefronts and require picometer-level observatory wavefront control. Starshades are "external" coronagraphs that block starlight before it enters the telescope. They enable exoplanet detection without extreme control of optical wavefronts, but they are separate spacecraft that must be maneuvered and flown in formation with the telescope. We seek proposals that address technology gaps in all three scopes. These gaps are described at: https://exoplanets.nasa.gov/internal_resources/1123/.

Scope Title: Control of Scattered Starlight with Coronagraphs

Scope Description:

This scope addresses the unique problem of the 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 1 million to 10 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, which include 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 flightlike 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:
Under this scope, 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, large ultraviolet/optical/infrared telescope (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.
- Exoplanet Exploration—Planets Beyond Our Solar System: https://exoplanets.jpl.nasa.gov
- 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/
- Goddard Space Flight Center: https://www.nasa.gov/goddard

Scope Title: Control of Scattered Light with Starshades

Scope Description:

As with the scope addressing coronagraphs, this scope addresses the unique problem of the 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 1 million to 10 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) antireflection 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:
Under this scope 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 flightlike 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), infrared/optical/ultraviolet (IR/O/UV) space telescope, 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 PRV 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:

- Fischer et al.: "State of the Field: Extreme Precision Radial Velocities," 2016, http://adsabs.harvard.edu/abs/2016PASP..128f6001
- 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

- 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
- 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:

- Gris-Sanchez, I. et al.: "Multicore fibre photonic lanterns for precision radial velocity Science," 2018, https://academic.oup.com/mnras/article/475/3/3065/4769655
- Jovanovic, N. et al.: "Integrated photonic building blocks for next-generation astronomical instrumentation I: the multimode waveguide." *Optics Express*, 20, 17029, 2012.

Astrocombs:

- 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.
- 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
- Suh, M.-G., et al.: "Searching for exoplanets using a microresonator astrocomb," *Nature Photonics*, 13(1), pp. 25–30, 2019.
- Obrzud, E., et al.: "A Microphotonic Astrocomb," *Nature Photonics*, 13(1), pp. 31–35, 2019.
- Metcalf, A., et al.: "Stellar Spectroscopy in the Near-infrared with a Laser Frequency Comb," *Optica,* 6(2), 2019.
- Lee, S.H., Oh, D.Y., Yang, Q. et al.: "Towards visible soliton microcomb generation," *Nat Commun*, 8, 1295, 2017.

Nonlinear waveguides:

- 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
- 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:

- 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:
The need for continued innovation on optical systems and fabrication technologies as applied to ultraviolet to far-infrared telescopes should be encouraged by the participation of small businesses and others. New composite materials, advanced and nanotechnology manufacturing, and new optical techniques could provide the necessary advancements for the new challenging astrophysical missions. 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

Infrared/Optical/Ultraviolet (IR/O/UV) Space Telescope calls for deployed apertures as large as 15 m in diameter; and the Origins Space Telescope (OST), for operational temperatures as low as 4 K. 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:

(1) 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.

(2) 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.

(3) 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 in 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 of 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 IR/O/UV Space Telescope mission concepts. Ultra-stable optomechanical systems are listed as a "critical" technology gap with an "urgent" priority in the LUVOIR STDT (Science and Technology Definition Team) Final Report for the Astro2020 Decadal Survey and are also highly applicable to the IR/O/UV Space Telescope proposed in the 2021 Decadal Survey "Pathways to Discovery in Astronomy and Astrophysics for the 2020s."

References:
- Large UV/Optical/IR Surveyor (LUVOIR): https://asd.gsfc.nasa.gov/luvoir/
- Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/
- Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/
- Exoplanets: https://exoplanets.nasa.gov/what-is-an-exoplanet/technology/
- 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 to Mid/Far-Infrared Telescopes (SBIR)

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

Subtopic Introduction:
Accomplishing NASA’s high-priority science at all levels (Flagship, Probe, Medium-Class Explorers (MIDEX), Small Explorers (SMEX), CubeSats, Pioneers, sounding rockets, and balloons) requires low-cost, ultra-stable, normal-incidence mirror systems with low mass-to-collecting-area ratios—where a mirror system is defined as the substrate, supporting structure, with associated mechanisms and active wavefront or thermal sense and control systems. After performance (diffraction limit, wavefront stability, and collecting area), the most important metrics are affordability or areal cost (cost per square meter of collecting aperture) and mass. Also important is the ability to predict ‘in-use’ performance via validated integrated structural thermal optomechanical performance (STOP) modeling.

This subtopic solicits technology solutions ranging from advanced mirror/structure materials to innovative fabrication and test processes/tools that address technology gaps identified by the 2022 Astrophysics Biennial Technology Report (https://apd440.gsfc.nasa.gov/technology.html) and the 2022 Exoplanet Exploration Program Technology Gap List (https://exoplanets.nasa.gov/internal_resources/2269/). Successful proposals will show traceability to an identified technology gap and present a feasible plan to develop the proposed technology for infusion into a potential NASA Mission.

Previously, this subtopic had multiple scopes each sponsored by its own NASA center. Starting this year, there are only three scopes. Scope #1 seeks mirror system solutions for all potential missions. Scope #2 seeks technologies to manufacture, test, and control mirror surfaces. Scope #3 contains narrowly defined 'special' topics that will be solicited for 1 or 2 years.

Scope Title: Materials, Substrates, Structures, and Mechanisms for Advanced Optical Systems

Scope Description:
This scope solicits mirror system technology solutions that enable or enhance telescopes for missions of any size (from balloon or CubeSat to Probe or Flagship) operating at any wavelength from UV/optical to mid/far-infrared. A mirror system is defined as the substrate (material and core structure), supporting structure, with associated mechanisms and active wavefront or thermal sense and control systems. After mission-specific performance specifications, the most important metrics are affordability or areal cost (cost per square meter of collecting aperture) and mass. Also important is the ability to predict 'in-use' performance via validated integrated structural thermal optomechanical performance (STOP) modeling.
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; and Mid-IR missions require 2-m-class telescopes diffraction limited at 5 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 should have a radius of curvature 3 m (nominal) and a mass <150 kg.

Potential FIR space missions require telescopes with apertures up to 6 m monolithic or 16 m segmented with diffraction-limited performance as good as 5 µm (400 nm rms transmitted wavefront), 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. Ideally, the mirror should have less than 100 nm rms surface figure change from 300 to 10 K. Mirror areal density goal is 25 kg/m^2 for the primary mirror substrate and 50 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. Potential solutions include, but are not limited to, materials with a low coefficient of thermal expansion (CTE), homogenous CTE, and high thermal conductivity; metal alloys, nanoparticle composites, carbon fiber, graphite composites, ceramic, or SiC materials; and additive manufacture or direct precision machining.

Potential ultraviolet/optical (UVO) space missions require telescopes with apertures up to 6-m monolithic or 16-m segmented with better than 500 nm diffraction-limited performance (40 nm rms transmitted wavefront) achieved either passively or via active control operating at 250 to 270 K (nominal). Optical components need to have <5 nm rms surface figures. Additionally, a potential exoplanet mission, using an internal coronagraph, requires total telescope wavefront stability of less than 3 pm rms. This stability specification places severe constraints on the dynamic mechanical and thermal performance. Potential enabling technologies include: ultrastable mirror substrate and support structures (60 to 500 Hz first mode), athermal telescope structures, athermal mirror struts, ultrastable joints with low CTE, vibration compensation or isolation of >140 dB, and active thermal control of <1 mK.

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 new heavy lift vehicle. Regarding areal cost, a good goal is to keep the total cost of the primary mirror at or below $100M. Thus, a 6-m-class mirror (with ~30 m^2 of collecting area) should have an areal cost of less than $3.5M/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.

CubeSAT missions need low-cost, compact, scalable, diffraction-limited, and athermalized off-axis reflective and on-axis telescopes. One potential mission is for near-infrared/short-wave-infrared- (NIR/SWIR-) band optical communication. A NIR/SWIR optical-communication system needs to have an integrated approach that includes fiber optics, fast-steering mirrors, and applicable detectors.

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
- Research

Desired Deliverables Description:

An ideal Phase I deliverable would be an optical component or telescope system of at least 0.25 m or a relevant subcomponent of a system leading to a successful Phase II delivery and a 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 further advances the technology to produce a flight-qualifiable and scalable optical system, subsystem or relevant components (with TRL in the 4 to 5 range) with the required performance. 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 SOA (state-of-the-art) 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 $100K/m^2 and $1M/m^2.

Current SOA balloon mission mirrors require lightweighting to meet balloon mass limitations and have difficulty meeting optical to mid-IR diffraction-limited performance over the wide temperature range because of the CTE limitations and gravity sag change as a function of elevation angle.

Currently, SOA optical communications on-axis or axisymmetric designs are problematic because of the central obscuration. Off-axis designs provide superior optical performance because of the clear aperture; however, they are more complex to design, manufacture, and test.

Relevance / Science Traceability:
This subtopic scope primarily matures technologies for potential Astrophysics Division missions ranging from advanced mirror/structure materials to innovative fabrication and test processes/tools that address technology gaps identified by the 2022 Astrophysics Biennial Technology Report (https://apd440.gsfc.nasa.gov/technology.html) and the 2022 Exoplanet Exploration Program Technology Gap List (https://exoplanets.nasa.gov/internal_resources/2269/).

Specific examples include large-aperture ultra-stable telescopes and large-aperture cryogenic telescopes. Additionally, it matures technologies for potential balloon missions flying higher than 45,000 ft to perform UV and mid/far-IR science at wavelengths inaccessible from the ground. 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.

References:

NASA: "2022 Astrophysics Biennial Technology Report," https://apd440.gsfc.nasa.gov/technology.html
NASA: "2022 Exoplanet Exploration Program Technology Gap List," https://exoplanets.nasa.gov/internal_resources/2269/
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: https://www.csbf.nasa.gov/docs.html
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
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

Scope Title: Fabrication, Test, and Control of Optical Components and Telescopes

Scope Description:
The ability to fabricate, test, and control optical surfaces 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, control of the shape of optical components "in flight," and fully characterize surface errors.

Given that deterministic optical fabrication is relatively mature, technology advances are solicited that primarily reduces 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; roller embossing at optical tolerances; and slumping, or replication, technologies.

To achieve high-contrast imaging for exoplanet science using a coronagraph instrument, systems must maintain wavefront stability to <3 pm rms during critical observations. This requires 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 uses 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: 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 co-phase segmented aperture mirrors to diffraction-limited tolerances. Depending upon the mission, these mechanisms may need precisions of <1 nm rms and the ability to operate at temperatures as low as 10 K. Potential technologies include superconducting mechanisms.

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
- 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. 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 demonstrate the manufacturing process, metrology instrument, or sense and control system on a flight-traceable optical component. Phase II deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing properties. A successful mission-oriented Phase II would have a credible plan for how to integrate the technology into a 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:
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 sensing using star images, including dispersed-fringe and phase-retrieval methods, is at TRL 6, qualified for space by Webb. WF sensing and control for coronagraphs, including electric field conjugation and low-order wavefront sensing (LOWFS), is at TRL4 and is being developed and demonstrated by the Wide Field Infrared Survey Telescope Coronagraph Instrument (WFIRST/CGI). But none of these technologies have the precision and frequency bandwidth to enable <3 pm rms stability needed for exo-Earth coronagraphy.
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 wavefront 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 are more precision than necessary and are expensive. Furthermore, they are not adequate for UVO applications.

Potential solutions for achieving <3 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.

Relevance / Science Traceability:
This subtopic scope primarily matures fabrication/test and wavefront control technologies for potential Astrophysics Division missions that address technology gaps identified by the 2022 Astrophysics Biennial Technology Report (https://apd440.gsfc.nasa.gov/technology.html) and the 2022 Exoplanet Exploration Program Technology Gap List
(https://exoplanets.nasa.gov/internal_resources/2269/https://exoplanets.nasa.gov/internal_resources/2269/).
Specific examples include large-aperture ultra-stable telescopes and large-aperture cryogenic telescopes. Fabrication and testing technologies for deterministic optical manufacturing are enabling/enhancing for large monolithic and segmented aperture telescopes for missions ranging from UV to optical to far-IR. Control technologies are enabling for coronagraph-equipped space telescopes and segmented space telescopes.

References:
NASA: "2022 Astrophysics Biennial Technology Report," https://apd440.gsfc.nasa.gov/technology.html
NASA: "2022 Exoplanet Exploration Program Technology Gap List,"
https://exoplanets.nasa.gov/internal_resources/2269/

Scope Title: Special Topics: Near Angle Scatter and Ultra-Stiff Biologically Inspired Mirror Substrates

Scope Description:
Topic #1: Near Angle Scatter
Near angle scatter from surface microroughness, optical coating columnar structure, surface defects, contamination, radiation exposure, and micrometeoroid impacts can limit the ability to detect and characterize Earth-like planets in the habitable zones of Sun-like stars. Models, validated by experiment, that predict scattered light amplitude at angular separation from the host star from 40 to 500 milliarcseconds as a function of these sources are needed to help define component specifications for a potential 6-m mission to perform exo-Earth science.

Topic #2: Ultra-Stiff Biologically Inspired Mirror Substrates
This special topic solicits companies that can manufacture exotic mirror substrate structures, either of their own design or of NASA's design. Telescope stability is enabling for missions at all wavelengths (ultraviolet (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. Stiffness is also important for balloon missions which need to minimize change in gravity sag of its primary mirror as a function of elevation angle. 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
- Software

Desired Deliverables Description:
For Topic #1: Near Angle Scatter

- Phase I detailed theoretical analysis of how to predict near angle scatter in the 40 to 500 milliarcseconds region and an implementable test plan to validate the model.
- Phase II data that validates with greater than 99% confidence a model for predicting near-angle scatter in the 40 to 500 milliarcseconds region.

For Topic #2: Ultra-Stiff Biologically Inspired Mirror Substrates

- 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:
For Topic #1: Near Angle Scatter
Rayleigh-Rice surface scatter theory is widely accepted for smooth surfaces but is physically unrealistic for describing near angle scatter in 40 to 500 milliarcseconds regime. Harvey-Shack scatter theory is widely accepted for rough surfaces and includes the effects of mid-spatial errors. But it has a lower limit and may or may not be valid below 500 milliarcseconds.

For Topic #2: Ultra-Stiff Biologically Inspired Mirror Substrates
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. Special Topic #1 is directly traceable to the Decadal recommended exo-planet mission. Special Topic #2 has applicability to any mission requiring a large-aperture low-mass stiff telescope.

References:
NASA: "X-ray and Cryogenic Facility," https://optics.msfc.nasa.gov/tech-2/

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

Subtopic Introduction:
The National Academy Astro2020 Decadal Report identifies studies of optical components and the 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 the 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 areas of interest:

- X-ray manufacturing, coating, testing, and assembling complete mirror systems in addition to maturing the current technology.
- Coating technology includes carbon nanotubes (CNTs) for a wide range of wavelengths from x-ray to IR (x-ray, EUV, UV, vacuum UV (VUV), visible, and IR).

- Free-form optics design, fabrication, and metrology for CubeSat, SmallSat, and various coronagraph instruments.

Scope Title: X-Ray Mirror Systems Technology

Scope Description:
NASA large x-ray observatories require low-cost, ultrastable, preferably 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 1 arcsec or better angular resolutions and 1 to 5 m^2 collecting areas 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); 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 the collecting aperture; and effective design of stray-light suppression in preparation for the Decadal Survey of 2020. Additionally, we need epoxies that impart little to no stress on the mirrors during application and curing. For silicon 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 the inside and/or outside of a 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 better than 2.5 arcsec HPD on the 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 is an 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 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 observatories.
- 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: 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 (NIR)) 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 a 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 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 the 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 (e. g. 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:

- "Application for Freeforms Optics at NASA," https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170010419.pdf
- "Alignment and Testing for a Freeform Telescope," https://ntrs.nasa.gov/citations/20180007557
- "Freeform Surface Characterization and Instrument Alignment for Freeform Space Applications," https://ntrs.nasa.gov/citations/20190025929

Focus Area 11 Spacecraft and Platform Subsystems

Led by the Science Mission Directorate (SMD), NASA 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 maybe a challenge to get a spacecraft or data back from. A major objective of the NASA science spacecraft and platform subsystems development efforts is 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 range from unpiloted 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://nap.nationalacademies.org/.

Subtopic: S13.03: Extreme Environments Technology (SBIR)

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

Scope Title: Extreme Environments Technology

Scope Description:
NASA's missions support a diversity of environments with extreme conditions that are not observed on Earth. Traditional approaches for building a spacecraft for these environments call for the use of environmental protective housings to keep the instruments and other hardware in Earth-like conditions. These environmental protective housings are mass and power intensive. To eliminate the need for these environmental protective housings with large size, weight and power (SWaP), this subtopic develops technologies for producing space systems and instruments that can directly operate in the extreme environments of NASA missions.
This subtopic addresses NASA's need to develop space technologies and 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 one of the following conditions:

1. Very low temperature environments (as low as -240 °C) (e.g., temperatures at the surfaces of Titan and of other ocean worlds, and in permanently shadowed craters on the Moon).
2. Combination of low-temperature and high-radiation environments (-180 °C with 2.9 Mrad of radiation) (e.g., surface conditions of Europa).
3. Very high temperature and high pressure and chemically corrosive environments (480 °C, 90 bar) (e.g., Venus surface conditions).

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 (>10 days) balloons, rovers, 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 or in low-temperature environments such as those of Titan, Europa, Ganymede, Mars, the Moon, asteroids, comets, and other small bodies. In addition, proposals are sought for technologies that enable NASA's long-duration missions to environments with wide temperature swings and high cosmic radiation. High reliability, ease of maintenance, low size, weight, and power (SWaP), and low outgassing characteristics are highly desirable. Special interest lies in the 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 control electronics for precision actuators and sensors.

- Wide-temperature-range, radiation-hard sensors and actuators for autonomous robotic missions.
- Wide-temperature-range feedback sensors with subarcsecond/nanometer precision.
- Long-life, long-stroke, low-power, and high-torque force actuators with subarcsecond/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 gearboxes 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 08 Sensors and Instruments
- Level 2: TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research
- Analysis

Desired Deliverables Description:

Provide research results 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 and technology development work 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. Current state-of-practice for development of space systems is to place the hardware developed with conventional technologies into bulky and power-inefficient environmentally protective 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. More recently, researchers have worked on technologies that are tolerant to extreme environments. Example of such technologies include sensor and electronic platforms in silicon carbide, silicon germanium, and III-nitrides. However, these developments are still at the early stages and need to be advanced to higher technology readiness levels (TRLs) to be applicable to NASA missions. This solicitation seeks to change the state of the practice by supporting technologies that will enable development of low-SWaP, 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. This year a preference will be given to those proposals that would benefit in situ studies of planets with extreme environments. Specific examples include techniques that would be beneficial to systems that will descend through kilometers of cryogenic ice in ocean worlds, 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 (total ionizing dose) 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 -240 °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:

- Proceedings of the Extreme Environment Sessions of the IEEE Aerospace Conference: https://www.aeroconf.org/ (or via IEEE *Xplore* Digital Library)
- Proceedings of the meetings of the Venus Exploration Analysis Group (VEXAG): https://www.lpi.usra.edu/vexag/
- 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 in order 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, 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. May include technologies, approaches, techniques, and/or models, including accompanying data validation reports and modeling code demonstrating how the product will enable spacecraft compliance with PP and CC requirements.
- Phase II deliverable: As relevant to the proposed effort—detailed modeling/analysis or prototype for testing. May include 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, and 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 PP and CC. 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 PP and science requirements, and support model-based assessments of PP requirements for biologically sensitive missions (e.g., outer planets and sample return).

References:

- NASA: "Planetary Protection," https://planetaryprotection.nasa.gov/
- NASA JPL: "Planetary Protection Center of Excellence," https://planetaryprotection.jpl.nasa.gov/
- NASA: "Handbook for the Microbial Examination of Space Hardware," https://explorers.larc.nasa.gov/2019APSMEX/SMEX/pdf_files/NASA-HDBK-6022b.pdf
- McCoy, K. et al.: "Europa Clipper planetary protection probabilistic risk assessment summary," *Planetary and Space Science*, 196, February 2021, 105139.

Z2.02: High-Performance Space Computing Technology (SBIR)

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

Subtopic Introduction:
In order to meet the foreseeable needs of future NASA missions, it is apparent that an evolution in general-purpose computing is required from the current state of the art used in space applications. A 100X increase in computational capability for the same power utilization of current space-based processors is envisioned for the next generation of computation capability. Potential use cases include crewed exploration missions in cislunar and Mars environments, robotic science missions destined to outer planets, and science observatories in Earth orbit. The qualities that NASA needs that might not naturally be provided by commercially available solutions are:

- Radiation tolerance.
- Fault tolerance.
- Mechanical robustness.
- Energy management combined with scalable power efficiency.

Scope Title: Time-Sensitive Networking (TSN) and Time-Triggered Ethernet (TTE)

Scope Description:
Create a proof-of-concept fault-tolerant network leveraging open standards like Ethernet, Time-Sensitive Networking (TSN), Time-Triggered Ethernet (TTE), and remote direct memory access (RDMA) over Converged Ethernet (RoCE) that supports:

- Processor clustering.
- Time synchronization.
  - Relative synchronization.
  - Interoperability with multiple synchronization domain.
- Fault tolerance.
  - Omission failure tolerant.
  - Multiple device failure tolerant (e.g., simultaneous end system and switch failure).
  - Transparent and bounded-time failure recovery.
- Bounded traversal time.
- Compatible with heterogenous networks.
- Ability for low-cost noncritical devices to synchronize without specialized hardware (e.g., TSN network interface card (NIC)), allowing the possibility for a software implementation.
- Guaranteed formal correctness or a clear path for formal verification.
  - Formal proofs for key properties:
    - Self-stabilization
    - Cold start
    - Integration
    - Clique detection

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 Exploration Systems Development Mission Directorate (ESDMD) and the Space Operations Mission Directorate (SOMD). It is also enabling for key Space Technology Mission Directorate (STMD) technologies that are needed by ESDMD-SOMD. 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:

- RISC-V: https://riscv.org/news/2019/09/risc-v-gains-momentum-as-industry-demands-custom-processors-for-new-innovative-workloads/
- Next Generation Space Interconnect Standard: http://www.rapidio.org/wp-content/uploads/2014/10/RapidIO-NGSIS-Seminar-July-23-2014.pdf
- He, J., et al. Provably Correct Systems. Formal Techniques in Real-Time and Fault-Tolerant Systems. pp. 288-335. ProCoS. 1994.
- Reis, G.A. SWIFT: Software Implemented Fault Tolerance. International Symposium on Code Generation and Optimization. IEEE. 2004.
- Wessman, N., et al. De-RISC: The First RISC-V Space-Grade Platform for Safety-Critical Systems. pp. 17-26. IEEE Space Computing Conference Proceedings. 2021.
- Franconi, N., et al. Signal and Power Integrity Design Methodology for High-Performance Flight Computing Systems. pp. 17-26. IEEE Space Computing Conference Proceedings. 2021.

- Yanguas-Gil, A., et al. Neuromorphic Architectures for Edge Computing under Extreme Environments. pp. 39-45. IEEE Space Computing Conference Proceedings. 2021.
- Sabogal, S., et al. A Methodology for Evaluating and Analyzing FPGA-Accelerated, Deep-Learning Applications for Onboard Space Processing. pp. 143-154. IEEE Space Computing Conference Proceedings. 2021.

Scope Title: Coprocessors for Digital Signal Processing (DSP) and Artificial Intelligence (AI)

Scope Description:

Create a proof-of-concept (POC) end-to-end software/firmware/field-programmable gate array (FPGA) bitstream stack using an open-source framework (like OpenCL) to enable heterogeneous compute offload for space-grade processors. Coprocessors to (a) accelerate onboard AI applications or (b) perform 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 internet protocol (IP) cores that can be implemented in a radiation-hardened FPGA. Preferred processor interface is Compute Express Link (CXL) or, alternatively, Peripheral Component Interconnect Express (PCIe).

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:

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:

Commercial AI coprocessor devices exist, but with unknown radiation performance and applicability to NASA onboard processing tasks.

Relevance / Science Traceability:

The high-performance spaceflight computing (HPSC) ecosystem is enhancing to most major programs in the Exploration Systems Development Mission Directorate (ESDMD) and the Space Operations Mission Directorate (SOMD). It is also enabling for key Space Technology Mission Directorate (STMD) technologies that are needed by

ESDMD-SOMD. 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:
Possible existing open-source projects for consideration, in order of relevance:
- nVDLA - http://nvdla.org – Open-source deep learning accelerator successfully implemented in FPGAs (Xilinx): https://github.com/nvdla/hw
- nVDLA on RISC/V - SiFive sponsored work. Details in this codebase: https://github.com/CSL-KU/firesim-nvdla
- Miaow - https://github.com/VerticalResearchGroup/miaow - Open-source GPU.
- FlexGrip - https://github.com/Jerc007/Open-GPGPU-FlexGrip- - Open-source GPU from the University of Turin and U MASS.
    - http://www.ecs.umass.edu/ece/tessier/andryc-fpt13.pdf
- VeriGPU - https://github.com/hughperkins/VeriGPU - Open source - Amateur project with plans to use SYCL.

Alternately, license a GPU, TPU, or DSP core from a vendor and prototype it in the FPGA:
- https://www.design-reuse.com/sip/?q=GPU
- https://www.xilinx.com/products/technology/dsp.html
- https://www.microsemi.com/product-directory/technology/1742-dsp

Experience of Qualcomm enabling code generation for their Hexagon DSP with LLVM:
https://www.llvm.org/devmtg/2011-11/Simpson_PortingLLVMToADSP.pdf

Scope Title: Solid-State Memory Drives

Scope Description:
Proof-of-concept of nonvolatile storage systems extending industrial and enterprise solid-state drives for space applications targeting the following capabilities:
- High reliability.
- Space-radiation tolerant.
- Space-temperature tolerant (especially extreme cold).
- Endure the high shock/vibration environments of space launch.

Concept must have a minimum of 1-TB capacity with a targeted transfer rate of 1,500 MB/s. Concept should leverage industry standard interfaces like Peripheral Component Interconnect Express (PCIe) or Ethernet and be compliant with NVM Express (NVMe) software stack.

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

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:
Radiation-hardened memories lack capacity and/or performance, while COTS-based memories are susceptible to radiation-induced upsets.

Relevance / Science Traceability:
The high-performance spaceflight computing (HPSC) ecosystem is enhancing to most major programs in the Exploration Systems Development Mission Directorate (ESDMD) and Space Operations Mission Directorate (SOMD). It is also enabling for key Space Technology Mission Directorate (STMD) technologies that are needed by ESDMD-SOMD. 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:

- RISC-V: https://riscv.org/news/2019/09/risc-v-gains-momentum-as-industry-demands-custom-processors-for-new-innovative-workloads/
- Next Generation Space Interconnect Standard: http://www.rapidio.org/wp-content/uploads/2014/10/RapidIO-NGSIS-Seminar-July-23-2014.pdf
- He, J., et al. Provably Correct Systems. Formal Techniques in Real-Time and Fault-Tolerant Systems. pp. 288-335. ProCoS. 1994.
- Reis, G.A. SWIFT: Software Implemented Fault Tolerance. International Symposium on Code Generation and Optimization. IEEE. 2004.
- Wessman, N., et al. De-RISC: The First RISC-V Space-Grade Platform for Safety-Critical Systems. pp. 17-26. IEEE Space Computing Conference Proceedings. 2021.
- Franconi, N., et al. Signal and Power Integrity Design Methodology for High-Performance Flight Computing Systems. pp. 17-26. IEEE Space Computing Conference Proceedings. 2021.
- Yanguas-Gil, A., et al. Neuromorphic Architectures for Edge Computing under Extreme Environments. pp. 39-45. IEEE Space Computing Conference Proceedings. 2021.
- Sabogal, S., et al. A Methodology for Evaluating and Analyzing FPGA-Accelerated, Deep-Learning Applications for Onboard Space Processing. pp. 143-154. IEEE Space Computing Conference Proceedings. 2021.

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 an 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 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, high-fidelity simulations, 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, plus include flight instrumentation and ground testing relevant to EDL. In future solicitations, the intent is to maintain these general subtopic categories and revise their content based on Agency needs and priorities along with the evolution and maturation of EDL technologies. Focal STTR solicitations will also be included in the annual solicitations for advancing EDL capabilities.

The SBIR subtopics and their overarching content descriptions are:

- Z7.01 Entry, Descent, and Landing Flight Sensors and Ground Test Technologies: Seeks sensors and components for safe precision landing, entry-environment characterization, heatshield instrumentation, and other EDL flight systems and ground-test diagnostics and electronics capabilities.
- 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, instrumentation, and landing attenuation systems.
- The STTR subtopic covers various EDL technologies for high-performance simulations, advanced algorithms, materials, sensors, instrumentation, testing, or other EDL-related capabilities.

Please refer to the subtopic write-ups for the specific content and scope solicited this year.

Z7.01: Entry, Descent, and Landing Flight Sensors and Ground-Testing Technologies (SBIR)

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

Subtopic Introduction:
The Entry, Descent, and Landing (EDL) Flight Sensors and Ground-Testing Technologies subtopic seeks flight sensors and components for precision landing and hazard detection, as well as diagnostic techniques for ground-test facilities that support validation of analytical tools used in computation of flow-field environments and modeling of aerothermal heating experienced by a spacecraft during atmospheric entry.

Scope Title: Measurement of Electron Number Density in High-Speed Flows Produced in Ground-Test Facilities

Scope Description:
Understanding the spacecraft environment during the high-speed planetary entry phase of a mission requires accurate modeling of thermal nonequilibrium formation and relaxation mechanisms and knowledge of high-speed chemical kinetics under conditions of thermal nonequilibrium. At high entry velocities and temperatures, the chemical mechanisms may be driven by electron impact processes, where ionization can reach several percent of the flow field, accelerating reaction kinetics and electronic state excitation that is responsible for radiative heating of spacecraft. At lower velocities, the formation of low concentrations of electrons (10^{-8} to 10^{-4} mole fraction) can still play a role in kinetics but also causes radio blackout during the entry phase. Data regarding electron formation in shock waves can be obtained through ground tests in shock tube facilities, and early-stage ionization models may be validated against flight data based on available radio blackout data. NASA is seeking methods to measure electron number densities with good temporal resolution in shock tube facilities to better quantify these phenomena. Characteristics of the diagnostics being sought include the following:

- High speed (>1 MHz) measurement of n_e.
- Low spatial resolution (<5 mm resolution in the direction of motion).
- Line-integrated or point measurements are acceptable.
- Nonintrusive diagnostics are preferable.
- Measurement ranges spanning 2 to 3 orders of magnitude between 10^{12} and 10^{23} m^{-3} over pathlengths of 10 to 50 cm.

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: Assessment study of potential diagnostic techniques, including the approach to identify a product solution that meets performance aspects and stays within cost constraints.
Phase II Goals: Prototype diagnostic system demonstration in a relevant environment with hardware delivery to NASA.

State of the Art and Critical Gaps:
Electron number density measurement in a shock-heated test gas using Stark broadening has been demonstrated in the NASA Ames Electric Arc Shock Tube (EAST) facility. Specifically, the electron density was obtained by measuring Stark width of atomic hydrogen across a range of operating pressures and velocities in the shock tube. The desired measurement ranges and characteristics described in this solicitation improve upon past measurements obtained in EAST.

Relevance / Science Traceability:

Understanding radiative heating environments and validation of analytical tools used in spacecraft design are crucial for supporting NASA's future robotic and human exploration missions. Ground testing at more extreme environments to support these missions will challenge existing capabilities, and there is a strong need now to advance diagnostic techniques beyond the current state of the art. The Mars Sample Return Program's Sample Retrieval Lander (high-mass entry) and Earth Entry System, along with the Artemis program's high-speed crewed Earth return, are all examples of entry vehicles that will experience aerothermal heating, and accurate modeling of the radiation is needed.

References:

1. B. Cruden, "Electron Density Measurement in Reentry Shocks for Lunar Return," Journal of Thermophysics and Heat Transfer, Vol. 26, No. 2, April-June 2012.
2. J. Grinstead, et al., "Ames Electric Arc Shock Tube (EAST): Optical Instrumentation and Facility Capabilities," 2nd International Workshop on Radiation of High Temperature Gases in Atmospheric Entry, held 6-8 September 2006 at University "La Sapienza," Rome, Italy. Edited by A. Wilson. ESA-SP Vol. 629, Nov. 2006.

Scope Title: Component Technologies for Lidar Sensors and In Situ Navigation Beacons Applicable to Guidance, Navigation, and Control (GN&C) for Precise Safe Landing

Scope Description:

NASA is seeking the development of hardware component technologies for advanced lidar sensors and in situ navigation beacons 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. A second instrumentation focus of lunar landings, for instance, is the development of in situ ground and orbital sensors, such as beacons for precision landing. 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 system-level hardware components, rather than complete solutions. To be considered, the proposals must include a hardware element and show a development path to operation within the applicable EDL/DDL spaceflight environment (radiation, thermal, vacuum, vibration, etc.). The specific system-level hardware component technologies desired include:

1. Advanced lidar hardware component technologies that can significantly improve functionality of existing lidar sensors and/or reduce size, mass, and power.

The desired hardware component technologies include, but are not limited to, laser transmitter, beam-steering system/method, photonics integrated circuits, focal plane array, etc., that when integrated into a complete lidar system could improve system performance in any or all of the following EDL/DDL applications:

- Hazard Detection and Avoidance: Operation from 1 km to 500 m slant range to map a 100-m-diameter landing area, detect hazardous terrain features greater than 30 cm radius, and register their locations in a sensor/vehicle reference frame to better than 10 cm precision.
- Terrain Relative Navigation: Operation from 20 km to 2 km altitude to generate surface elevation data that can be compared with known surface topography features to determine the vehicle position relative to a landing location to less than 50 m.

- Velocity and/or Altitude Sensing: Operation from 20 km range down to less than 10 m with (1) velocity as high as 2 km/sec along the line of sight (LOS) with a precision on order of 20 cm/sec (1-sigma) at 20 km altitude and 2 cm/sec at 2 km altitude, and (2) altitude data with better than 2 m precision, 1-sigma.

Proposed technologies must address operation in presence of vehicle dynamics and motions (e.g., velocity, attitude variations, vibration).

2. Navigation receivers compatible with planned navigation services.

NASA is investing in and pursuing deployment of lunar communication and navigation services through the Lunar Communications Relay and Navigations Systems (LCRNS) and LunaNet Interoperability Specifications releases. Through this and other beacon development efforts, NASA is deploying these services to provide navigation support to vehicles on and around the Moon. Development is needed of user terminals that can receive the reference navigation signals and messages to perform localization of the user. These can be integrated into a lander to support external positioning, velocity, and timing updates prior to, during, and post descent phases of flight, reducing the reliance and increasing the robustness of lander navigation. NASA is seeking proposals on technologies enabling low size, weight, and power (SWaP) LunaNet Navigation-compatible receivers with accurate clock references to provide a solution to a potential user.

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:

Missions to solar system bodies must meet increasingly ambitious objectives requiring highly reliable precision landing and hazard avoidance capabilities. Examples of these capabilities include precise measurements of vehicle relative proximity, velocity, and orientation, as well as high-resolution elevation maps of the surface during the descent to the targeted body. While current technologies may be available with this functionality, a key part of this solicitation is to address compatibility with the spaceflight environment and to pursue component technologies to improve upon the current state of the art.

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. An element of PL&HA capabilities has already been utilized in the Mars 2020 lander, and several others will be demonstrated on upcoming Commercial Lunar Payload Services (CLPS) missions.

References:

1. A. Martin, et al. (2018), "Photonic integrated circuit-based FMCW coherent LiDAR," 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. Andrew E. Johnson and Tonislav I. Ivanov, “Analysis and Testing of a LIDAR-Based Approach to Terrain Relative Navigation for Precise Lunar Landing,” AIAA 2009.
5. Farzin Amzajerdian, Vincent E. Roback, Alexander E. Bulyshev, Paul F. Brewster, William A. Carrion, Diego F. Pierrottet, Glenn D. Hines, Larry B. Petway, Bruce W. Barnes, and Anna M. Noe, “Imaging flash lidar for safe landing on solar system bodies and spacecraft rendezvous and docking,” Proc. SPIE Vol 9465 (2015).
6. Nikolas Trawny, Andres Huertas, Michael Luna, Carlos Y. Villalpando, Keith E. Martin, John M. Carson III, Andrew E. Johnson, Carolina Restrepo, Vincent E. Roback, “Flight testing a Real-Time Hazard Detection System for Safe Lunar Landing on the Rocket-powered Morpheus Vehicle,” Proc. of AIAA Science and Tech. Forum, 2015.
7. Lunar Communications Relay and Navigation Systems (LCRNS) homepage: https://esc.gsfc.nasa.gov/projects/LCRNS
8. "LunaNet: Empowering Artemis with Communications and Navigation Interoperability," https://www.nasa.gov/feature/goddard/2021/lunanet-empowering-artemis-with-communications-and-navigation-interoperability Oct. 2021.

Z7.03: Entry and Descent System Technologies (SBIR)

Lead Center: LaRC
Participating Center(s): ARC

Subtopic Introduction:

NASA is advancing deployable aerodynamic decelerators and traditional entry concepts 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 (LEO). 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.

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 (HIADs), (2) In Situ Thermal Conductivity Measurements in Formed 3D-Woven Thermal Protection System (TPS) Heat Shields, and (3) Material Selection and Development to Enable Lower Cost Deployable Solutions From Low Earth Orbit (LEO) and at Mars.

Scope Title: Gas Generators for Hypersonic Inflatable Aerodynamic Decelerators (HIADs)

Scope Description:
Development is desired of gas generator technologies to be used as inflation systems that result in improved mass efficiency and system complexity over current pressurized cold gas systems for inflatable structures. 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 between a range of 250 and 10,000 standard liters per minute (SLPM) are sought. This range spans a broad number of potential applications. Thus, a given response or solution need not address the entire range, but can instead focus on a narrower range and application. Additionally, the final delivery gas and its byproducts must not harm aeroshell materials such as the fluoropolymer liner of the inflatable structure. While pure gas chemistries are desired, 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. The focus of Phase I development can be subscale manufacturing demonstrations that show proof of concept and lead to Phase II manufacturing scale-up and testing in relevant environments for applications related to human-scale Mars entry, Earth return, or launch vehicle asset recovery.

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. The focus of Phase I development can be subscale manufacturing demonstrations that show proof of concept and lead to Phase II manufacturing scale-up and testing in relevant environments for applications related to human-scale Mars entry, Earth return, or launch vehicle asset recovery.

State of the Art and Critical Gaps:

The current state of the art for gas generators is limited due to the novelty of this technology. Development of gas generator technologies that improve gas chemistries and materials, improve mass and structure efficiency, reduce system complexity, improve filtering and thermal performance, and lower costs over current pressurized cold gas systems for inflatable structures is needed.

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 LEO. Commercial companies also have a growing interest in advanced deployable aerodynamic decelerators for use in launch vehicle asset recovery. ESDMD (Exploration Systems Development Mission Directorate), SOMD (Space Operations Mission Directorate), STMD (Space Technology Mission Directorate), SMD (Science Mission Directorate), and commercial companies can benefit from this technology for various applications.

References:

- Hughes, S.J., et al., “Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development Overview,” AIAA Paper 2011-2524.
- Bose, D.M, et al., “The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Mission Applications Study,” AIAA Paper 2013-1389.
- Hollis, B.R., “Boundary-Layer Transition and Surface Heating Measurements on a Hypersonic Inflatable Aerodynamic Decelerator with Simulated Flexible TPS,” AIAA Paper 2017-3122.
- Olds, A.D., et al., “IRVE-3 Post-Flight Reconstruction,” AIAA Paper 2013-1390.
- Del Corso, J.A., et al., “Advanced High-Temperature Flexible TPS for Inflatable Aerodynamic Decelerators,” AIAA Paper 2011-2510.

Scope Title: In Situ Thermal Conductivity Measurements in Formed 3D-Woven Thermal Protection System (TPS) Heat Shields

Scope Description:
NASA is developing single-piece TPSs manufactured from a flat 3D-woven material that is formed/molded to the final heat shield geometry and infused with resin to rigidize to the needed shape. The current forming process results in substantial movement of the yarns in the woven preform, which can result in wrinkles and other deformations that may impact properties and lead to differences in thermal conductivity compared to conductivities measured on flat 3D-woven panels. NASA is interested in methods to measure in situ thermal conductivity, initially through the thickness, with the stretch goal of also adding in-plane thermal conductivity, on complex 3D shapes such as 45° sphere-cone heat shield geometries. The ability to make absolute value measurements is desired; however, systems that enable comparison of relative thermal conductivities (changes on the order of 10%) are also of interest. The intent of these measurements is to identify hot spots on the heat shield where the thermal conductivity is significantly higher than other regions – allowing rejection of the heat shield prior to bonding to structure. The ability to account for edge effects at the perimeter of the heat shield is crucial to a successful technology. Materials with thermal conductivities in the range of 0.1 to 0.3 W/mK at room temperature are being evaluated with material thicknesses of ~1 to 1.5 inches. The maximum temperature the materials can be exposed to is ~50 °C. The focus of Phase I development can be a design with some modeling to demonstrate how such a measurement would be made and the rationale, based on experience with the materials or the technology. That would lead into Phase II, where the design is developed and demonstrated on relevant material with the technology being made ready for adoption by NASA missions.

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 that are designed and developed. The focus of Phase I development can be a design with some modeling to demonstrate how such a measurement would be made and the rationale, based on experience with the materials or the technology. That would lead into Phase II, where the design is developed and demonstrated on relevant material with the technology being made ready for adoption by NASA missions.

State of the Art and Critical Gaps:

The current state of the art for in situ measurements of 3D-woven materials is limited due to the novelty of this technology. In situ thermal conductivity measurements can be made on more standard materials and are common practice. The adaptation or extension of these existing techniques to 3D-woven materials must be explored to determine whether or not a completely new technique must be developed. NASA is interested in developing this capability for use on future missions.

Relevance / Science Traceability:

NASA needs advanced in situ measurement techniques 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. ESDMD (Exploration Systems Development Mission Directorate), SOMD (Space Operations Mission Directorate), STMD (Space Technology Mission Directorate), and SMD (Science Mission Directorate) can benefit from this technology for various exploration missions.

References:

- 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.

Scope Title: Material Selection and Development to Enable Lower Cost Deployable Solutions From Low Earth Orbit (LEO) and at Mars

Scope Description:

Advancements are desired in textile manufacturing technologies that can be used to simplify production (e.g., weave architectures, weave-ability, joining techniques), reduce cost (e.g., lower cost fibers and materials for less severe environments), reduce the mass (e.g., flexible gas barriers, improved insulations), or reduce the stowed volume of mechanically deployed structures, inflatable structures, or their flexible TPS. NASA's Adaptable, Deployable Entry Placement Technology (ADEPT) concept and subsequent drag-modulated aerocapture (DMA) concepts were developed primarily for harsh aero environments at Venus. In contrast, current commercial and scientific interests are evaluating deployables at more reasonable scales (i.e., less than 3 m deployed diameter) for applications from LEO and at Mars, where the environments are not as severe and the desired advancements could offer significant improvements. Proposals need not be restricted to fabric-based ADEPT/DMA deployable concepts; approaches that allow for rigid plates that collapse for packaging should also be considered. Likewise, advancements in HIAD thermal protection concepts can lead to better improvements in thermal management efficiency of radiant and conductive heat transport at elevated temperatures (exceeding 1,200 °C). These concepts can be either passive- or active-dissipation approaches. For smaller scale inflatable systems, less than 1.5 m in diameter, thin-ply or thin-film manufacturing approaches are of particular interest for reducing the minimum design gauge. Materials that can serve as good insulators while also providing good structural integrity are of interest as well. The focus of Phase I development can be material coupons and/or subscale manufacturing demonstrations that show proof of concept and lead to Phase II manufacturing scale-up and testing in relevant environments for applications related to Mars and other planetary entry, Earth return, launch asset recovery, or the emergent small satellite entry community.

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 materials, hardware, or prototypes developed. The focus of Phase I development can be material coupons and/or subscale manufacturing demonstrations that show proof of concept and lead to Phase II manufacturing scale-up and testing in relevant environments for applications related to Mars and other planetary entry, Earth return, launch asset recovery, or the emergent small satellite entry community.

State of the Art and Critical Gaps:

ADEPT and subsequent DMA concepts have been developed primarily to facilitate probes and landers at Venus (e.g., ADEPT) and small spacecraft as secondary payloads of opportunity (e.g., DMA) through aerocapture at Venus. The selection of carbon fabric and the 3D weaving were necessary to meet the entry environments at Venus. For entries from LEO and at Mars, the environments are not as severe as Venus, and many commercial and scientific interests are evaluating LEO and Mars deployables at reasonable scales (i.e., less than 3 m deployed diameter). Likewise, there is still room for advancement in HIAD thermal protection concepts, which can lead to better improvements in thermal management efficiency of radiant and conductive heat transport at elevated temperatures (exceeding 1,200 °C). Therefore, selection of appropriate lower cost fibers, weave architectures, weave-ability, and joining techniques that can decrease cost, enable rapid manufacturing, and provide options that are compatible with these entry environments can lead to lower cost deployable approaches.

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 LEO. ESDMD

(Exploration Systems Development Mission Directorate), SOMD (Space Operations Mission Directorate), STMD (Space Technology Mission Directorate), and SMD (Science Mission Directorate) can benefit from this technology for various exploration missions.

References:

- Hughes, S.J., et al., “Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development Overview,” AIAA Paper 2011-2524.
- Bose, D.M, et al., “The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Mission Applications Study,” AIAA Paper 2013-1389.
- Hollis, B.R., “Boundary-Layer Transition and Surface Heating Measurements on a Hypersonic Inflatable Aerodynamic Decelerator with Simulated Flexible TPS,” AIAA Paper 2017-3122.
- Olds, A.D., et al., “IRVE-3 Post-Flight Reconstruction,” AIAA Paper 2013-1390.
- Del Corso, J.A., et al., “Advanced High-Temperature Flexible TPS for Inflatable Aerodynamic Decelerators,” AIAA Paper 2011-2510.
- 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.
- Cassell, A., et al., “ADEPT Sounding Rocket One Flight Test Overview,” AIAA Paper 2019-2896.
- 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.
- Austin, A. et al., “SmallSat Aerocapture: Breaking the Rocket Equation to Enable a New Class of Planetary Missions,” 70th International Astronautical Congress, 21-25 October 2019.
- Austin, A. et al., "SmallSat Aerocapture to Enable a New Paradigm of Planetary Missions," 2019 IEEE Aerospace Conference, Big Sky, MT, USA, 2019, pp. 1-20.
- Strauss, B. et al., “Aerocapture Trajectories for Earth Orbit Technology Demonstration and Orbiter Science Missions at Venus, Mars, and Neptune,” 31st AAS/AIAA Space Flight Mechanics Meeting, 2021.

Z7.04: Landing Systems Technologies (SBIR)

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

Subtopic Introduction:
Landing system technologies will be focused on advancing NASA capabilities in plume-surface interaction (PSI) instrumentation, landing systems, and supplemental technologies. Scope 1 is focused on developing tools or abilities to predict, characterize, and analyze the induced landing environment from a terminal landing phase of flight. Scope 1 also includes further development of tools that can ingest PSI-ejecta field data to predict the effects on the vehicle and surface environment for mission planning and design. Scope 2 is focused on innovation toward reusable landing surfaces with embedded navigation sensors to ensure landing capabilities within induced environments. Scope includes in situ landing sensors developed to aid landing during terminal phases of flight.

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.
5. Ejecta tools or analysis that use PSI-ejecta field data to predict effects on the vehicle and surface infrastructure for landing and mission design.

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: 2 to 5

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 prospective 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 data products, hardware demonstration, and progression toward 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 to provide data for tool validation.

The current post-landing analysis of planetary landers (on Mars) is performed in a cursory manner with partially 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:

- Lander Technologies: https://www.nasa.gov/content/lander-technologies
- 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.
- 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).
- Mehta, M., et al. (2013). Thruster plume surface interactions: Applications for spacecraft landings on planetary bodies. AIAA Journal, 51(12), 2800-2818.
- 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, In Situ Landing Sensors, and Landing Site Preparations

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 kilograms. 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.) or reusable surfaces resilient to induced environments for landing and ascent.

In situ landing sensors used during terminal phases of flight 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 embedded navigation sensors for reusable landing pads, 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 post-flight 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.
This solicitation is not intended for embedded sensors for entry and descent or navigation of the landing vehicle.
Proposal must show a knowledge of current state of NASA and development of near-term NASA goals.

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:

- 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:

- Lander Technologies: https://www.nasa.gov/content/lander-technologies
- Commercial Lunar Payload Services: https://www.nasa.gov/content/commercial-lunar-payload-services
- Lunar Exploration and Transportation Services: https://www.nasa.gov/nextstep/humanlander3
- JAXA Hyabusa2: https://www.hayabusa2.jaxa.jp/en/
- JPL ATHLETE Rover: https://www-robotics.jpl.nasa.gov/how-we-do-it/systems/
- 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 scientific 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 the 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, the assimilation of real data into a highly sophisticated physics model is needed. Information technology is also being used to allow better access to scientific 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 on 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.

S14.01: Space Weather Research-to-Operations-to-Research (R2O2R) Technology Development and Commercial Applications (SBIR)

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

Scope Title: Space Weather Research-to-Operations-to-Research (R2O2R) Technology Development and Commercial Applications

Scope Description:
The term "space weather" is applied to the variable conditions within space that has effects throughout the solar system. More specifically, conditions on the Sun (e.g., sunspots, filaments) often produce various types of eruptions (e.g., flares, coronal-mass ejections) that have the possibility of producing damaging effects to spacecraft, crew, and even ground-based technologies and infrastructure (e.g., power grids, pipelines). 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. NASA’s work includes research that advances operational and commercial space-weather science and technology that will ultimately protect human life, assets on the ground, and assets in space and will allow the continuing exploration of the universe.

Space weather directly impacts programs under the Exploration Systems Development Mission Directorate (ESDMD) that are critical to Artemis and to planning for NASA’s Moon to Mars explorations. An understanding of space weather is also needed for successful operations under the Space Operations Mission Directorate (SOMD), which is responsible for continuing missions in Earth orbit. Programs under these directorates include Orion, Space Launch System, Exploration Ground Systems, Gateway, Human Landing System, and Extravehicular Activity and Human Surface Mobility. Crewed and uncrewed assets are both susceptible to the radiation effects caused by space weather in near-Earth, cis-lunar, and interplanetary space; thus, solutions to mitigate these effects are necessary for safe operations.

This subtopic solicits new, enabling space-weather technologies as part of NASA’s response to national objectives. While this subtopic will consider all concepts demonstrably related to NASA’s R2O2R 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 and back to research environments. This work 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 uncrewed missions to cis-lunar and lunar-surface locations (e.g., ESDMD programs).
- 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 in spacecraft-anomaly resolution and assist 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 are also desired.

(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 of NASA space-weather data in novel ways and will support decision making by a diverse community of users with whom 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 Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites (TRACERS), HelioSwarm, Polarimeter to Unify the Corona and Heliosphere (PUNCH), Electrojet Zeeman Imaging Explorer (EZIE), SunRISE, Extreme Ultraviolet High-Throughput Spectroscopic Telescope (EUVST), Multi-slit Solar Explorer (MUSE), Escape and Plasma Acceleration and Dynamics Explorers (ESCAPADE), Atmospheric Waves Experiment (AWE), 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), 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 effort 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 our operational capabilities (metrics) are.
- 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 uncrewed 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 NASA Space Weather Program establishes an expanded role for NASA in space-weather science under a single program, consistent with the recommendation of the National Research Council (NRC) Decadal Survey and the OSTP/SWORM 2019-NSWSAP. NASA Space Weather Program competes ideas and products, leverages existing agency capabilities, collaborates with other agencies, and fosters partnership with user communities. NASA Space Weather Program is distinguishable from other Heliophysics research programs in that it is specifically focused on investigations that significantly advance understanding of space weather and enable advancements in forecasting and nowcasting 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 the NASA Space Weather Program. 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:

- Public Law 116-181—Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act**:** The Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act 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.
- 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.
- 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.
- National Space Weather Strategy and Action Plan**:** 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.
- 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.
- 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.
- The Space Weather Science and Observation Gap Analysis for the National Aeronautics and Space Administration (NASA), compiled by the Applied Physics Laboratory (APL), was released April 2021. The document was the result of an analysis for the Space Weather Science Application Program (SWxSA) within NASA's Heliophysics Division (HPD) by space-weather experts from academia, the commercial sector, and the space weather operational and end-user community. The purpose was to assess the current state of NASA's space weather observational and predictive capabilities and to identify high-priority measurements necessary to improve forecasting and nowcasting of space-weather events.
- Exploration Systems Development Mission Directorate (ESDMD) defines and manages systems development for programs critical to the NASA’s Artemis program and planning for NASA’s Moon to Mars exploration approach in an integrated manner. ESDMD manages the human exploration system development for lunar orbital, lunar surface, and Mars exploration. ESDMD leads the human aspects of the Artemis activities as well as the integration of science into the human system elements. ESDMD is responsible for development of the lunar and Mars architectures. Programs in the mission directorate include Orion, Space Launch System, Exploration Ground Systems, Gateway, Human Landing System, and Extravehicular Activity (xEVA) and Human Surface Mobility.

- Space Operations Mission Directorate (SOMD) is responsible for enabling sustained human exploration missions and operations in our solar system. SOMD manages NASA's current and future space operations in and beyond low Earth orbit (LEO), including commercial launch services to the International Space Station. SOMD operates and maintains exploration systems, develops and operates space transportation systems, and performs broad scientific research on orbit. In addition, SOMD is responsible for managing the space transportation services for NASA and NASA-sponsored payloads that require orbital launch, and the agency's space communications and navigation services supporting all NASA's space systems currently in orbit.

S17.01: Technologies for Large-Scale Numerical Simulation (SBIR)

Lead Center: ARC
Participating Center(s): GSFC, LaRC

Scope Title: Scope No: 1 Exascale Computing

Scope Description:
The largest challenge facing the high-performance computing (HPC) community today is the tremendous amount of refactoring that is typically required of existing large-scale applications in order to address the hardware paradigm shift that has taken place over the past 5 to 10 years to usher in the exascale era, which is now upon us—and this shift is expected to continue and become even more heterogeneous in the coming years. There is an urgent need for application refactoring and performance portability in this environment. To address these challenges, the approach of this subtopic is to seek novel software technologies such as artificial intelligence (AI) and machine learning that will provide notable benefits to NASA's supercomputing users and facilities and to infuse these technologies into NASA supercomputing operations.

NASA scientists and engineers are increasingly turning to large-scale numerical simulation on supercomputers to advance understanding of complex Earth and astrophysical systems and to conduct high-fidelity aerospace engineering analyses. The goal of this subtopic is to increase the mission impact of NASA's investments in supercomputing systems and associated operations and services. Specific objectives are to:

- Decrease the barriers to entry for prospective high-performance computing (HPC) cloud users.
- Increase the usability of the JupyterLab/hub environment by allowing users to transparently make use of existing or dynamic cloud resources.
- Minimize the supercomputer user's total time-to-solution (e.g., time to discover, understand, predict, or design).
- Increase the achievable scale and complexity of computational analysis, data ingest, and data communications.
- Enhance and accelerate the execution of CFD (computational fluid dynamics) models using artificial intelligence (AI) to assist with handling of the high-dimensionality field and computational expensiveness.
- Reduce the cost of providing a given level of supercomputing performance for NASA applications such as FUN3D with help from AI and machine learning.
- Enhance the efficiency and effectiveness of NASA's supercomputing operations and services.
- Enhance the supercomputer application area towards data analytics and AI and expand to other mission customers.
- Develop next-generation performance analysis tools, incorporating AI to recognize patterns in an application software.

Expected outcomes are to improve the productivity of NASA's supercomputing users, broaden NASA's supercomputing user base, accelerate advancement of NASA science and engineering, and benefit the supercomputing community through dissemination of operational best practices.

The approach of this subtopic is to seek novel software technologies that provide notable benefits to NASA's supercomputing users and facilities and to infuse these technologies into NASA supercomputing operations. Successful technology development efforts under this subtopic would be considered for follow-on funding by, and infusion into, NASA's high-end computing (HEC) projects: the High-End Computing Capability project at Ames and the Scientific Computing project at Goddard. To assure maximum relevance to NASA, funded SBIR contracts under this subtopic should engage in direct interactions with one or both HEC projects, and with key HEC users where appropriate.

Expected TRL or TRL Range at completion of the Project: 5 to 7

Primary Technology Taxonomy:

- Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
- Level 2: TX 11.6 Ground Computing

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software

Desired Deliverables Description:

Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration. Offerors should demonstrate awareness of the state of the art of their proposed technology and should leverage existing commercial capabilities and research efforts where appropriate, including open-source software and open standards. Note that the NASA supercomputing environment is characterized by:

- HEC systems operating behind a firewall to meet strict information technology (IT) security requirements.
- Communication-intensive applications.
- Massive computations requiring high concurrency.
- Complex computational workflows and immense datasets.
- The need to support hundreds of complex application codes, many of which are frequently updated by the user/developer.
- Encourage to develop new application areas like AI and machine learning.

State of the Art and Critical Gaps:

The state of the art and the critical gaps of the main technology areas are:

1. NASA science requires at least 100x more powerful supercomputers and 1,000x higher application parallelism in 10 years, at the same power.
2. Current technologies for high-fidelity computational simulation and data analytics are distinct, and interfacing them is inefficient.

Relevance / Science Traceability:

Virtually all high-end computing systems and applications can benefit from the deliverables of this subtopic. As the demand for high-end computing continues to grow, there is an increasing need for the solicited technologies in both the government and industry.

References:

- "NASA High-End Computing Program User Needs Assessment 2020," https://hec.nasa.gov/workshop20/HEC_Needs_Assessment_2020.pdf
- Wang, Bo and Wang, Jingtao: "Application of Artificial Intelligence in Computational Fluid Dynamics," *Ind. Eng. Chem. Res.,* 60, 7, 2021, pp. 2772–2790, https://pubs.acs.org/doi/10.1021/acs.iecr.0c05045
- Usman, A. et al.: "Machine Learning Computational Fluid Dynamics," 2021 Swedish Artificial Intelligence Society Workshop (SAIS), 2021, pp. 1-4, https://ieeexplore.ieee.org/document/9483997
- Xu, Z. et al.: "A mesh quality discrimination method based on convolutional neural network," 2020 IEEE International Conference on Artificial Intelligence and Computer Applications (ICAICA), 2020, pp. 481-486, https://ieeexplore.ieee.org/document/9182623

S17.02: Integrated Campaign and System Modeling (SBIR)

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

Subtopic Introduction:
This subtopic seeks innovations across a broad spectrum of modeling and simulation (M&S) areas. These advancements are of interest across nearly all of NASA, including SMD (Science Mission Directorate), Exploration Systems Development Mission Directorate (ESDMD), and Space Operations Mission Directorate (SOMD). Although there is a vast range of potential areas of interest, this year the emphasis is on Interoperability. This emphasis is further decomposed into two focus areas:

(1) **Campaign and System Modeling Methods and Tools.** The first focus area is intended to remain focused on "generic" modeling and simulation interoperability challenges such as variable fidelities, time scale inconsistencies, precision, uncertainty representation, surrogate model integration into workflows, etc. The scope of this area ranges from the process of model creation within various NASA use cases, model development, model integration and validation/certification, model aggregation into useful results, visualizing and understanding these results, closing the loop (completing and reporting back) on lessons learned, and libraries and efficient archival/retrieval. We seek solutions to any combination of these challenges.

(2) **Digital Engineering Applications.** This second focus area places the emphasis on more specific M&S challenges associated with the emergence of Model-based, or Digital, transformations and associated applications. The promise of orders-of-magnitude improvements in process speed, quality, design robustness, reuse, etc., has created a large swell of both demand and efforts in this area. These efforts have uncovered some of the challenges in doing this kind of operability extension across disciplines, domains, life cycle phases, project/center customizations, and of course, various cultural barriers. Solutions to these challenges are desired. Ideally, the solutions are scalable and meet the needs of a variety of users/use cases. These proposals need not be centered on SysML, but interoperability is key. Ideally, the proposed solutions should leverage digital engineering/digital transformation methods and approaches being piloted across NASA to allow for easier integration of disparate model types, and also be compatible with current agile design processes.

In both areas, the emphasis of Phase I efforts will be ensuring that the NASA Use cases are clearly understood and that the proposers are able to frame their solutions in a NASA-relevant context.

Scope Title: Scope1: Campaign and System Modeling and Simulation

Scope Description:
As described above, this year NASA is focused on interoperability and its impact on general M&S challenges and solutions. 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:

1. Define, design, develop, and execute future NASA campaigns (collections of missions) and missions (human, robotic, mixed) by developing and utilizing advanced methods and tools that empower more comprehensive, broader, and deeper system and subsystem insights (typically via analysis using models), while enabling these insights to be achieved earlier in the lifecycle where the potential influence on the outcome is greater.
2. Enable disciplined system analysis for the design of future missions or campaigns, 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. 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 variants of systems and subsystems.
5. 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).
6. 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.

Define, design, develop, and execute future NASA campaigns (collections of missions) and missions (human, robotic, mixed) by developing and utilizing advanced methods and tools that empower more comprehensive, broader, and deeper system and subsystem insights (typically via analysis using models), while enabling these insights to be achieved earlier in the lifecycle where the potential influence on the outcome is greater:

1. Enable disciplined system analysis for the design of future missions or campaigns, including modeling of decision support for those missions and integrated models of technical and programmatic aspects of future missions.
2. Evaluate technology alternatives and impacts, science valuation methods, and programmatic and/or architectural trades.
3. 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 variants of systems and subsystems.

4. 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:
5. To support emerging usage of autonomy, both in mission operations and flight software as well as in growing usage of autocoding.
6. 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.
7. 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).
8. 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.

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

- Prototype
- Software
- Research
- Analysis

Desired Deliverables Description:

Phase I will result in a final report that describes the methodology and a clear proof of concept, and/or a prototype, clearly 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.

Relevance / Science Traceability:

As science missions continue to explore, they are growing in scope and complexity and will increasingly rely on modeling, simulation, and virtual qualification. The payoffs from more sophisticated integration and usage of M&S are enormous: greater scope and depth of trade space exploration, reduction in development times and iterations due to increased connectedness, and earlier verification and validation (V&V) to name a few. However, any goal worth achieving has its challenges, and this one is no different. Increased complexity can be exacerbated by lack of interoperability; by inconsistent management of data and workflows; and by inconsistencies in fidelity, assumptions and scopes. There are challenges both with deploying M&S as V&V surrogates and also in V&V of the M&S itself.

There are several large complex campaigns underway including Artemis and Mars Sample Return. These campaigns consist of multiple spacecraft and complex interoperations and span almost 2 decades. This complexity is exacerbated by the distribution of roles and functions across multiple organizations both within and outside the U.S. The ability to share, collaborate, and manage data at a wide variety of levels, layers. and disciplines will be key to success.

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. In addition, every planetary mission requires significant M&S across a variety of possible trade spaces. They are also supported by the general and specific aspects of this subtopic.

References:

- INCOSE: "Systems Engineering Vision 2035," https://www.incose.org/about-systems-engineering/se-vision-2035
- NASA: "LUVOIR: Large Ultraviolet Optical Infrared Surveyor," https://asd.gsfc.nasa.gov/luvoir/
- NASA: "Origins Space Telescope," https://asd.gsfc.nasa.gov/firs/
- NASA: "Habitable Exoplanet Observatory (HabEx)," https://www.jpl.nasa.gov/habex/
- NASA: "The Lynx Mission Concept," https://wwwastro.msfc.nasa.gov/lynx/
- NASA: "LISA: Laser Interferometer Space Antenna," https://lisa.gsfc.nasa.gov/
- NASA: "Nancy Grace Roman Space Telescope," https://www.nasa.gov/content/goddard/nancy-grace-roman-space-telescope
- NASA: "Mars Exploration Program Missions," https://mars.nasa.gov/programmissions/
- NASA: "Jet Propulsion Laboratory Missions," https://www.jpl.nasa.gov/missions/
- "NASA Science," https://science.nasa.gov
- NASA: "Artemis," https://www.nasa.gov/specials/artemis/
- NASA: "Mars Sample Return Mission," https://mars.nasa.gov/msr/

Scope Title: Scope 2: Digital Engineering Applications

Scope Description:

The explosion of MBx (model-based anything) has led to a proliferation of models, modeling processes, pedigree of models and associated data, 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 "authoritative source of truth," others are looking for the generation and exploration of massive trade spaces. Both greater precision and greater robustness will require addressing a number of cross-cutting challenges. This explosion of interoperability, via Digital Transformations, or Model-Based Anything, has led us to create this second focus area.

NASA seeks innovative methods and tools addressing the following needs: Define, design, develop, and execute future project and programs by developing and utilizing advanced methods and tools that fully integrate all of the digital engineering and science activities across the entirety of the project/program lifecycle and allow for interagency/NASA-industry collaboration and datacentric information exchange. Ideally, the proposed solutions should leverage standard industry tools where at all possible, allow for easier integration of disparate tools and data, and be compatible with current NASA science and systems engineering processes.

There is specific interest in the integration of tools and data for rapid generation of function or behavior of complex systems, at either the system or the subsystem level across all lifecycle phases from a datacentric approach and an integrated design/science environment between NASA and its various partners:

- To support emerging collaboration between NASA and domestic industry and international program partners, understanding standard approaches to integrating toolchains and data models, while protecting International Traffic in Arms Regulations (ITAR) and/or proprietary information.
- To support integration of existing toolchains and workflows.
- To be capable of using/developing standardized ontology/ies to enable modern information exchange, integration, and contract data deliverables to ensure all parties receive the information needed in the format expected and most useful, all the while minimizing integration of the productions of multiple suppliers.
- To be capable of standardizing model complexity to optimize complexity vs. managing, sustaining, and model proliferation.
- The ability to provide a standard approach for the validation of models, for customizing these validations, and for profiling this pedigree along not only with the model itself, but also with the data generated/provided by said models.

Note that this topic area focus is focused on Digital Transformation and is a special case of the broader topic.

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

- Research
- Analysis
- Prototype
- Software

Desired Deliverables Description:

We seek innovative solutions that address NASA needs to integrate engineering and science activities across the program/project lifecycle. The solution can investigate processes, data products, translation between the lifecycle gates. The goal is to support streamlining of engineering or science business processes, achieving high-value collaboration and interaction, and accelerate risk-informed and evidence-based decision making. The Phase I products and deliverables should identify a Phase II plan that will provide a more NASA-focused/relevant collection of products and deliverables that support integrating complex and disparate data into cohesive patterns.

State of the Art and Critical Gaps:

The current, relevant shortfalls in the state of the art in this area includes:

1. Each discipline tends to have their own tools and toolchains.
2. Tools and models are emerging, but they may not be consistent with each other. These inconsistencies also occur at the workflow/process level and lower at the data exchange level.
3. A lack of a common architectures and approaches for validating data source(s) that fit within the NASA workflow. These separate but connected Authoritative Sources of Truth are often a source of conflict during the project life cycle.
4. Vendors may provide portions of the toolchain and are often incompatible with each other. This often forces a variety of inefficiencies on NASA, including: (1) requiring manual data entry, or worse, data checking; (2) choosing the "least worst" monolithic solutions; (3) making it difficult for NASA to implement cultural changes; (4) making it difficult for NASA to avoid duplicative efforts, or worse, contradictory efforts; and (5) making it difficult for NASA to leverage/utilize merging technology breakthroughs.

Relevance / Science Traceability:
NASA's Robotic and Human Exploration efforts are complex, challenging endeavors. Requirements for any/all of these programs and projects trace back to science; either science we are doing now or science that will be enabled. Traceability between and among requirements is key, and in particular, the traceability from any given requirement to the science source(s) and reference(s) that it traces to. This traceability will lead to interoperability and NASA's endgame goal: to be able to integrate seamlessly between engineering, science missions, and operations with a deeply integrated approach to tooling and data exchange across NASA and all of its partners.

References:

- INCOSE: "Systems Engineering Vision 2035," https://www.incose.org/about-systems-engineering/se-vision-2035
- "NASA Science," https://science.nasa.gov
- NASA: "Artemis," https://www.nasa.gov/specials/artemis/
- NASA: "Mars Sample Return Mission," https://mars.nasa.gov/msr/
- NASA: "Mars Exploration Program Missions," https://mars.nasa.gov/programmissions/
- 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 and space 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 for both Earth and space weather. The current state-of-the-art simulations remain coarse enough that the physics of certain phenomena cannot be modeled at the current grid scale. Therefore, subscale or subgrid parameterizations are used as approximations to a full physics model, such as for convection, microphysics, turbulence, radiation, cloud

cover, and more. These parameterizations rely on heuristic approaches that are highly time consuming, are computationally intensive, and can result in large uncertainties.

NASA is seeking proposals that apply artificial intelligence (AI), machine learning (ML), and/or deep learning (DL) in support of model parameterization to improve efficiency of the model runs and the accuracy of model forecasts. Further, NASA is highly interested in approaches to subgrid parameterizations that are physically constrained, explainable, and have well defined uncertainties. As an alternative to traditional methods of model parameterization, the application of AI/ML/DL methods have the potential to result in a more complete state of the natural system while supporting faster and better forecasts for the following:

- Short term, to understand the risk for localized extreme events.
- Longer term, for seasonal to subseasonal and potentially decadal predictions.
- Retrospective reanalysis, to provide a more accurate historical record.

Proposals MUST specify and be in alignment with existing and/or future NASA/NOAA. 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 any resulting data products will be publicly accessible.

In general, the desired outcomes for this subtopic include, but are not limited to, the following:

- New methods, approaches, and/or applications for model parameterization that can be used and infused into NASA/NOAA simulations.
- Labeled training data sets and trained models specifically for 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 that include 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 are making large strides in the use of AI technologies (which include both ML and DL). This subtopic is looking to improve this by providing trained models that have the possibility of creating a better understanding of the state of the physical system (i.e., Earth, solar wind, etc.) to improve predictability, 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:

This subtopic has broad applicability across the decadal surveys and satellite development requirements to improve the quality and granularity of system forecasts:

- Improved measurements could provide better gap analysis for future mission requirements.
- Global Modeling and Assimilation Office (GMAO): Improved model parameterizations for increased computational performance and more accurate short-term, seasonal-to-subseasonal, and retrospective forecasts.
- Goddard Institute for Space Studies (GISS): Improved model parameterizations for increased computational performance and more accurate decadal and retrospective forecasts.
- Carbon Cycle Ecosystems Office (CCEO): Wide variety of applications, given the diversity of data sets from sparse in situ to global satellite measurements.
- The Community Coordinated Modeling Center (CCMC): A multi-agency partnership performing research on space science and space weather models; improve predictability of short-term forecasts.
- Earth Science Technology Office (ESTO/AIST): New technology and services to exploit NASA and non-NASA data leading to digital twins of physical systems.
- NOAA Joint Center for Satellite Data Assimilation (JCSDA) - Joint Effort for Data assimilation Integration (JEDI)
- NOAA Global Forecast System (GFS
- 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:

- 2017-2027 Decadal Survey for Earth Science and Applications from Space
- The most recent NASA Science Decadal Surveys: https://science.nasa.gov/about-us/science-strategy/decadal-surveys
- 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, 50–51, 2013, https://doi.org/10.1002/swe.20022
  - National Research Council: "Solar and Space Physics: A Science for a Technological Society," Washington, DC, The National Academies Press, https://doi.org/10.17226/13060
- NASA Global Modeling and Assimilation Office: https://gmao.gsfc.nasa.gov/
- NASA Goddard Institute for Space Studies: https://www.giss.nasa.gov/
- NASA Earth Science Data: https://earthdata.nasa.gov/
  - The Community Coordinated Modeling Center: https://ccmc.gsfc.nasa.gov
- NOAA Joint Center for Satellite Data Assimilation (JCSDA) - Joint Effort for Data assimilation Integration (JEDI)
  - https://www.jcsda.org/jcsda-project-jedi
- NOAA Global Forecast System (GFS)
  - https://www.ncei.noaa.gov/products/weather-climate-models/global-forecast
- NASA Center for Climate Simulation: https://www.nccs.nasa.gov/
- NASA High-End Computing (HEC) Program: https://www.hec.nasa.gov/

- PUBLIC LAW 115-25—APR. 18, 2017: "Weather Research and Forecasting Innovation Act of 2017."
- 2019 OSTP/OMB memo: "Fiscal Year 2021 Administration Research and Development Budget Priorities."

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. Manufacturing and construction approaches tailored to the Lunar environment will pave the way toward addressing challenges such as lowering the cost of exploration and enabling efficient, reliable operations in extreme environments. The Materials Research, Advanced Manufacturing, Structures, and Assembly focus area seeks innovative advanced materials processing and structural concepts that enable effective use of in-situ resources to establish planetary infrastructures that can support affordable and reliable Lunar surface operations. Integration of advanced tools to accelerate the implementation of the required technologies is critical to closing gaps in the systems architecture.

Since this focus area covers a broad area of interest, 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 to 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 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 [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 laboratory 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

Subtopic Introduction:
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 launch volumes are of high interest for long-duration, exploration-class missions. Currently, NASA and several companies in the space industry are developing inflatable space structures under the Next Space Technologies for Exploration and Partnerships (NextSTEP) and Commercial Low Earth Orbit (LEO) Destinations (CLD) programs, to which the research under this subtopic could be directly applied. This subtopic seeks activities to mature inflatable softgoods through the integration of sensing capabilities for structural health monitoring and development of accelerated test techniques to reduce the time of long-duration creep testing of candidate webbing and cordage materials.

Scope Title: Structural Health Monitoring for Inflatable Softgoods

Scope Description:
Integrated sensing capabilities in crewed inflatable softgoods systems are critical to monitoring the performance of the structural restraint layer in situ over long-duration missions. This can include measuring load/strain, detecting damage and impacts, and predicting 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 gages, 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 multilayer softgoods structure and continually monitor performance throughout its life. The proposed work should seek to demonstrate not just a sensor, but the approach and method to its robust integration into a high-strength synthetic webbing or cord (e.g., Vectran or Kevlar), with consideration of the ingress/egress of any wiring and connectors if required, and where/how the control electronics are attached and located. Innovative solutions to the following system properties and requirements are sought and should be considered in the specification and design of any proposed structural health monitoring (SHM) system:

Primary properties of interest for a sensor system (individual or combined sensing):

- Strain, load, and/or impact detection (magnitude and location) in structural restraint layer:
    - For strain measurement (long-duration creep), sensors must be able to tolerate an initial strain of 2 to 5% while the inflatable deploys, then must be sensitive to 0 to 0.5% creep strain once in service, with enough resolution to track those changes over the mission life (i.e., there may only be 0.1% change over a year).
    - For load measurement, typical high-strength webbings and cordage used in these structures can have operational loads of up to 5,000 lb/in., i.e., a 2-in.-wide webbing could operate at 10,000 lb.
    - For damage or impact detection, the desire is to have enough coverage of sensors to localize where damage has occurred and be able to evaluate its severity. This would ideally be combined with or utilize the strain or load sensing capability.

Sensor System Softgoods Integration Focus:

- There should be a strong focus on the method and vetting of integration of any sensor system with high-strength webbing and/or cordage that makes up the structural restraint layer.
- The impact on the properties of the softgoods due to the integration of the sensor system should be addressed, i.e., bonding, coating, integration of new yarns, and integration, attachment and ingress/egress of any wiring or control hardware needed.
- Complexity and additional work added to integrate and operate the sensor system should also be considered for its impact on the fabrication process of the inflatable structure and any additional work required on the mission to operate or read data from the system.
- Desire is to have a system with broad applicability to different inflatable architectures.

Other Desired System Properties:

- Minimize mass, power, and required auxiliary components where possible.
- Automated system activation and data readout, i.e., does not require astronaut or external agent.
- Launch and mission environment (consideration of path to flight):
    - Survive handling, integration, and packaging/deployment from a compressed state.

    - Survive launch environment and cold vacuum prior to system deployment (once deployed the structural layer is near the interior, thus operation at close to room temperature is possible).
    - Mission life of up to 15 years without maintenance.
- Ability to collate/unify distributed sensor system data to track structural health and predict further degradation/potential failures.

Design Notes:

- The structural layer where the sensors are needed has multiple softgoods layers in front and behind it as part of a multilayer system; thus, is nonaccessible or observable during the mission, and the layer is in close contact with the layers around it.
- The outer layers typically have multilayer insulation (MLI), which incorporates thin metallic depositions. If wireless sensing equipment is to be used externally, this should be considered for any possible interference.
- The interior of the inflatable structure will likely have a large amount of logistics deployed and installed once the structure is inflated, which could obscure direct access to large portions of the shell from the interior. In addition, these structures should be considered for any possible interference they may cause to wired or wireless sensor systems.

For this activity, a system concept that addresses the desired properties above and preliminary breadboard testing would be expected under Phase I on an applicable high strength softgoods component(s) as a proof of concept. Integration into an inflatable softgoods structure or higher fidelity subcomponent test(s) is expected as part of Phase II to validate the feasibility of the approach and how it would be scaled to a full-scale crewed inflatable structure.

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:

Approach to SHM for inflatable softgoods identified and a laboratory proof of concept to establish the efficacy of approach. Phase I demonstrates a system concept that addresses the desired properties specified in the scope and preliminary breadboard testing on an applicable high-strength softgoods component(s).

Phase II:

Integration into an inflatable softgoods structure or higher fidelity subcomponent test(s) to validate the feasibility of the approach and how it would be scaled to a full-scale crewed inflatable structure.

State of the Art and Critical Gaps:

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 multilayerered and fundamentally different from typical rigid habitat structures. New techniques, such as flexible electronics, wireless systems, and fiber optics, are also generally unproven in a flight scenario for SHM and must be robust enough to integrate, package, and deploy with the inflatable structure.

Relevance / Science Traceability:

Current work on inflatable softgoods is taking place under NASA's NextSTEP Habitat program and the CLD program. NextSTEP has been ongoing since 2016 and focuses on design of next generation habitat systems for cislunar space, the lunar surface, and Mars transit scenarios. CLD is focused on the next generation of orbiting space station. The work under this subtopic will strongly complement ongoing work under these programs and increase the potential for infusion of inflatable softgoods into future habitation concepts by reducing risks associated with understanding and predicting material behavior prior to and on a mission. Work could also serve to benefit entry/descent/landing systems that use inflatables, and terrestrial applications for integrated sensing and long-duration characterization of high strength softgoods materials that have wide use in industry and military.

References:

- Jones, Tom and Litteken, Doug. "Certification Guidelines for Crewed Inflatable Softgoods Structures." JSC-67721. https://ntrs.nasa.gov/citations/20220011425
- Litteken, Doug. "Inflatable Habitat Inspection Needs." In-Space Inspection Workshop. 2017 31 January. https://www.asnt.org/~/media/Files/Events-Meetings/Conferences/ISIW/2017/3a_4_Litteken_NASA-JSC_Inflatable-Habitat-Inspection-Needs
- Valle, Gerard, Litteken, Doug, and Jones, Tom. "Review of Habitable Softgoods Inflatable Design, Analysis, Testing and Potential Space Applications." AIAA SciTech. January 2019.
- Litteken, 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
- Valle, Gerard, Edgecombe, John, and de la Fuente, Horacio. "Damage Tolerance Testing of a NASA TransHab Derivative Woven Inflatable Module." 50th AIAA/ASMESCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference. 4-7 May 2009. https://arc.aiaa.org/doi/10.2514/6.2009-2167

Scope Title: Accelerated Creep Testing for Softgoods

Scope Description:

In implementing inflatable softgoods in habitation structures, one of the primary long-term risks 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 months to years, therefore new test methods need to be developed to reduce the time of long-duration creep testing of candidate webbing and cordage materials to help reduce the overall development time of softgoods structures for flight. Creep testing is currently a schedule driver for this class of structures. NASA has performed real-time creep testing of Vectran, and Kevlar webbings rated at 6,000 lb/in. and 12,500 lb/in. This data can be provided as a verification and validation data set to compare to an accelerated technique. These materials and load ratings are typical for inflatable habitats, but it is desirable that the proposed methodology could be applied to other high-strength synthetic webbings and cordage.

Typical creep acceleration methods using stepped isothermal or isostress approaches have had poor correlation to real-time results to date. Elevated temperatures affect the oils and sizing applied to the softgoods components, which may change the interfiber frictional properties and mechanical behavior, in parallel to the creep behavior. In addition, the stepped isostress approach is impacted by the nonlinear, stress-dependent behavior of these components that are often dominated by the architectural/constructional strain (decrimping) at stresses below ~50% of ultimate, versus being driven by the elastic strain of the fibers above that.

Properties of Proposed Approach:

- May include novel test methods to reduce the duration of the test, while minimizing test effects on parameters outside of creep.
- May include combination of test methods and modeling approaches to accelerate generation and capture of creep data that can accurately characterize the long-duration behavior of the softgoods.
- If elevated temperature test approach is used: Addresses thermal effects on the material that may occur in parallel to the creep behavior and incorporates that in the post-processing of the data.
- If elevated stress test is used: Addresses impact of nonlinear mechanical behavior effects on the creep response and incorporates that in the post-processing of the data.
- Can be performed in a typical mechanical load frame with environmental chamber (if needed).

It is understood that procuring and testing these specific materials under Phase I is challenging, thus demonstration and detailing of accelerated approaches can be performed on different materials and strengths of webbing and/or cordage if they address the issues mentioned and can be validated as doing so. Collaboration with industry or university partners is encouraged. Phase II work would be expected to apply the methodology and approach more generically to a series of materials of interest and demonstrate it via test and comparison to real-time testing.

Expected TRL or TRL Range at completion of the Project: 2 to 3
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

Desired Deliverables Description:
Phase I:
Demonstration and detailing of accelerated approaches; performance of testing on different materials and strengths of webbing and/or cordage.

Phase II:
Apply the methodology and approach more generically to a series of materials of interest and demonstrate it via test and comparison to real-time testing.

State of the Art and Critical Gaps:
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 (1) burst and (2) creep to failure 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, reduce development time, and reduce risk.

Relevance / Science Traceability:
Current work on inflatable softgoods is taking place under NASA's NextSTEP Habitat program and the Commercial LEO Destinations (CLD) program. NextSTEP has been ongoing since 2016 and focuses on design of next generation habitat systems for cislunar space, the lunar surface, and Mars transit scenarios. CLD is focused on the next generation of orbiting space station. The work under this subtopic will strongly complement ongoing work under these programs and increase the potential for the infusion of inflatable softgoods into future habitation concepts by reducing risk associated with understanding and predicting material behavior prior to and on mission. Work could also serve to benefit entry/descent/landing systems which use inflatables, and terrestrial applications for integrated sensing and long-duration characterization of high-strength softgoods materials that have wide use in industry and the military.

References:
Jones, Tom and Litteken, Doug. "Certification Guidelines for Crewed Inflatable Softgoods Structures." JSC-67721. https://ntrs.nasa.gov/citations/20220011425
Jones, T. C., Doggett, W. R., Stanfield, C., and Valverde, O. "Accelerated Creep Testing of High Strength Aramid Webbing," AIAA 2012-1771. 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference. April 2012.
Valle, Gerard, Litteken, Doug, and Jones, Tom. "Review of Habitable Softgoods Inflatable Design, Analysis, Testing and Potential Space Applications." AIAA SciTech. January 2019.
Le Boffe, Vincenzo, Jones,Tom, and Kenner, Winfred. "Development of a Compact, Low Cost Test Fixture to Evaluate Creep in High Strength Softgoods Materials Under Constant Environmental Control." https://ntrs.nasa.gov/citations/20205005004

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:
Nondestructive evaluation (NDE) is the use of nondestructive interrogating energy to determine the integrity of materials. NDE activities can also be considered nondestructive inspection (NDI) or nondestructive testing (NDT). Systems interrogated may be organic or inorganic, simple or complex, and may be structural or nonstructural.

Flight fracture-critical components used in NASA missions require inspection and often require adaptation of advanced NDE technologies in order to be applicable for flight. Nondestructive integrity determination includes characterization of engineering properties, strain, stress, load verification, cracks, voids, inclusions, disbonds, delaminations, bonding, corrosion, erosion, constitutive components, volume fraction, orientation, impact damage, age, pressure, mass loss, mass gain, thinning, alignment, thermal diffusivity, emissivity, leaks, signature, contamination, elements, etc.

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), lunar regolith, 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. 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. This includes systems that can help identify flaws such as cracks, as well as systems that can help locate and characterize leaks on the International Space Station (ISS) or Gateway. 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, 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, such as 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.

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 NDE 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 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). Other related topics of high interest for in-space NDE, related to exploration and geotechnical characterization, include field-portable solutions for ground-penetrating radar (GPR), acoustic/vibration-based measurements (seismography), and regolith/drill core sample analysis (e.g., to determine density, composition, ice content, etc.).

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 additively manufactured parts in space. These parts may be manufactured in an additive manufacturing (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 AM, 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.

NASA's NDE SBIR program is developing and implementing tools for future use on NASA's most critical missions. NDE requires development and constant improvement of tools, methods, instruments, and personnel. Development activities in the SBIR NDE program range from development of cutting-edge software to hardware prototype development. Development and deployment of these NDE systems with properly trained personnel is the goal of the NDE SBIR program for NASA's current and future missions.

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 to a TRL of 2 to 4.

All Phase 1 proposals will include 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. Solicitations for assessing structural health of lunar habitats will also be considered.

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:

- Burke, E. R.; Dehaven, S. L.; and Williams, P. A.: Device and Method of Scintillating Quantum Dots for Radiation Imaging. U.S. Patent 9,651,682, Issued May 16, 2017.
- 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.
- 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.
- 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.
- 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.
- 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.
- 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.
- 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.
- 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.
- 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.
- 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.

- 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.
- 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.
- Gregory, E. D.; Campbell Leckey, C. A.; Schneck, W. C.; Swindell, P: A Versatile Simulation Framework for Elastodynamic Modeling of Structural Health Monitoring; https://ntrs.nasa.gov/citations/20190001865.

Z4.07: Advanced Materials and Manufacturing for In-Space Operations (SBIR)

Lead Center: LaRC
Participating Center(s): MSFC

Subtopic Introduction:
Planned sustained exploration of the Moon, and eventually Mars, is dependent on the utilization of in-situ sourced resources. There are currently a number of In-Situ Resource Utilization (ISRU) efforts focused on the extraction and primary refinement of these resources. However, there are still significant gaps in the essential conversion of the raw resources into useful products. A look at terrestrial industrial production shows the complexity of the processes that are required to make even the most commonplace products. For the successful utilization of ISRU-derived resources, first on the Moon and then on Mars, there is going to be the need to develop processes and machinery that work in those environments to enable manufacturing from the available raw materials. This subtopic is scoped to cover processing of metallic and cementitious raw materials extracted from regolith to support the establishment of the envisioned lunar infrastructure.

Scope Title: ISRU-Based Metallic Structural Elements for the Assembly of Lunar Infrastructure

Scope Description:
As humanity returns back to the lunar surface for sustained exploration, there is an emphasis on building infrastructure that is based on ISRU [1-6]. Conversion of the raw resources produced by ISRU extraction into useful components requires manufacturing processes and equipment that are capable of operating in the lunar environment subject to various constraints.

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 the construction of lunar infrastructure.

In this solicitation, proposals are invited for approaches that utilize aluminum (Al), iron (Fe), and mongrel alloys produced from ISRU to produce structural angles, rods, and tubes in the lunar South Pole region. Typical components for a structural truss would be:

- Truss cross-section
    - Square rod: 5 mm, 10 mm, 15 mm square
    - Angle: flange length 10 mm, 20 mm, 40 mm; flange thickness 1.0 mm, 2.0 mm, 4.0 mm, 6.0 mm
- Length: 0.75 m, 1.0 m, 1.5 m
- Quantity: 564 for one 50-m-tall tower

Proposals to the current solicitation can assume the metals extracted and processed in the ISRU activities to be available in molten form at purity levels ranging from less-refined mongrel alloys (slag) to 99% pure metal. The selection of a particular material for the manufacturing must take into account a demonstrated or projected ability to support tensile and bending loads in the lunar gravity environment and include justification for its proposed producibility and performance. Note that stress levels found in some early lunar infrastructure designs are relatively low due to reduced gravity and operational loads, thus resulting in the potential utility of lower strength materials such as untempered 1-series aluminum. For example, truss elements from 99% pure aluminum should target properties of 1-series untempered material: Modulus = 10 Msi, Yield strength = 5 ksi, density = 0.098 lbs/in^3.

Proposal elements of interest include, but are not limited to, the following:

- Equipment required for the efficient production of truss elements that address the size/scale, power requirements, production rates, molten material handling, and operating environments.
- Equipment and production systems that account for limited availability of resources such as coolant on the Moon in forming and processing the metal to provide the desired performance.
- Proposals must account for the mechanical performance, straightness, and finish that is required and achievable to ensure performance of the elements, as well as their subsequent joining and other operations.
- Preliminary proof-of-concept experiments for feasibility of the proposed material systems, processing methods, and equipment.
- Concepts that will be able to routinely produce hundreds of elements during a given production cycle.
- Concepts for the extension of the process to other structural forms, including thin plates and tubes.

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.X Other Manufacturing, Materials, and Structures

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I will provide concepts for demonstration of the production of structural truss elements (rods and angles) on the lunar surface given the available resources. The concept will include the equipment that would be required and how that equipment succeeds in operating in the lunar environment.

Phase II would look at pilot scale demonstrations of the materials processing capabilities needed to produce the structural elements. These would include designing and building of relevant equipment and potential processing of commercially available material that may match the materials expected to be available on the Moon, either in raw form or from other processes.

State of the Art and Critical Gaps:

Sustainable long-term exploration of the Moon will be dependent on the utilization of lunar resources. While there are various efforts looking at the excavation and initial processing of those lunar resources, there are currently gaps in understanding the detailed process requirements for converting various material feedstocks into useful products. These require understanding of the material properties through the process cycle and how these would be impacted 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. Among the envisioned futures for infrastructure construction on the lunar surface is robotic assembly of truss-based structures, which directly addresses the following:

- Blueprint Objectives:
    - LI-1 Development of a Global Power Grid.
    - LI-3.1 Industrial Scale Construction Capabilities – Roads with Autonomous Navigation Aids and Assembly of Towers.
- STMD Strategic Thrust, “Live: Sustainable Living and Working Farther from Earth.”
- Several STMD technology gaps associated with assembly of infrastructure (tall towers, blast containment shields, shelters, habitats).

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 07/23/2022].
2. Lunar Sourcebook, edited by Grant H. Heiken, David T. Vaniman, Bevan M. French, 1991, Cambridge University Press. https://www.lpi.usra.edu/publications/books/lunar_sourcebook/ [accessed 09/11/2022].
3. 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 07/23/22].
4. Gerald (Jerry) Sanders, Aspects of ISRU on the Moon NASA Perspective I, National Academies of Sciences, Engineering, Medicine Decadal Survey on Planetary Science and Astrobiology: Panel on Mercury and the Moon, August 6, 2021. https://www.nationalacademies.org/event/08-06-2021/docs/D82946FD16B3AE425055B6FF5C4711A22E17EA36D81C [accessed 07/26/22].
5. Geoffrey A. Landis, Materials Refining for Solar Array Production on the Moon, NASA/TM—2005-214014. https://ntrs.nasa.gov/api/citations/20060004126/downloads/20060004126.pdf [accessed 07/26/2022].
6. Geoffrey A. Landis, Materials refining on the Moon, Acta Astronautica, Volume 60, Issues 10–11, 2007, Pages 906-915, ISSN 0094-5765. https://www.sciencedirect.com/science/article/pii/S0094576506004085 [accessed 07/26/22].

Scope Title: Using In-Situ Resource Utilization (ISRU) Process Waste for In-Situ Manufacturing and Construction

Scope Description:
Objective: Develop the capability via intentional technology to take byproducts and waste products from ISRU oxygen-extraction processes and turn them into cement precursors, metal powders or wire/filament, or other material for advanced in-situ manufacturing and in-situ construction.

Proposals should address taking waste products from ISRU oxygen-extraction processes and turning them into cement precursors, metal powders or wire/filament, or other materials (e.g., processing carbon scrubber waste into polymer feedstock) that could be used for (1) in-situ advanced manufacturing, (2) construction, or (3) outfitting of infrastructure element (habitats, shelters, landing pads, blast shields, roads, etc.).
Proposals should

- Describe the process, including chemical methods, energy usage, and a flight-readiness assessment of the process.
- Provide samples of in-situ manufacturing or construction material to be characterized at an independent lab.
- Include a presentation describing the work and interpreting the results.

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.X Other Manufacturing, Materials, and Structures

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Proposal deliverables should include a document describing the process, including chemical methods, energy usage, and a flight-readiness assessment of the process; samples of in-situ manufacturing or construction material to be characterized at an independent lab; and a presentation describing the work and interpreting the results.

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:

State of the Art:

- At present there are additively constructed house neighborhoods in Austin, TX, and southern Mexico with a level of secure remote operations capability.
- NASA Lunar Plume Alleviation Device (PAD) Team. A project by the NASA Proposal Writing and Evaluation Experience (NPWEE) team that won their proposal effort. A landing pad design (20-ft diameter, subscale) was printed at Camp Swift in Bastrop, TX. Subsequent hot fire testing proved their design does keep the surrounding regolith from being disturbed.
- Army Corps of Engineers demonstrated development of forward operating base construction technologies (Additive Construction of Expeditionary Structures) at Champaign, IL.
- Ductile iron and steel alloys were produced from ionic liquid extracted materials from martian regolith simulant and Bosch carbon from an environmental control and life support systems reactor experiment.

Critical Gaps:

- Full-scale lunar (in-situ) hardware.
- Autonomous surface operations.
- In-situ material utilization to minimize launch mass. "Living off the Land" and remote construction. Examples of desired infrastructure are power plants, habitats, refineries and greenhouses, launch and landing pads, and blast shields.
- Lack of in-situ design and analysis criteria, engineering standards, and fabrication of mechanical, electrical, and plumbing (MEP) system components.

Relevance / Science Traceability:

- This technology is very much applicable in the Space Technology Mission Directorate's (STMD's) support of NASA, other Government agencies, and industry customers.
- STMD for Science Mission Directorate (SMD) - Radio telescope structural support (far side of the Moon).
- Exploration Systems Development Mission Directorate (ESDMD) and Space Operations Mission Directorate (SOMD) Human Habitats - Space infrastructure, as in buildings, landing pads, roads, berms, radiation protection, custom building sizes and shapes.
- Aeronautics Research Mission Directorate (ARMD) and Earth-based Government agencies - In-situ construction capabilities both locally and remotely.
- Rapid construction - small building within 24 hours.

References:

Don’t Take It – Make It: NASA’s Efforts to Address Exploration Logistics Challenges Through In Space Manufacturing and Extraterrestrial Construction for Lunar Infrastructure. R.G. Clinton, Jr., PhD; Tracie Prater, PhD; Jennifer Edmunson, PhD; Mike Fiske; Mike Effinger. Novel Orbital and Moon Manufacturing, Materials, and Mass-efficient Design (NOM4D) Kick-Off, December 14-15, 2021.
https://ntrs.nasa.gov/api/citations/20210025774/downloads/NOM4D%20KO%2012.15.2021.pdf

Scope Title: Integrated Computational Materials Engineering (ICME) for In-Space and Extraterrestrial Surface Operations

Scope Description:

In-space and lunar- and Martian-surface-based metals manufacturing will be enabling to surface power transmission and communications infrastructure to enable a lunar economy; to structures, habitats, outfitting, and repair; and to the manufacture of large-scale vehicles, habitats, and instruments. Currently there is limited information on how materials react to processing in microgravity and low-gravity environments across a variety of processes required to generate feedstock from in-situ resources and a variety of processes that will be used to manufacture components. For commercial interests to be successful delivering these capabilities in the longer term, an understanding of what feedstock and what quality of component can be delivered is needed. ICME is ideal for these early efforts. Experimental approaches are costly and limited compared to the wide range of processing options, and ICME has reached a readiness that can inform and effect later decisions as to preferred processing methods. Modeling techniques that capture the physical extremes of space, such as variable gravity, temperature, and atmosphere, are of greatest importance. Anchoring of models to relevant data sets and generation of new empirical data sets are of interest.

Space and the lunar and Martian surfaces present an extreme set of environments that require novel manufacturing and materials solutions to fully deploy and expand human exploration, enable colonization, and make possible the exploitation of in-situ resources. Manufacturing and materials processing in those locations are subject to variable gravity, vacuum or reduced pressure, and large temperature variations compared to terrestrial processing conditions. Currently, there are no available processing parameters that account for these physical changes, and thus, critical manufacturing processes cannot be performed. Examples of critical manufacturing processes include welding, cutting, forming, additive manufacturing, and machining (such as drilling/milling).

In this solicitation, proposals are invited for approaches that develop virtual manufacturing frameworks for the manufacturing of in-space, lunar, and Martian resources such as aluminum and iron derived from ISRU using ICME approaches. All stages of the processing of regolith and recycling of existing metals in space to manufacturing a structure with joining processes are of interest for the current proposal solicitation.

Proposal elements of interest include, but are not limited to, the following:

1. A virtual model that can demonstrate materials behavior in the environment of space, the lunar surface, or the Martian surface.
2. A virtual model that shows a materials response to manufacturing processes in the environment of space, the lunar surface, or the Martian surface.
3. A design or prototype of a physical testbed that could be used to demonstrate materials processes at the coupon level in the environments of space, the lunar surface, or the Martian surface. The testbed could be ground based or designed for flight experiments (either in parabolic flight or in space).

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:

- Hardware
- Software
- Prototype
- Analysis

Desired Deliverables Description:

Phase I will provide concepts of a testbed or a framework of a virtual model for demonstration of the behavior of materials for manufacturing in space, on the lunar surface, or on the Martian surface. The concept for a testbed will describe the equipment that would be required and how that equipment succeeds in operating in the environment of space, lunar surface, or Martian surface. The framework of a model will be able to demonstrate the behavior of a material under processing conditions in space, on the lunar surface, or on the Martian surface.

Phase II would look at pilot scale demonstrations of the materials processing and modeling capabilities. These would include prototyping a materials processing testbed and demonstrating its capabilities on Earth, and demonstrating the function of a high-fidelity virtual process model that could compare processing behaviors and conditions of materials between Earth and one of the following environments: space, the lunar surface, or the Martian surface.

State of the Art and Critical Gaps:

A vibrant lunar economy and sustained lunar presence by NASA will require the manufacture of products in space or on another celestial body. Goals such as nuclear thermal propulsion (NTP) vehicles and large observatories will benefit from welding and other manufacturing operations performed in space. These efforts will be developed most efficiently with an understanding of the effects on processing in space and surface environments such as variable gravity, vacuum or reduced pressure, and large temperature variations compared to terrestrial processing conditions.

There are many gaps associated with the use of these processes that can be more effectively addressed computationally before investing heavily in specific processes. Gaps addressed include:

- Lunar surface manufacturing and outfitting with metals.
- ISRU-derived materials for feedstocks (e.g., Al, Si) – lunar and Martian.
- Model-based technologies for materials, structures, and manufacturing.
- On-demand manufacturing of metals, recycling, and reuse.

Relevance / Science Traceability:

This topic has relevance to the following Space Technology Mission Directorate (STMD) Strategic Framework thrusts and outcomes:

1. Live: Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities.
2. Explore: Develop technologies supporting emerging space industries, including Satellite Servicing & Assembly, In-Space/Surface Manufacturing, and Small Spacecraft technologies.

Exploration goals will require the use of lunar and Martian resources to minimize the transport of materials and components from Earth. Commercial entities developing the lunar economy will require infrastructure that is most effectively manufactured on-site. Science missions will leverage the ability to manufacture large structures that do not have to sustain launch loads. The enabling processes for these efforts can be modeled through ICME, which will identify the next level of gaps to be addressed and will inform trade studies to help decisions with respect to funding specific processes.

References:

Sowards, J., et al. (2021). Topical. Permanent Low-Earth Orbit Testbed for Welding and Joining: A Path Forward for the Commercialization of Space [White Paper]. National Academy of Sciences' Decadal Survey. http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/623127/6378869/64-ad4bc01012d6dab107e27cf82a2a7b73_SowardsJeffreyW.pdf

Z14.02: Extraterrestrial Surface Construction (SBIR)

Lead Center: MSFC

Participating Center(s): KSC, LaRC

Subtopic Introduction:

As NASA works toward the development of a sustainable lunar presence and robust space economy, there will be a need for building significant lunar infrastructure, including a lunar power grid, launch/landing pads, shelters, and habitats. It is expected that a combination of regolith works (use of bulk regolith), structural assembly, and in situ construction (e.g., additively manufactured structures) and the use of in-situ resource utilization (ISRU) based materials and construction feedstock will be necessary to achieve the NASA Moon-to-Mars Objectives for construction of sustainable infrastructure on the lunar surface and then on to Mars. For example, assembly of structures such as truss-based power towers, arches for shelters, and domes for pressurized habitats could be initially constructed using Earth-sourced structural elements (trusses, panels, joints, etc.) but then transition to the use of ISRU-based elements as the ISRU processing and advanced manufacturing capabilities mature. Similarly, technologies for the in situ construction (i.e., additive manufacturing) of launch/landing pads (LLPs) as well as advanced shelter and habitat concepts is also an important focus area. Together these technologies will provide a robust suite of construction capabilities needed for global lunar infrastructure construction.

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 of up to 127 °C (261 °F) during sunlit periods and as low as -170 °C (-274 °F) during periods of darkness. These construction systems must also be able to operate for at least 2 years, with a goal of 5 years without substantial maintenance in the harsh lunar environment.
Phase I efforts can be demonstrated at any scale and will likely emphasize feasibility studies; Phase II efforts must be scalable up to anticipated product dimensions.

Another key area is associated with the outfitting of the infrastructure, i.e., in situ integration of subsystems into the structures, including wiring for power and data transmission, lighting, gas or fluid systems (Environmental

Control and Life Support System, which includes water, hydraulics, coolants, etc.), elevators and cranes (lifting aids), and other habitat or operational infrastructure or subsystems. To the extent reasonable, these subsystems can be pre-integrated into modules and the modules assembled in situ, which extends outfitting from within a structure to across structures. A fundamental attribute of outfitting is assembly; outfitting is thus distinct from deployment, because deployment does not require assembly. To the extent reasonable, outfitting can be accomplished autonomously; however, the specific agents (robotic or human) performing the outfitting are part of the co-design of the overall excavation, construction, and outfitting (ECO) system.

Scope Title: Extraterrestrial Surface Construction: Assembly of Tall Truss-Based Power Towers

Scope Description:
Assembly of truss-based structures is one of the leading candidates for establishing some of the early lunar infrastructure—for example, tall towers (50- to 80-m total height, which includes the attached payload height) for solar power generation, blast containment shields for launch and landing pads, shelters, etc. While structural assembly on Earth is a well-established construction approach, many technology gaps exist for the automated assembly of truss infrastructure on the Moon. Specifically, joining technologies and robotic tools are required to enable autonomous/automated assembly of these structures, which are often composed of hundreds of individual elements.

Proposals are invited for the development of assembly and joining concepts and the robotic tools required to assemble large-scale truss structures. The primary focus of this activity is the assembly of a tall (50- to 80-m class) truss-based tower. However, extensibility of the joining concepts and robotic tools to other structural assemblies is desirable. Joining methods can include, but are not limited to, mechanical fastening (e.g., rivets), welding, and bonding (both reversible and nonreversible approaches to joining). Proposals to the current solicitation can assume that the truss elements being assembled are between 0.75 and 1.5 m in length, with either an angle or square prismatic cross sections (cross-section dimensions listed below). It is expected that early assembly missions will use Earth-sourced truss elements and that these elements may be either aluminum or composite. However, over time, it is expected that ISRU-based aluminum truss elements will replace Earth-sourced elements for large-scale infrastructure development. Thus, concepts that support assembly of Earth-sourced and ISRU-based truss elements are favored. Finally, it is also assumed that a commercial space-capable robotic manipulating arm will be available and that proposals shall concentrate on the development of specialized robotic tooling required for assembly; however, it is desirable for proposers to specify the estimated infrastructure and robot capabilities assumed (reach, payload capacity, etc.).

Proposal elements of interest include, but are not limited to, the following:

- Joining concepts for assembly of composite and/or aluminum truss structures (including the joining method and any necessary fittings/tooling/jigging).
- Joint/node designs.
- Robotic tools for assembly that are compatible with commercially available robotic manipulator arms.
- Considerations for operating in lunar daytime environment (1/6 gravity, temperature, radiation, vacuum, lighting, power requirements).
    - Note: Proposal does not have to produce space-rated equipment; however, the processes shall be applicable to the lunar environment. Justification of design choices shall be included.
- Concepts that maximize structural efficiency, minimize power requirements and complexity, and maintain suitable tolerances during assembly (not to exceed a 1-degree tilt when assembled on a horizontal surface).
- Concept of operations describing process to assemble a tall tower using the robotic tools and joining methods developed.

- Description of the assumed robotic system(s) and infrastructure necessary for the proposed approach, including reach, payload, etc., of the individual robotic agents.
- Preliminary proof-of-concept demonstrations, methods, and equipment.
- Outline application to other truss-based assemblies, e.g., walls, arches, and domes.

Focused application for development: Assembly of a tall tower:

- Tower height: 50- to 80-m class.
- Tower payload: 1,500 kg at top of tower (250 kg Earth equivalent for 1/6 gravity loads).
- Assembly tolerance: Straight to within ±1-degree tilt when assembled on a horizontal surface.
- Factor of safety of 5 on buckling and 10,000 psi maximum stress.
- Assume assembly site is level to within ±2.5 degrees.
- Assume a suitable foundation/interface is available for assembly; however, proposals are free and encouraged to provide/derive their own foundation/interface requirements.
- NASA concept of operations (ConOps) = Module build and lift assembly approach (i.e., assemble a truss module, lift up and assemble the next module below, repeat until tower is fully erected).

Assume the following truss elements are available for use in the assembly:

- Truss element lengths: 0.75 to 1.5 m (it can be assumed that intermediate lengths can be obtained if necessary).
- Truss element cross section:
  - Square rod: 5 mm^2, 10 mm^2, 15 mm^2
    - Angle: flange length 10 mm, 20 mm, 40 mm; flange thickness 1.0 mm, 2.0 mm, 4.0 mm, 6.0 mm
- Truss material:
  - Earth sourced = aluminum 6061, graphite-epoxy
  - ISRU-based = 98% pure aluminum (properties similar to 1-series untempered aluminum; E = 10 Msi, yield >5 ksi)

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 must include the design and test of critical elements associated with the proposed joining and robotic technologies to assemble truss-based structures, leading to a 50- to 80-m-tall tower in Phase II. For example, joint designs, structural analysis, and associated fabrication and testing must be included. Phase I must also include a concept of operations for the assembly of the tower and the design and testing of the robotic assembly system concept. Phase I proposals should result in at least TRL 4 structures and robotic assembly system.

- NOTE: It is expected that not all element lengths or cross sections will be applicable to the design of a 50-m-tall tower; however, preference will be given to proposals with versatile approaches that accommodate larger combinations of the truss elements described above.

Phase II deliverables must include demonstration of a 50-m tower assembly. The tower is expected to be constructed using robotic systems and implements and joint designs developed in Phase I. Structures and systems must be developed to a minimum of TRL 5. Phase II assembly shall also include the integration and deployment of a surrogate 100-kWe solar array.

- NOTE: Proposers should be aware of a complementary SBIR topic scope on outfitting of wiring harnesses and junction boxes and may take advantage of potential synergies between topics.

State of the Art and Critical Gaps:

While civil engineering and construction are well-established practices on Earth, automated lunar applications remain at low TRLs. Large-scale lunar infrastructure will require the construction of towers, landing pads, shelters, and habitats, many of which can be accomplished by the assembly of common structural elements such as trusses and panels. To date, very few activities have been conducted to develop robotic assembly of large-scale truss-based structures such as 50- to 100-m-tall towers or arches for shelters and habitats. Most assembly technologies have been proof-of-concept and developed at a small scale. Thus, to accomplish large-scale structural assembly on the lunar surface, joining technologies and robotic assembly systems are needed.

NASA Moon to Mars Objectives: LI-1 Development of a Global Power Grid, and LI-3.1 Industrial Scale Construction capabilities – Roads with autonomous navigation aids & Assembly of towers.

The NASA Space Technology Mission Directorate (STMD) STARPort database currently includes four technology gaps related to assembly of structures, for example, power towers:

- Assemble truss-based tower.
- Structural elements for assembly.
- Structural joints/joining technology.
- Autonomy and robotics to assemble the tower.

Relevance / Science Traceability:

Robotic assembly of truss-based structures directly addresses the STMD Strategic Thrust "Live: Sustainable Living and Working Farther from Earth," and the following Moon to Mars Objectives:

- LI-1 Development of a Global Power Grid.
- LI-3.1 Industrial Scale Construction capabilities – Roads with autonomous navigation aids and Assembly of towers.

References:

- Doggett, William. "Robotic assembly of truss structures for space systems and future research plans." Proceedings, IEEE Aerospace Conference. Vol. 7. IEEE, 2002.
- Belvin, Wendel K., et al. In-space structural assembly: Applications and technology. 3rd AIAA Spacecraft Structures Conference, 2016.
- Komendera, Erik, et al. Truss assembly and welding by intelligent precision jigging robots. 2014 IEEE International Conference on Technologies for Practical Robot Applications (TePRA). IEEE, 2014.
- Moses, R.W., and Mueller, R.P. (2021). Requirement’s development framework for lunar in situ surface construction of infrastructure. Earth and Space 2021, pp. 1141-1155.

Scope Title: Foundations and Assembly Technologies for Lunar Landing/Launch Pad Structures

Scope Description:
Proposals are invited for the development of technologies for foundations and assembly of lunar landing/launch pad structures using advanced construction techniques and ISRU materials. Materials extracted from in situ lunar and planetary resources (e.g., materials extracted from the minerals in the regolith present on the surface) have the potential to radically reduce the cost and increase the scale of ambitious future space exploration activities and sustainable infrastructure. The design and fabrication of such systems and associated technologies so that construction and subsequent outfitting can be effectively accomplished locally is essential to their utilization. Design scaling for eventual outfitting should be considered.

Materials, components, and systems that would be necessary for the proposed technology must be able to operate on the lunar surface in temperatures up to 127 °C (261 °F) during sunlit periods and as low as -170 °C (-274 °F) during periods of darkness. 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., robots), and later astronauts, will be ongoing not more than tens of meters away from the local fabrication, construction, and/or outfitting activities. Phase I efforts can be demonstrated at any scale; Phase II efforts must be scalable up to relevant size.
Each of the following specific areas of technology interest may be developed as a standalone technology.

- Enabling foundation emplacement capable of withstanding the lunar seismic environment. Proposals should include the design of an interface with regolith that will allow for one or more of the following: (1) mitigation of lunar seismic activity for infrastructure element stability (e.g., flexible foundation designs and dampening); (2) “sealing” to the regolith (the physical interface between the integrated system and regolith that allows pressurization of structures placed on the foundation) to allow emplacement of a foundation material with relatively high vapor pressure in a temporary pressurized volume at a build site; (3) wear resistance of the foundation materials; and (4) structural anchoring technologies.
- Novel structural systems: Proposals should address novel structural systems for Human Landing System (HLS) lunar lander launch/landing pads that can be fabricated from as much local extraterrestrial material as possible, can be assembled locally with robotics and/or astronaut-assisted construction, and are designed for easy and effective maintenance to maintain performance. Some materials may be transported from Earth, but these should be minimized. Proposals should address the following attributes: low and/or predictable coefficients of thermal expansion, strength, mass, reliability, radiation protection, waste heat rejection in lunar or other planetary environments, energy efficiency, and cost. Design considerations for the outfitting of landing pads are encouraged.

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:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I proposal deliverables should include a document describing appropriate materials, design, interfaces, and behavior in the lunar seismic environment, as well as a presentation describing the work and interpreting the

results. Extensibility of the foundation concept to other lunar surface infrastructure elements such as tall towers, shelters, and habitats is desirable.

Phase II deliverables must be a demonstrated foundation concept to other lunar surface infrastructure element(s) in Earth 1g but should include design recommendations for mass reductions due to operations in lunar gravity (1/6 gravity) deployment.

State of the Art and Critical Gaps:
State of the Art:

1. At present there are additively constructed concrete house neighborhoods in Austin, TX, and southern Mexico with a level of secure remote operations capability.
2. NASA Lunar Pad Team - Subscale development of concrete landing pad printing and testing at U.S. Army Camp Swift, TX. October 2020.
3. U.S. Army Corps of Engineers, Engineering Research and Development Center (ERDC), Construction Engineering Research Laboratory (CERL), Development of forward operating base construction technologies, Champaign, IL.

Critical Gaps:

1. Technologies and lunar construction materials for larger scale development of Earth-based landing pads.
2. Autonomous operations and emplacement technologies.
3. In situ material utilization to minimize launch mass associated with raw materials capabilities: "Living off the land" and remote construction. Examples of desired infrastructure are power plants, habitats, refineries, greenhouses, launch and landing pads, and blast shields.
4. Design criteria and civil engineering standards for these first in situ infrastructure assets.
5. Thermal transfer of heat from plume impingement in a vacuum environment.
6. Mitigation of regolith blast ejecta from plume impingement.
7. Maintenance and repair for long lifetimes (>5 years).

Relevance / Science Traceability:
This technology is very much applicable in Space Technology Mission Directorate (STMD) support of its NASA, Government, and industry customers.

- STMD for Science Mission Directorate (SMD) - Radio telescope structural support (back side of the Moon).
- Exploration Systems Development Mission Directorate and Space Operations Mission Directorate (ESDMD-SOMD) Human Habitats - Space infrastructure, as in buildings, landing pads, roads, berms, radiation protection, custom building sizes and shapes.
- Department of Defense (DoD) and Earth-based Government agencies - In situ construction capabilities both locally and remote.

References:

- Gelino, N.J.; Mueller, R.P.; Moses, R.W.; Mantovani, J.G., Metzger, P.T., Buckles, B.C., and Sibille, L. (2021). 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.
- Moses, Robert W.; and Mueller, Robert P. Requirements Development Framework for Lunar In Situ Surface Construction of Infrastructure. Earth and Space 2021, pp. 1141-1155.
- Clinton, R.G., Jr., PhD; Prater, Tracie, PhD; Edmunson, Jennifer, PhD; Fiske, Mike; and Effinger, Mike. Don’t Take It – Make It: NASA’s Efforts to Address Exploration Logistics Challenges through In Space Manufacturing and Extraterrestrial Construction for Lunar Infrastructure. Novel Orbital and Moon

Manufacturing, Materials, and Mass-efficient Design (NOM4D) Kick-Off December 14-15, 2021. https://ntrs.nasa.gov/api/citations/20210025774/downloads/NOM4D%20KO%2012.15.2021.pdf

- Mueller, R.P.; Moses, R.; Wilson, D.; Carrato, P.; and King, T. (2020). Lunar Mega Project: Processes, Work Flow and Terminology of the Terrestrial Construction Industry versus the Space Industry. ASCE Earth & Space Conference (No. KSC-E-DAA-TN78054).

Scope Title: Outfitting of Lunar Surface Structures: Tall Truss-Based Power Towers

Scope Description:

The assembly and outfitting of truss-based structures, and in particular, tall solar power towers, is a leading candidate for some of the earliest lunar infrastructure in support of these Moon-to-Mars Objectives: LI-1 Development of a Global Power Grid and LI-3.1 Industrial Scale Construction Capabilities – Roads with autonomous navigation aids and Assembly of towers. The assembly of tall truss-based solar power towers is the topic of a separate SBIR Phase I scope in this subtopic. The outfitting of these tall towers with wiring harnesses and junction boxes for power, lights, and sensors is a critical gap in creating a functioning power grid.

Proposals are invited for the development of outfitting concepts and the robotic tools required to outfit a 50- to 80-m-tall truss-based tower with electrical harnesses for a 100- to 200-kWe solar power tower, as specified below. Additionally, wiring junction boxes at various harness connection locations are needed for these different outfitting applications. Making wiring harness connections is not the focus of this topic; however, proposers are strongly encouraged to understand and report on a viable connection strategy to be used during the outfitting process. For example, it is likely that Earth-sourced wiring harnesses will come complete with connectors, and approaches for managing these connectors are highly desirable. Thus, technology development and demonstration that includes the connector feature is encouraged.

Attachment methods for outfitting may include, but are not limited to, mechanical fastening (rivets, tie wraps, twist-ties, clips); however, other methods may be viable and are encouraged. Proposals to the current solicitation can assume that the various wiring harnesses will be attached to the truss elements used in the assembly. It can be assumed that the truss elements are between 0.75 and 1.5 m in length, with either an angle or square prismatic cross sections (a range of cross-section dimensions is listed below), and that the truss elements are joined together using joint elements and mechanical fasteners. It is assumed that no specific accommodations are made for the outfitting of the truss structure (i.e., truss members and joints do not have dedicated mounting features for harnesses or junction boxes pre-integrated).

Robotic systems and/or tools required to complete the outfitting are also desired. Proposers are encouraged to utilize/incorporate commercially available solutions but can also propose specialized concepts if desired. For example, it is assumed that a commercial space-capable robotic manipulating arm will be available and that proposals should concentrate on the development of specialized robotic tooling required for the outfitting. Justification for all concept elements should be made. A description of the proposed outfitting concept of operations is requested and can be based on an outfitting strategy for any one or more stages during or after tower assembly. Additionally, concepts that are extensible to other truss-based structures, such as curved walls, arches, and domes, are also encouraged.

Proposal elements of interest include, but are not limited to:

- Concepts for outfitting truss-based structures with electrical harnesses for applications, including:
    - Sensors and instruments stationed along the length of the tower.
    - Power transmission lines for the collection of solar energy.
    - Sun-tracking motors that rotate the solar arrays toward the sun; these can be located at the top, bottom, or midspan of the tower.
    - Communications packages located at the top of the tower.
- Concept of operations to outfit a tall tower using the robotic tools and outfitting methods developed.
- Robotic tools/systems for outfitting of truss structures.

- Considerations for operating in lunar environment (1/6 gravity, temperature, radiation, vacuum, lighting, power requirements). Note: proposal does not have to produce space-rated equipment; however, the processes shall be applicable to the lunar environment. Justification of design choices shall be included.
- Concepts that maximize operational efficiency and minimize power requirements and complexity.
- Preliminary proof-of-concept demonstrations, methods, equipment.
- Suggested outfitting accommodations (i.e., suggested mounting features/aids incorporated into future truss or joint/node elements).
- Describe possible extensions of proposed technology to outfitting of other truss-based assemblies, e.g., walls, arches, domes.
- Describe possible application of proposed technology to management of nonwiring outfitting tasks, e.g., piping, ECLSS systems.

Assume the following truss elements are used in the tower assembly:

- Truss element lengths: 0.75 to 1.5 m
- Truss element cross section:
  - Square rod: 5 mm, 10 mm, 15 mm square
  - Angle: flange length 10 mm, 20 mm, 40 mm; flange thickness 1.0 mm, 2.0 mm, 4.0 mm, 6.0 mm
- Truss material:
  - Earth sourced = aluminum 6061, graphite-epoxy
  - ISRU based = 98% pure aluminum (properties similar to 1-series untempered aluminum (E = 10 Msi, Yield > 5 ksi)

Tower details and design assumptions:

- Tower height: 50 to 80 m.
- Assume the truss elements are joined together using joint elements and mechanical fasteners.
- Assume assembly site is level to within ±2.5 degrees.
- Assume a suitable foundation/working area is available at the base of the tower to stage the outfitting process; however, proposals are free and encouraged to provide their own foundation requirements.
- Current NASA ConOps for truss tower assembly = vertical build and lift assembly approach (i.e., assemble a truss module, lift up and assemble the next module below, repeat until tower fully erected).

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:

- Analysis
- Prototype

Desired Deliverables Description:

Phase I must include the design and test of critical elements associated with the proposed outfitting technologies. For example, harness and junction box attachment concept design and testing must be included. Phase I must also include a concept of operations for the outfitting of the tower and the design and testing of the robotic outfitting system and tools. Phase I proposals should result in at least TRL 4 robotic outfitting system.

Phase II deliverables must include demonstration of the outfitting concept at a relevant scale. The demonstration shall be designed and justified by the proposer. The outfitting is expected to be accomplished using the robotic systems, implements, and outfitting concepts developed in Phase I. Preliminary plan for maturing the outfitting technology for a future lunar demo. All elements of the outfitting concept must be developed to a minimum of TRL 5.

State of the Art and Critical Gaps:
Lunar and planetary surface outfitting is not a current capability. The state of the art is terrestrial-based construction technology. Current technologies for outfitting robots are low TRL, application specific, and fragile with respect to environmental uncertainties. To enable the outfitting of lunar and planetary structures, these technologies must be made more resilient.

A common problem across a broad class of applications (electrical, fiber, fluids, gases, etc.) with different size, stiffness, and bend radius combinations is conductor/cable and piping/tubing line management. This area encompasses both conductors and tubing, and considerations include installation (securing, strain relief, etc.), interfaces and expansion to include splicing/connecting in the presence of environmental factors, micrometer protection, radiation shielding, and management of coefficients of thermal expansion (CTE) mismatch between the conductor or tubing and substrate. Correct design of these critical features is necessary for robust and reliable outfitting of surface infrastructure.

To date, very few activities have been conducted to develop robotic outfitting of truss-based structures. Thus, to accomplish large-scale structural outfitting on the lunar surface, a variety of new technologies and robotic systems are needed.

Outfitting of tall towers is directly applicable to the following Moon to Mars Objectives:

- LI-1 Development of a Global Power Grid; and, more broadly,
- LI-3.1 Demonstrate industrial-scale autonomous construction capabilities necessary to support global lunar utilization and continuous human presence, including […] roads with autonomous navigation aids, landing pads/berms, […] and assembly of structures such as towers or buildings.

Relevance / Science Traceability:
Robotic outfitting of infrastructure directly addresses the STMD Strategic Thrust “Live: Sustainable Living and Working Farther from Earth” and the following Moon to Mars Objectives:

- LI-1 Development of a Global Power Grid.
- LI-3.1 Industrial Scale Construction Capabilities – Roads with autonomous navigation aids and assembly of towers.

References:

- Doggett, William. Robotic Assembly of Truss Structures for Space Systems and Future Research Plans. Proceedings, IEEE Aerospace Conference. Vol. 7. IEEE, 2002.
- Belvin, Wendel K., et al. In-Space Structural Assembly: Applications and Technology. 3rd AIAA Spacecraft Structures Conference, 2016.
- Komendera, Erik, et al. Truss Assembly and Welding by Intelligent Precision Jigging Robots. 2014 IEEE International Conference on Technologies for Practical Robot Applications (TePRA). IEEE, 2014.
- Moses, R.W.; and Mueller, R.P. (2021). Requirements Development Framework for Lunar In Situ Surface Construction of Infrastructure. Earth and Space 2021, pp. 1141-1155.

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 testing 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 vehicles 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 the safety/reliability of NASA's test and launch operations includes the 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 technology development is enabled by rigorous ground testing to mitigate the propulsion system risks that are inherent in launch and spaceflight. In general, development testing is part of standard practice to design and implement propulsive elements for a launch or space vehicle propelled by chemical rocket propulsion for boost stage or in-space propulsion. Development testing involves a combination of engine-level and subcomponent testing to demonstrate the propulsion hardware was designed to meet the performance requirements for a specified operational envelop over robust margins and shown to be sufficiently reliable prior to its first flight.

This topic area seeks to develop advanced ground rocket propulsion test technology components and system-level ground test systems that enhance advanced propulsion technology development and certification.
This subtopic seeks innovative technologies in the following areas:

- Noncavitating cryogenic valves capable of handling high pressure drop (ΔP > 5,000 psi).
- Cost-effective cryogenic vessels for high pressures (>8,000 psi) that are lightweight (relative to current technology double-walled and jacketed vessels) and efficient to manufacture.
- Robust and reliable components compatible with liquid oxygen with the ability to maintain their structural integrity and function reliably in severe vibration environments (Grms in excess of 100g up to 1,000g and Overall Sound Pressure Levels (OASPLs) of 160 dB), and under shock loading conditions.
- Additively manufactured components, i.e., injectors, cryogenic valves, and pressure vessels, compatible with environments outlined above, with similar performance as current counterparts.
- Compact, lightweight (1,000 vs. 6,000 lb) actuators capable of precise control of large, high-pressure valves (ΔP > 5,000 psid and 500 lbm/s flow rate) with a fast response time (response time < 500 ms).
- Innovative cryogenic quick couplers and components designed to function reliably at cryogenic temperatures (-297 °F to -423 °F).
- Temperature sensing devices (resistance temperature detectors (RTDs) and thermocouples (TCs)) with good response times (63% of final temperature value within 1 to 2.5 s) and capable of enduring high mass flow rates (>500 lbm/s).

- Flowmeters capable of measuring mass flow rates within a broad range of flows (0.1 lbm/s to greater than 500 lbm/s) within 1% of industry accepted standard accuracy, compact, lightweight (1,000 vs. 6,000 lb).

The goal is to advance propulsion ground test technologies to 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 the potential to substantially reduce the costs and improve safety/reliability of NASA's test and launch operations.

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 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.

Technologies are needed to support rocket propulsion testing. Multiple issues remain with 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 Exploration Systems Development Mission Directorate (ESDMD), Space Operations Mission Directorate (SOMD), all test programs at Stennis Space Center (SSC), and other propulsion system development centers.

References:

Stennis Space Center Home Page
https://www.nasa.gov/centers/stennis/home/index.html:
Technology Development and Transfer at Stennis Space Center
https://technology.ssc.nasa.gov/

Computational Fluid Dynamics Forecast Study: CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences - NASA Technical Reports Server (NTRS)
https://ntrs.nasa.gov/citations/20140003093

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 planetary or lunar surface-based infrastructure and processes used to assemble, verify, validate, support, load, and maintain launch vehicles and payloads (including non-spacecraft payloads) in preparation for flight. Launch systems are planetary or lunar-surface-based infrastructure and processes that 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 include 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 the 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 verification after mating 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, including complex fluid systems, 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.
    - Advanced planning, forecasting, and decision-making algorithms and applications that manage operational constraints, prioritize activities, and schedule tasks.
    - 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-diagnostic systems and components to inform condition-based maintenance.
    - Software to aid robotic agents or systems to learn IM&R functionality.
    - Multiagent collaboration and interaction of robotic caretakers for performing operations and maintenance, including optimizing asset usage.
- 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, kits, and consumables.
    - Automated/autonomous inventory management for asset tracking.
    - 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 to support interoperability.
- Standardization of ground systems design (design for maintainability, commonality, and reusability).

For all the 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 component's 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 multicustomer 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 Exploration Systems Development Mission Directorate (ESDMD) and Space Operations Mission Directorate (SOMD) 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. Space Policy Directive 1: Presidential Memorandum on Reinvigorating America's Human

Space Exploration Program, 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:

- NASA Technology Taxonomy (https://www.nasa.gov/offices/oct/taxonomy/index.html)
- 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 spacecraft, thermal is seen as an enabling function of a vehicle. All temperatures must be maintained within design limits, whether those be cryogenic for science instruments or near room temperature for comfortable shirt sleeve operations of the crew. As missions evolve and thermal environments become more extreme, 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 that result in minimal impact on thermal system mass, volume, and power.

Z2.01: Spacecraft Thermal Management (SBIR)

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

Subtopic Introduction:
NASA seeks new technologies that will facilitate low-mass and highly reliable thermal control systems for the exploration of our solar system. Proposals should discuss how the innovation will improve upon, interface with, or replace the current state-of-the-art technologies and techniques. This solicitation specifically targets proposals for new technologies and methods that clearly address one of the following areas:

- Lunar Habitat Thermal Technologies
- High-Temperature Heat Acquisition and Transport
- Topology Optimization of Thermal Control Systems

These areas are considered of equal priority, and no award preference is expected for one area over another.

Scope Title: Lunar Habitat Thermal Technologies

Scope Description:
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 with long-duration habitation on the lunar surface, where temperatures range from -193 °C or lower in shadowed regions (including night) to 120 °C at the equatorial subsolar point. Technologies are needed that allow a single habitat or a pressurized rover 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, but are not limited to, the following:

- Methods for preventing or restoring radiator optical properties that have degraded due to exposure to the space environment (radiation, etc.).
- Development of engineered solar reflective coating with high infrared (IR) transparency with the following properties:
    - Solar reflectance >0.85 (threshold) to 1 (goal).
    - IR transmittance >0.85 (threshold) to 1 (goal).
    - Is electrically dissipative, i.e., low exposed surface resistivity (to manage potential static charge buildup).
    - Is compatible with a variety of substrates: novel thermochromic materials, standard spacecraft metals, and flexible thermal control tapes.
- Contamination-insensitive evaporators/sublimators to enable long mission life.
- Self-healing coolant tubes for MMOD-impact resilience.
- Incorporation of elastocaloric heat pumps into a payload thermal control system.
    - ~50 to 100 W of heat lift.
    - Cold side temperature <4 °C.
    - Hot side temperature ~ambient (heat sunk to air or liquid cooled interface).

Unless otherwise stated, technologies should be suitable for use with crewed vehicles having variable heat loads averaging between 2 and 6 kW and should consider dormancy (mission time while uncrewed) impacts. All technologies should support a minimum operational duration of at least 5 years and be compatible with applicable mission environments. For example, ground processing/launch site environments (humidity, general contamination, etc.) and in-space environments (ultraviolet (UV), solar wind, etc.).

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 validate the assumptions used within the model.

State of the Art and Critical Gaps:

This scope strives 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. 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. Namely, the need to provide variable heat rejection through the complex lunar temperature profile has provided the opportunity for many novel heat rejection system technologies to be developed and evaluated. However, among the most significant challenges associated with modulating radiator efforts is the ability to provide the desired optical properties in the solar spectra while achieving the desired IR transmission for tunable products. An engineerable solar reflective coating with high transmission in the IR spectra is expected to address this gap while also providing a general tool capability to tune solar and IR properties of static coatings. This scope also acknowledges the need to improve system robustness while minimizing impact to other systems.

Relevance / Science Traceability:

- Deep space habitats and crewed vehicles (Moon, Mars, etc.)
  - Orion
  - Gateway
  - Human Landing System (HLS)
- Mars transit vehicles
- SmallSats/CubeSats
- Rovers and surface mobility

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. Kauder, L. Spacecraft Thermal Control Coatings References. NASA/TP-2005-212792. 2005.
4. Dudon, J.P., et al. Development of Variable Emissivity Coatings for Thermal Radiator. ICES-2021-063. 50th International Conference on Environmental Systems. July 2021.
5. Snodgrass, R., and Erickson, D. A Multistage Elastocaloric Refrigerator and Heat Pump With 28 K Temperature Span. Sci Rep 9, 18532. 2019.

Scope Title: High-Temperature Heat Acquisition and Transport

Scope Description:

NASA is seeking the development of thermal transport systems for spacecraft applications that require the transfer of large amounts of thermal energy from a reactor (e.g., nuclear) 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 reactor, at a supply temperature of 1,200 to 1,400 K with 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. A maximum system temperature drop of 50 to 150 K from the reactor interface to power conversion working fluid is also desired. 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 needs to be gamma- and neutron-radiation tolerant, 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 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.

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 validate the assumptions used within the model.

State of the Art and Critical Gaps:

This scope strives 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. Namely, few design technologies exist that are capable of managing the heat transport between nuclear reactor and power conversion systems with high efficiency. This is a critical element of nuclear electric propulsion working architecture that must be improved to increase the viability of future systems. The ability to transport very high heat loads over considerable distances, with high transport efficiency, is expected to be a gap for future space systems that utilize nuclear energy.

Relevance / Science Traceability:

- Nuclear electric propulsion (NEP) systems
- Nuclear power system (lunar surface power)

References:

1. 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.
2. General Atomics Project 3450. Thermionic Fuel Element Performance Final Test Report, TFE Verification Program. GA-A21596 (UC-224). Prepared under Contract DE-AC03-86SF16298. Department of Energy. 1994.
3. Ashcroft, J. and Eshelman, C. Summary of NR Program Prometheus Efforts. LM-05K188. 2006.
4. Aerojet. SNAP-8 Performance Potential Study, Final Report. NASA-CR-72254. 1967.
5. Horner-Richardson, K., et al. Fabrication and Testing of Thermionic Heat Pipe Modules for Space Nuclear Power Systems. 27th IECEC, San Diego, CA. Paper Number 929075. 1992.
6. Ernst, D.M. and Eastman, G.Y. High Temperature Heat Pipe Technology at Thermacore – An Overview. AIAA-85-0981. 1985.
7. Voss, S.S. and Rodriguez, E.A. Russian System Test Program (1970-1989). American Institute of Physics Conference Paper 94-0101. 1994.

8. Stone, J.R. Alkali Metal Rankine Cycle Boiler Technology Challenges and Some Potential Solutions for Space Nuclear Power and Propulsion Applications. NASA-TM-106593. July 1994.
9. Demuth, S.F. SP 100 Space Reactor Design. Progress in Nuclear Energy. 42(3). 2003.
10. Ashcroft, J. and Eshelman, C. Summary of NR Program Prometheus Efforts. LM-05K188. 2006.
11. Davis, J.E. Design and Fabrication of the Brayton Rotating Unit. NASA-CR-1870. March 1972.
12. Richardson-Hartenstein, K., et al. Fabrication and Testing of Thermionic Heat Pipe Modules for Space Nuclear Power Systems." 27th IECEC, Paper Number 929075. 1992.

Scope Title: Topology Optimization of Thermal Control Systems

Scope Description:
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 topology optimization (TO) design tools for thermal control systems involving fluid flow heat exchangers, considerable work remains to make the use of those tools standard practice for a wider range of spacecraft thermal systems that include radiation heat transfer.

This solicitation requests the development and demonstration of either pre-existing or new TO software that can optimize spacecraft thermal radiator architectures, minimizing mass and maximizing heat transfer efficiency. NASA requests limited usage rights of compiled software at the completion of this SBIR period.

Recommended optimization variables shall include radiator size, thickness, and shape. Input variables shall include radiator heat load, environmental heat load, nonuniform view factor blockage, and radiator structural support locations.

The optimization process shall be demonstrated. Documented savings in mass shall be trended along each step of the optimization path. The optimization algorithm should be sufficiently versatile to solve generalized coupled thermal conduction and radiation problems.

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 software. Any delivered math models should include supporting data that validate the assumptions used within the model.

State of the Art and Critical Gaps:
These scopes 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. Topology optimization (TO) in particular 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 is capable of doing 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:

- Mars transit vehicles
- SmallSats/CubeSats
- Rovers and surface mobility
- Nuclear electric propulsion (NEP) systems
- Future science missions

References:

1. Watkins, R. Designing optical instruments for space applications: Multiphysics topology optimization. 2019.
2. Watkins, R. Topology optimization: a shift towards computational design. 2016.
3. Kambampati, S., Gray, J., and Kim, H.A. Level set topology optimization of load carrying heat dissipation devices. AIAA Aviation 2019 Forum. 2019.
4. Kambampati, S., and Kim, H.A. Level set topology optimization of cooling channels using the Darcy flow model. Structural and Multidisciplinary Optimization. 1-17. 2020.
5. Feppon, F., et al. Topology optimization of thermal fluid–structure systems using body-fitted meshes and parallel computing. Journal of Computational Physics. Vol. 417, 109574. 2020.

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 the tools, technologies, and concepts that enable new generations of civil aircraft that are safer, more energy-efficient, and have a smaller environmental footprint. The program focuses on enabling major leaps in the safety, efficiency, and environmental performance of subsonic fixed and rotary wing aircraft to meet challenging and growing long-term civil aviation needs; pioneering low-boom supersonic flight to achieve new levels of global mobility and advancing fundamental hypersonic research while sustaining hypersonic competency for national needs. In collaboration with academia, industry, and other Government agencies (e.g., FAA), AAVP pioneers fundamental research and matures the most promising technologies and concepts for transition to system application by the aviation industry. The program works with the DoD to ensure that NASA and DoD vehicle-focused research is fully coordinated and leveraged. TACP cultivates multi-disciplinary, revolutionary concepts to enable aviation transformation and harnesses convergence in aeronautics and non-aeronautics technologies to create new opportunities in aviation. The program's goal is to demonstrate the initial feasibility of internally and externally originated concepts to support the discovery and initial development of new, transformative solutions for all six ARMD Strategic Thrusts. The program provides flexibility for innovators to explore technology feasibility and provide the knowledge base for transformational aviation concepts through sharply focused activities. The program solicits and encourages revolutionary concepts, creates the environment for researchers to become immersed in new ideas, performs ground and small-scale flight tests, allows failures and learns from them, and drives rapid turnover into new concepts. The program also supports research and development of major advancements in cross-cutting computational tools, methods, and single-discipline technologies to advance the research capabilities of all aeronautics programs.

A1.02: Quiet Performance - Airframe Noise (SBIR)

Lead Center: **LaRC**
Participating Center(s): **GRC**

Scope Title: Airframe 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 to 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 noise prediction and noise control are needed for subsonic, transonic, and supersonic vehicles. Solutions are sought that target airframe noise sources and the noise sources due to the aerodynamic and acoustic interaction of the airframe and engines. Innovations in the following specific areas are solicited:

Noise Prediction:

- Prediction and/or mitigation of aerodynamic noise sources including those from the airframe, propulsion-airframe interactions, or aeroacoustic integration effects associated with high-aspect-ratio truss-braced vehicles. However, engine-only noise sources are excluded from this call.
- System-level noise prediction methodologies for operational aspects (as opposed to certification conditions) of high-aspect-ratio truss-braced subsonic transports or technology variants thereof.
- Prediction of sound propagation from the aircraft through a complex atmosphere to the ground. This should include interactions between noise sources and the airframe and its flow field.

Noise Analysis and Characterization:

- Fundamental and applied computational fluid dynamics techniques for aeroacoustic analysis that can be adapted for design purposes.
- Innovative source identification techniques for airframe (e.g., landing gear and high-lift systems) noise sources, including turbulence details related to flow-induced noise typical of separated flow regions, vortices, shear layers, etc. However, noise sources attributed solely to the engines are excluded from this call.

Noise Reduction:

- Concepts for active and passive control of broadband aeroacoustic noise sources for conventional, truss-braced, and other advanced aircraft configurations. Technologies of interest include adaptive flow control

- and noise control enabled by advanced aircraft configurations, including integrated airframe-propulsion control methodologies.
- Innovative design approaches or technologies, including acoustic liner or porous surface concepts, to reduce airframe noise sources and/or propulsion/airframe aeroacoustic interactions. However, engine nacelle liner applications are specifically excluded.

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

Primary Technology Taxonomy:

- Level 1 15 Flight Vehicle Systems
- Level 2 15.1 Aerosciences

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Concepts, technologies, and tools that enable rapid assessment of the noise impact of novel engine/airframe configurations, mitigate component noise issues associated with novel aircraft configurations, and/or aid in the development and optimization of noise control approaches for component noise sources that enable new aircraft configurations such as truss-braced wing and small-core turbofan engines. Example Phase I deliverables include laboratory demonstrations that establish proof of concept of noise reduction technologies and also applications of novel computational tools with limited scope that demonstrate the potential for success on problems of greater scope. Example Phase II deliverables include system or subsystem demonstrations concurrent with the establishment of a realistic path to concept production and also the incorporation of novel computational tools into existing modeling toolchains with validation cases to document capabilities.

State of the Art and Critical Gaps:

State-of-the-art technologies for noise reduction on conventional transport aircraft are generally passive and do not incorporate advanced material systems or adaptive mechanisms that can modify their performance based on the noise state of the vehicle. Advanced material systems for airframe noise control are still in their infancy, especially in the context of certifiability and robustness. Novel material systems that could be applied to component noise sources on the aircraft are needed, such as shape memory alloy actuators and active or adaptive systems. In addition, future sustainable aircraft design configurations are envisioned that either leverage the noise benefits of complex geometrical configurations or introduce noise challenges with engine/airframe integration. Efficient computational tools that enable rapid-turn evaluations of multiple configurations at the design stage are lacking. Numerical methods to study complex engine/airframe configurations are complex and difficult to leverage at the aircraft design stage where configuration details are not specified. Improvements to numerical methods and models for studying the noise aspects of advanced airframe configurations, including engine integration, would ease consideration of acoustics in the design, rather than leaving acoustics to the late design stage where noise control solutions are costly and less effective. Improved tools would also enable more rapid evaluation and development of innovative noise control approaches that may be needed for these novel aircraft configurations.

Relevance / Science Traceability:

AAVP: The Advanced Air Transport Technology (AATT) and Commercial Supersonic Technology (CST) Projects would benefit from noise reduction technologies that could reduce the aircraft noise footprint at landing and takeoff. Configurations with novel engine placement, such as above the fuselage, can reduce the noise footprint, but technologies are needed to efficiently model the performance and noise impacts of these novel engine installations. In addition, novel configurations and technologies such as truss-braced wing and small-core turbofan engines will introduce new noise challenges that must be addressed to enable their successful deployment.

TACP: The Transformational Tools and Technologies (TTT) Project would benefit from tool developments to enhance the ability to consider acoustics earlier in the aircraft 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 noise, as these component technologies could have applications in numerous vehicle classes in the AAVP portfolio, including subsonic and supersonic transports as well as vertical lift vehicles.

References:

- AAVP - Advanced Air Transport Technology (AATT)
  Project: https://www.nasa.gov/aeroresearch/programs/aavp/aatt
- AAVP - Commercial Supersonic Technology (CST)
  Project: https://www.nasa.gov/aeroresearch/programs/aavp/cst
- TACP - Transformational Tools and Technologies (TTT)
  Project: https://www.nasa.gov/aeroresearch/programs/tacp/ttt

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 energy storage systems, power electronic modules for electric aircraft motor drives, and electric machines and converters 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 toward megawatt-class vehicles.

Specifically, novel developments are sought in these areas:

- Energy storage systems with specific energy >400 Whr/kg at the system level under continuous 2C rate discharge conditions. Materials or strategies to promote rapid charging, novel system designs incorporating passive thermal management, and novel battery designs to passively prevent the propagation of thermal runaway from cell to cell are desirable. This subtopic seeks energy solutions in the Technology Readiness Level (TRL) 3-5 range, appropriate for near-term applications.

- Converters (inverters/rectifiers) used to convert alternating current (AC) to AC frequency and AC to direct current (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.
- Power electric modules for electric aircraft motor drives that enable high efficiency and high power density. The modules must provide a continuous current rating of at least 250 A, achieve an RDS,on of 3.8 mΩ (at 25 °C), and do so with a 25% margin on Vgs below its absolute maximum rating. The module must achieve a total turn on + turn off switching loss of 12 mJ for a 200-A load while switching 800 V, with a stretch goal of 3 mJ. The module must also be capable of operating at an altitude of 41,000 ft without partial discharge (can be a simulated environment (e.g., vacuum chamber)), and follow DO-160G standards on shock and vibration tolerance. The module must achieve a voltage rating of no less than 1.2 kV. Optionally, it is desirable for the module to have high power density (<24 g per two device phase-leg module, or equivalent), to minimize output capacitance, to minimize stray inductance, to utilize a Kelvin source for gate driving, to provide sufficient cooling area to minimize heat flux (4.2 in2 per two device phase-leg module, or equivalent), to provide sufficient electrical isolation from the cooling surface to any metal oxide semiconductor field effect transistor (MOSFET) terminal, to include an embedded thermal sensor, and to possess a short circuit withstand capability of at least 3 µs. Modules with a voltage rating of 1.7 or 3.3 kV will be considered and can take exception to most of the requirements with justified replacement requirements. Altitude and shock/vibration requirements are mandatory.

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

Primary Technology Taxonomy:

- Level 1 01 Propulsion Systems
- Level 2 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) and how the proposed idea addresses the needs of the technology pull area and would 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. Phase II deliverables 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 started the 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:

- EAP is called out as a key part of Thrust 3 in the ARMD Strategic Implementation Plan: https://www.nasa.gov/aeroresearch/strategy
- Overview of NASA's EAP Research for Large Subsonic Aircraft: https://ntrs.nasa.gov/search.jsp?R=20170006235
- NASA X-57 Project: https://www.nasa.gov/aeroresearch/X-57/technical/index.html
- “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: A Framework for Wall-Modeled Large Eddy Simulation (WMLES) Solution Sensitivity Analysis

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 [Ref. 1] 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 Ref. 2]. For aircraft certification, prediction of maximum lift was considered one of the needed critical technologies highlighted in the study. A grand challenge problem in this technical area was defined in Reference 3, where technology gaps and potential areas of research are highlighted. Another grand challenge problem in the area of propulsion was developed in Reference 4. Solution of these challenge problems requires availability of robust, cost effective, and accurate eddy resolving computational tools.

Research to date has indicated that WMLES technology provides a good compromise between solution accuracy and computational cost for predicting complex turbulent flows, where the traditional Reynolds-Averaged Navier-Stokes (RANS) codes fall short. WMLES has been applied to various problems such as high-lift, turbomachinery, and surface heat transfer. However, grid point requirement estimates and the rate of solution convergence continue to remain significant challenges. There is a need to develop a rigorous framework to understand solution sensitivity with respect to computational grids for high-lift and other turbulent flow applications where scale-resolving simulations are needed to capture necessary physics. This framework must consider all the important geometric and flow parameters (e.g., surface curvature, pressure gradients, Reynolds number, and heat transfer). It is important to have the capability of automatically generating a minimal, but optimal, grid that yields aerodynamic quantities of interest within the required engineering accuracy. It is also important to consider the role and interplay of flow physics modeling (wall model and subgrid-scale model) and numerical discretization. The ultimate objective of this research is that the developed framework allows WMLES results to be obtained using minimal computational resources and human interaction, while accounting for all the important parameters that influence the outcome. Proposals are solicited for the development and demonstration of such a framework for WMLES. The developed technology must be demonstrated on one or more of the challenge or subchallenge problems cited above. It is important to note that the solicitation is not aimed at developing a new grid generation method, but to provide a framework that accounts for all the parameters that influence an optimal WMLES grid and then yields that grid for a given geometry and flow conditions.

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 15.1 Aerosciences

Desired Deliverables of Phase I and Phase II:

- Software
- Research
- Analysis

Desired Deliverables Description:

Phase I:

1. Formulate and develop the required framework.
2. Demonstrate the capability for one or two selected applications.
3. Write a report that describes the formulation and the results for the selected WMLES applications.

Phase II:

1. Complete development of the framework by including all the important parameters that influence the outcome of WMLES for a range of applications, not limited to high-lift.
2. Demonstrate the capability for a range of complex applications, including computational cost and accuracy.
3. Write a comprehensive final report to include (a) formulation of the framework, (b) software development, and (c) results of WMLES applications.
4. Deliver the developed software 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. WMLES technology demonstrated significant potential in accurate prediction of maximum lift prediction/stall in the recently held American Institute of Aeronautics and Astronautics (AIAA) High-Lift Prediction Workshop - 4. WMLES has been implemented in two NASA codes (LAVA and FUN3D), but automatic mesh generation that allows solution to be obtained with a minimum number of cells, which generates aerodynamic quantities of interest within required engineering quantities, remains a challenge. This solicitation addresses this significant technology gap in the existing computational tools capability.

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), Exploration Systems Development Mission Directorate (ESDMD), and Space Operations Mission Directorate (SOMD). WMLES capability has been implemented in NASA's unstructured-grid CFD code FUN3D, but the construction of an optimal grid remains a challenge and requires extensive human intervention. Having a framework that enables automation of unstructured grid generation for a given geometry and flow conditions would be hugely enabling. If Phase II is successful in automating the process, then there is significant potential of post Phase II funding from NASA, because the industrial scale-resolving simulation capability is the next big step in CFD.

References:

1. NASA’s CFD Vision 2030 Study: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140003093.pdf
2. NASA's A Guide for Aircraft Certification by Analysis Study: https://ntrs.nasa.gov/citations/20210015404
3. Slotnick, J. P. and Mavriplis, D. J., “A grand challenge for the advancement of numerical prediction of high-lift aerodynamics,” AIAA Paper 2021-0955.

4. Anand, M. S. et al., “Vision 2030 aircraft propulsion grand challenge problem: Full-engine CFD simulations with high geometric fidelity and physics accuracy,” AIAA Paper 2021-0956.
5. Advanced Air Vehicles Program: https://www.nasa.gov/aeroresearch/programs/aavp
6. Transformative Aeronuatics Concepts Program: https://www.nasa.gov/aeroresearch/programs/tacp

A1.06: Electric Vertical Take-Off and Landing (eVTOL) Vehicle Technologies for Weather-Tolerant Operations (SBIR)

Lead Center: **GRC**
Participating Center(s): **AFRC, LaRC**

Scope Title: Electric Vertical Take-Off and Landing (eVTOL) Technologies for Weather-Tolerant Operations

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 four rotors or propellers, have electric propulsion, carry two to six passengers, fly like a helicopter for vertical takeoff and landing (VTOL), and will fly relatively close to the ground and in proximity to buildings with many operational cycles per day. There are many technical challenges facing the industry’s development of safe, quiet, reliable, affordable, comfortable, and certifiable UAM vehicles and vehicle operations. This subtopic area in the NASA SBIR solicitation focuses on specific vehicle technologies in each year's solicitation. NASA's interest through this subtopic is to make technology and tool advancements that support the overall vehicle development and establishment of the market. The focus will be in different technology areas each year at component and subsystem level and not at the overall vehicle system level. The scope of this subtopic is on vertical lift technologies that support the safe, quiet, reliable, affordable, comfortable, and certifiable VTOL aircraft. The current vehicle focus is the VTOL aircraft that would be required for UAM and public good missions. 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 developing aircraft that are capable of safely flying during typical adverse weather conditions, including rain, icing, lightning, high winds, low visibility, and extreme temperatures.

The focus of this subtopic this year is on advanced vehicle technologies that enable UAM operations in various weather conditions. Innovations are being sought to address the technical areas noted in the following text. Proposals should address these areas, and proposals that are for other vehicle technologies or vehicle concepts are not of interest in this year's solicitation.

1. Erosion resistance: low-maintenance technologies are being sought that would mitigate erosion effects of rain, dust, and sand on vehicle surfaces, especially the rotor surfaces.
2. UAM Icing: There are numerous UAM vehicle configurations that have varying rotor/props configurations, combinations of lifting surfaces and different operational modes (such as stationary rotors during forward flight). Innovative approaches that employ lightweight, low-power active ice protection systems combined with unpowered, or passive (such as icephobic materials and coatings) are sought to prevent or mitigate ice accretion for these vehicles.
3. Sensing: technologies are being sought that would measure component degradation resulting from the various weather conditions and indicate if mitigations are needed to reduce in-flight risks. Such sensing might be for ice accretion on rotors or for rotor blade erosion due to rain, airborne particulate matter, etc.

Any technology advancements must also consider minimizing impact to overall vehicle performance such as to power consumption, system mass and volume, and vehicle aerodynamic efficiency in their design.

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.

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

Primary Technology Taxonomy:

- Level 1: TX 15 Flight Vehicle Systems
- Level 2: TX 15.X Other Flight Vehicle Systems

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.

Phase II of the SBIR should further develop the technology designs and validate achievement of goals through additional analysis, modeling, and simulation and through system/component testing to characterize performance and functionality. 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 aircraft 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. The market/application of these vehicles will be in urban and rural locations and be expected to have high use (life) in a broad range of weather conditions. The technologies to enable broadened weather-tolerant operations are needed.

Relevance / Science Traceability:

This subtopic is relevant to the Aeronautics Research Mission Directorate (ARMD) 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 the Advanced Air Mobility mission objective of V.6.3 Weather Tolerant Vehicle Technologies (Develop technology concepts for reliable and safe operations of UAM vehicles during weather-related challenges.).

References:

1. Silva, C., Johnson, W. R., Solis, E., Patterson, M. D., and Antcliff, K. R., "VTOL Urban Air Mobility Concept Vehicles for Technology Development," 2018 Aviation Technology, Integration, and Operations Conference, American Institute of Aeronautics and Astronautics, 2018. [AIAA 2018-3847]

2. 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.
3. UAM UML-4 ConOps https://sti.nasa.gov/
4. FAA UAM ConOps 1.0 https://nari.arc.nasa.gov/sites/default/files/attachments/UAM_ConOps_v1.0.pdf
5. National Academies Report: https://www.nap.edu/catalog/25646/advancing-aerial-mobility-a-national-blueprint
6. Wright, J., and Aubert, R., “Icing Wind Tunnel Test of a Full Scale Heated Tail Rotor Model,” AHS 70th Annual Forum, Montreal, CA, May 2014. [AHS 2014-0104]
7. Kreeger, R., Work, A., Douglass, R., Gazella, M., Koster, Z., and Turk, J., "Analysis and Prediction of Ice Shedding for a Full-Scale Heated Tail Rotor," AIAA Atmospheric and Space Environments Conference, Washington, D.C., June, 2016. [AIAA 2016-3443]
8. Sehgal, A., and Ernst, R., “MQ-8 Fire Scout Icing Solution Challenges,” AHS 72nd Annual Forum, West Palm Beach, FL, 16-19 May, 2016.
9. Avery, A., and Jacob, J., “Evaluation of Low Altitude Icing Conditions for Small Unmanned Aircraft,” AIAA 9th Atmospheric and Space Environments Conference, Denver, CO, 5-9 June, 2017. [AIAA 2017-3929]
10. Han, N., Hu, H., and Hu, H., “An Experimental Investigation to Assess the Effectiveness of Various Anti-Icing Coatings for UAV Propeller Icing Mitigation,” AIAA Aviation 2022 Forum, Chicago, IL, June, 2022. [AIAA 2022-3964]
11. Schneeberger, G., Palacios, J., and Wolfe, D., “Development of Ice Protective Surfaces via Reduction of Surface Roughness,” AIAA Aviation 2022 Forum (virtual), June 2020. [AIAA 2020-2803]
12. Dumont, C., Pellicano, P., Smith, T., and Riley, J., “Results From a Full-Scale Propeller Icing Test,” 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 2008. [AIAA 2008-432]

A1.08: Aeronautics Ground Test and Measurement Technologies: Sensors and Diagnostic Systems for High-Speed Flows (SBIR)

Lead Center: LaRC
Participating Center(s): ARC, GRC

Subtopic Introduction:
NASA's aeroscience ground test facilities include wind tunnels, air-breathing engine test facilities, and simulation and loads laboratories. They play an integral role in the design, development, evaluation, and analysis of advanced aerospace technologies and vehicles. These facilities provide critical data and fundamental insight required to understand complex phenomena and support the advancement of computational tools for modeling and simulation. The primary objective of the Aeronautics Ground Test and Measurements Technologies subtopic is to develop innovative tools and technologies that can be applied in NASA’s aeroscience ground test facilities to revolutionize testing and measurement capabilities and improve utilization and efficiency. Of primary interest are technologies that can be applied to NASA’s portfolio of large-scale ground test facilities.

Scope Title: Ultrafast Response Sensors for Hypersonic Applications

Scope Description:
Ultrafast response sensors (~1 MHz or greater) to be used as probes or as surface-mounted sensors (embedded in the model surface or tunnel walls) are needed to measure output related to pressure, shear stress, temperature, velocity, mass flux, or other flow properties. Spatially and temporally resolved measurements are desired, and the physical form factor of sensing elements shall be small (submillimeter range) to mitigate spatial averaging. Low

noise floor levels (minimum detectable signals) and high sensitivities are desirable to measure free-stream disturbances in ground-based facilities (to include blowdown tunnels, shock tunnels, and Ludwieg tubes) and flight. Sensors must be rugged and able to survive the harsh environment of hypersonic flow to include extreme values of temperature (>1,000 K), inertial load, and dynamic load. Sensors must demonstrate levels of electromagnetic interference (EMI) immunity necessary for flow quality measurements. Sensors shall be capable of performing in ground-based facilities or flight tests. Measurements shall be validated against accepted measurement techniques to determine accuracy and precision with preference given to approaches leading to National Institute of Standards and Technology (NIST) traceability. Sensor system needs to be fully characterized to include sensitivity along with frequency response function.

The use of these measurements in quiet tunnels is critical for the study/control of instability and transition and ultimately to control the aerothermal environment of high-speed vehicle concepts. Areas of emphasis for these measurements include measurements of supersonic/hypersonic boundary layer instabilities, free-stream disturbance environments, receptivity, shock boundary layer interactions, etc.

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 13.2 Test and Qualification

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Desired deliverables for Phase I would be detailed design and analysis of proposed hardware, preliminary concept demonstration, and a proposed path to system calibration and dynamic characterization.

Desired deliverables for Phase II would be prototype hardware that has been validated through test (ground-based or flight) and also traceable metrics for hardware calibration and characterization. The prototype hardware should be ready to use in hypersonic wind tunnel testing.

State of the Art and Critical Gaps:

Currently, fully characterized ultrafast response sensors with traceability to flow parameters are lacking. This is particularly the case in the high-temperature environments of hypersonic flows. As an example, high-bandwidth (~1 MHz) pressure transducers are available commercially, but these sensors are not dynamically characterized, have significant calibration uncertainties, and are not survivable when exposed to sustained high-temperature environments. Advancement in these measurements will lead to better predictive models (e.g., in transition and turbulence modeling) for development of future hypersonic vehicles.

Relevance / Science Traceability:

The scope of this activity ties in directly with Aeronautics Research Mission Directorate (ARMD) via the Hypersonics Technology Project (HTP) by providing technology critical to the development of systems under investigation at NASA and would have applications to the wider hypersonic community to include Department of Defense (DOD) and academia. This activity is particularly relevant to the HTP emerging Technical Challenge (eTC) on boundary layer transition. Potential hardware from this solicitation will provide improved measurement capabilities that can be implemented in the experimental investigations to be incorporated as part of a new boundary layer transition TC.

References:
ARMD Strategic Implementation Plan: https://www.nasa.gov/aeroresearch/strategy

Scope Title: Miniaturized Flow Diagnostics for High-Speed Flows

Scope Description:
Spatially resolved flow-field measurement diagnostics are sought for application in high-speed wind tunnel flows (transonic, supersonic, and hypersonic), both with and without combustion. Improved measurement capabilities are needed for velocity, temperature, density, and/or species concentrations in harsh wind tunnel environments. Molecular-based diagnostics are appropriate for multiparameter measurement approaches. Additionally, particle seeded or unseeded flow velocity measurement approaches can be proposed. Measurement systems should be both 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. Linear or planar, spatially resolved measurement approaches are preferred for the particulate-based seeding approaches.

Molecular approaches can be point based; however, linear and/or planar measurement domains are not discouraged. 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 a secondary benefit, but not required. Compact/miniaturized systems that could be installed inside a wind tunnel test article with external power, fiber optic, and/or data signal connections would be very desirable. For miniaturized measurement systems, an estimate of the volumetric requirements of the measurement head should also be clearly stated along with optical access requirements. Small planar windows are preferred over large curved optical access ports, which are ultimately defined by the test application.

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.

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 13.2 Test and Qualification

Desired Deliverables of Phase I and Phase II:
- Hardware
- Prototype

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 gas velocity, temperature, and density simultaneously. The techniques that are available are sensitive to background scattered light and tend to be point based. A planar-based technique capable of simultaneously and accurately measuring gas velocity and state variables would be a large advance in the state of the art. Another challenge is employing these optical diagnostic techniques in NASA's large-scale wind tunnels, where there may be limited optical access or large distances from a viewing window to the test article in the tunnel. An alternative approach could be to implement miniaturized point, line, and/or planar techniques for acquiring near-surface velocity measurements that are small enough to be integrated into the test model or to be flown onboard aircraft for in-flight measurements. Single optical port (or maximum of two optical access ports) access for obtaining near-surface (boundary layer) and short-standoff (several feet) measurement capabilities would both be highly desirable.

Relevance / Science Traceability:
The target application of this technology is at NASA's large-scale test facilities: National Transonic Facility (NTF) and Transonic Dynamics Tunnel (TDT) at Langley Research Center, the 8×6 Supersonic Wind Tunnel and 10×10 Abe Silverstein Supersonic Wind Tunnel at Glenn Research Center, and the Unitary Plan Wind Tunnels at Ames Research Center. The technology could also be applied to measure in-flow and near-wall conditions in other types of facilities like shock tubes and shock tunnels as well as conventional aeronautical testing facilities.

References:
ARMD Strategic Implementation Plan: https://www.nasa.gov/aeroresearch/strategy

A1.09: Zero-Emissions Technologies for Aircraft (SBIR)

Lead Center: **GRC**
Participating Center(s): **N/A**

Scope Title: Energy Conversion for Aircraft, Cryogenic Fuel Management, and Thermal Management

Scope Description:
NASA innovates for the benefit of humanity, and any new aircraft and technologies developed through this subtopic will help the United States achieve net-zero carbon emissions from aviation by 2050—one of the environmental goals articulated in the White House's U.S. Aviation Climate Action Plan.

NASA Aeronautics has always been about improving aviation efficiency and safety, while reducing noise, fuel use, and harmful emissions. For decades, our NASA-developed technologies have contributed to making aviation more sustainable—environmentally and economically. Now we are expanding research for sustainable aviation by developing and testing new green technologies for next-generation aircraft, new automation tools for greener and safer airspace operations, and new sustainable energy options for aircraft propulsion.
We're partnering with industry, academia, and other agencies through the Sustainable Flight National Partnership to accomplish the global aviation community's aggressive goal of net-zero carbon emissions by 2050.

During the next 10 years, we will demonstrate first-ever high-power hybrid-electric propulsion on a large transport aircraft, ultra-high efficiency long and slender aircraft wings, new large-scale manufacturing techniques of composite materials, and advanced engine technologies based on breakthrough NASA innovation. In partnership with the Federal Aviation Administration (FAA) and airlines, we'll also pioneer new air traffic management automation tools that safely and reliably put future aircraft on flight paths optimized for minimal environmental impact.

This subtopic targets aggressive innovations to reach zero emissions by providing research seed funds for small U.S. businesses. The technologies proposed should have both a technical and business pathway to introduction into the air fleet. They should have a path to application on transport aircraft that fall under FAA part 23 (<19 passenger) or FAA part 25 (>19 passenger) regulations.

Many radical aircraft configurations are being explored to get to zero-emission aviation. Many of the concepts require a step-change in technology as well as businesses that can supply this technology in an innovative and cost-effective way. When considering the requirements of the aircraft, it is useful to reference either an existing aircraft or an aircraft concept that has been published in open literature. An example concept is the Subsonic Single Aft Engine (SUSAN) transport aircraft concept described in the reference section; however, there are many other concepts that could be considered.

Demonstrations conducted under the proposed SBIR subtopic can be conducted using unpiloted subscale aircraft. NASA is currently designing an unpiloted, 25%-scale version of the SUSAN transport aircraft concept. Reference information for the 25% SUSAN flight research vehicle includes a wing span of 30 ft, a maximum takeoff weight between 1,500 and 2,000 lb, a maximum altitude of 15,000 ft, a maximum speed of 150 mph, a 500-lb-thrust-class engine (however, used to primarily power 150-kW generator), power at 150 kW total, individual converters at 40 kW, 10 kW operating on 300-VDC bus, and thermal management from pumped liquid cooling loops with a worst-case hot temperature of 60 °C.

This SBIR subtopic is open to any ideas that lead to zero emission or highly reduced emission aircraft. We are open to ideas that utilize sustainable aviation fuels, jet A, aviation gas, or batteries with greatly improved emissions as they may have a more near-term market and path to introduction. We are also open to ideas using fuels like liquid natural gas, hydrogen, or other green fuel ideas that may require more significant infrastructure changes.
Some specific areas we are focused on this year are:

1. Turbofan technologies demonstrated on a small turbofan engine in the 500-lb thrust class. Preferred are implementations that have a significant fraction (>65%) of power electrically and the remainder as thrust, with at least 150 kW of power production and 150 lb of thrust. Emphasis is on producing a full prototype turbine that is light and efficient enough to have a net benefit on aircraft fuel burn and emissions. Suggested technologies are:
    1. Combined cycles (topping, bottoming, other).
    2. Integration concepts of combustor and turbine for improved overall and component performance.
    3. Turbines that utilize highly advanced combustors like rotating detonation combustions (RDCs) or alternative fuels that are not already widely considered. RDCs that have the ability to be short, pressure gain devices and to burn H_2 with low NO_x.
    4. Solid oxide/turbine fuel cell combinations.
    5. Heat exchangers with waste heat recovery performance that results in aircraft-level benefits.
2. Technologies to make cryogenic fuels like liquid natural gas and liquid hydrogen practical on an aircraft.
    1. Tank technologies that address weight, boiloff, aircraft loads, safety requirements, and transport and refueling requirements at airports.
    2. Cryogenic pump technologies that address the requirements for cryogenic fuel distribution on aircraft and loading/unloading of cryogenic fuels into tanks.
    3. On-ground airport cryogenic management technologies.
3. Thermal management for turbofan and electrical systems on large hybrid aircraft in the 1- to 20-MW power range. These technologies must be shown to be compatible with typical transport aircraft requirements like external environments between -60 and +60 °C, g loads between +4g and -2g, varying aircraft orientation, and other typical operational constraints. Proposed thermal management technologies must be shown to have an aircraft-level energy use and emissions benefit.

1. Single-phase, two-phase, acoustic or other technologies to move heat from the heat source to the heat exchanger on the plane.
2. Heat pump systems to reject heat from the plane at a lower energy.
3. Liquid-to-air heat exchangers that take heat from the plane and transfer it to the surrounding airflow either through integration with the engine, electric engine, through the outer mold line of the aircraft, or through additional heat exchanger ducts.
4. Thermal capacitance systems that allow the peak thermal loads to be balanced across the aircraft mission, while being light enough to result in a fuel burn benefit.
5. Integrated thermal systems across the entire aircraft/engine platform.

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:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I work should include: (1) details how the specific technology and configuration of the technology in an aircraft concept leads to a benefit; (2) the plan to introduce the technology into a near-term market; (3) clear trade studies and analytical results to justify a Phase II investment; and (4) if possible, prototype hardware component or key parts for high-risk areas or areas of performance risk.

Phase II work should include: (1) final designs and supporting analysis, (2) analysis showing technology benefit to aircraft energy use or emissions, (3) technology to market plan and/or plan for Phase IIe or Phase III SBIR support, (4) hardware demonstrations of technology, (5) written test reports showing performance of hardware, and (6) comparison of analytical estimated performance and actual measured performance of technology or components.

State of the Art and Critical Gaps:

Power extraction from both shafts of a turbofan is still at low TRL and has not been demonstrated for very small turbofans. Most RDEs are not designed in a multidisciplinary and coupled manner with the turbine, and the combined systems lack range and robustness. Combined-cycle gas turbine-fuel cells are still too heavy for flight application and the cost must come down. Cryogenic tanks and pumps need to be made more reliable, less expensive, and lighter weight. The thermal management systems need to be made efficient, reliable, and light weight. Most of these items require a system approach to optimization and a focus on longer more rugged application and ability to keep the cost down.

Relevance / Science Traceability:

Projects that could use this technology are Transformational Tools and Technologies (TTT), Advanced Air Transport Technology (AATT) Project, and Convergent Aeronautics Solutions (CAS).

Zero-emissions technology is an emerging focus of the NASA Aeronautics Research Mission Directorate (ARMD). This topic allows us to engage small business in the activity with a potential path to further funding of ideas developed under this topic through the ARMD projects mentioned above.

Potential advocates Mark Turner (Senior Technologist, Aeropropulsion), Azlin Biaggi-Labiosa (TTT subproject manager), Amy Jankovsky (AATT subproject manager), Fayette Collier (Integrated Aviation Systems Program (IASP) Associate Director for Flight Strategy), Gaudy Bezos-Oconnor (Electrified Powertrain Flight Demonstration (EPFD) Project Manager), and Ralph Jansen.

References:

NASA ARMD Strategic Implementation Plan: https://www.nasa.gov/aeroresearch/strategy
NASA Aeronautics Research: https://www.nasa.gov/aeroresearch
NASA Aeronautics Sustainable Aviation: https://www.nasa.gov/aeroresearch/sustainable-aviation
Electrified Aircraft Propulsion: https://www1.grc.nasa.gov/aeronautics/eap/
NASA Aims for Climate-Friendly Aviation: https://www.nasa.gov/aeroresearch/nasa-aims-for-climate-friendly-aviation
Subsonic Single Aft Engine (SUSAN) Aircraft: https://www1.grc.nasa.gov/aeronautics/eap/airplane-concepts/susan/
Subsonic Single Aft Engine (SUSAN) Transport Aircraft Concept and Trade Space Exploration: https://arc.aiaa.org/doi/pdf/10.2514/6.2022-2179

A1.10: Structural Sensors for Health Monitoring of Hypersonic Vehicles (SBIR)

Lead Center: AFRC
Participating Center(s): GRC, LaRC

Subtopic Introduction:

The U.S. hypersonic ground- and flight-test communities require robust structural sensors that operate in relevant hypersonic environments. The focus of this subtopic is the development of advanced sensors (contact or noncontact) that can inform a vehicle structural health monitoring (SHM) system operating in extreme hypersonic environments (e.g., thermal, vibrational, and acoustic). The long-term goal for the application of this technology would be on an operational, reusable hypersonic aircraft. SHM on such a vehicle/system would allow maintenance requirements and life predictions to be based on the vehicle's/system's actual flight environment history, enabling shorter turnaround times and more "aircraft-like" operations. Such a capability may even offer input into real-time trajectory modification and flight planning in order to improve vehicle/system reliability. While the ultimate goal is the application to operational hypersonic systems, such a capability would also have application to high-speed flight test demonstrators as well as ground test facilities. Such a capability would also be critical to high-supersonic commercial aircraft; although not hypersonic, such systems may experience substantial aerodynamic heating and significant thermal cycling.

At the completion of Phase II and a $1M Small Business Innovation Research (SBIR) investment, the resulting sensor and SHM methodologies will benefit near-term ground- and flight-test opportunities in addition to bringing NASA closer to the goal of "aircraft-like" operations for reusable hypersonic vehicles.

Scope Title: Advanced Structural Sensors for Hypersonic Vehicle Structures and Materials

Scope Description:

High-speed programs in the United States focus on vehicle design, development, and eventual flight testing, with program success often hinging on the ability to use or adapt limited commercial-off-the-shelf technology for vehicle applications. The limited amount of data in the harsh environments [Ref. 1] of hypersonic flight hinders a program effort in at least four ways:

(1) limited data hinders a more complete understanding of vehicle performance in ground/flight testing, (2) it hinders the optimization of vehicle designs, (3) it hinders the ability to quickly assess the flight vehicle readiness for a next flight, and (4) it hinders the ability to recover from potential flight test anomalies more quickly.

Instrumentation systems are composed of sensors and systems, with the sensors being devices that detect or respond to a physical property and the systems being the devices that process and record the sensor response. Both sensors and systems must be developed that can survive and operate in the extreme environment of hypersonic flight (e.g., high temperature, vibration, and acoustic environments).

This scope focuses on the development of advanced sensors (contact or noncontact) for structures and materials operating in extreme environments, with application to both airframe and propulsion systems. Such sensors may include, but are not limited to, the following:

- High-temperature strain gauges for static strains in combined loading conditions.
- Temperature sensor integration on advanced materials and structures.
- Heat-flux gauges for severe temperature gradients in anisotropic materials.
- Acoustic noise measurements at high temperature and vibration levels.
- Vibration measurements at high temperature and acoustic levels.
- Nondestructive evaluation methods for inspection of large structures made from advanced materials.

Ideas are also sought for improved bonding/adhesion techniques as well as concepts that may include integral sensors and/or “smart” structures.

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
- Hardware

Desired Deliverables Description:

For a Phase I effort, the desired deliverable is a proof-of-concept demonstration of a sensor technology and a midterm report outlining the progress of the effort. Demonstration of the proposed sensor in a relevant hypersonic environment is desired but not required. A summary report is expected at the end of Phase I that describes the research effort’s proof-of-concept testing successes, failures, and the proposed path forward to demonstrate the sensor performance in a relevant hypersonic environment.

For a Phase II effort, a maturation of the sensor technology that allows for a thorough demonstration is expected. 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 environmental testing, to work in a flight environment. This relevant environmental testing would satisfy NASA’s technical readiness level expectations at the end of Phase II. At the completion of Phase II and a $1M SBIR investment, there will be a strong pull from both NASA and non-NASA organizations to provide resources to demonstrate and mature promising sensor technologies for near-term ground- and flight-test opportunities.

State of the Art and Critical Gaps:

Advancements in high-speed vehicle development are possible if insights can be gained, analyzed, and used to create new technologies. New insights will require an evolution of current measurement techniques as well as novel forms and integration techniques.
Known gaps include large-area distributive sensing techniques on advanced high-temperature material systems in extreme high-speed environments, advanced techniques for capturing all dimensions of system operation and vehicle health (spatial/spectral/temporal), and data analysis/assessment of the vehicle structure current and predicted future health.

Relevance / Science Traceability:
The technologies developed for this scope directly address the technical and capability challenges in Aeronautics Research Mission Directorate (ARMD) Advanced Air Vehicles Program (AAVP) in the areas of Commercial Supersonic Technology (CST) and Hypersonic Technology (HT) projects and may also support NASA's high-enthalpy ground test facilities, including those within the Aerosciences Evaluation and Test Capabilities (AETC) portfolio.

References:

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-208-2682; April-May 2008; https://ntrs.nasa.gov/citations/20080017096
2. https://www.nasa.gov/aeroresearch/programs/aavp
3. https://www.nasa.gov/aeroresearch/programs/aavp/cst
4. https://www.nasa.gov/aeroresearch/programs/aavp/ht
5. https://www.nasa.gov/aetc

Scope Title: Structural Diagnostic and Prognostic Methodologies for Hypersonic Vehicles

Scope Description:
The focus of this scope is the development of advanced methodologies that synthesize data from a range of extreme environment [Ref. 1] structural sensors into not only real-time SHM but also predictions of component maintenance requirements and life estimates. Such a capability could be applied not only to reusable hypersonic aircraft that experience significant thermal, mechanical, vibrational, and acoustic conditions but also potentially to high-enthalpy ground test facilities to guide maintenance and life predictions of key facility components. Such methodology could integrate data from a range of sensor types and locations—from thermocouple, strain gauge, acoustic, and vibrational measurements on structural elements to heat flux, pressure, and shear measurements of the flow field in and around the vehicle (airframe and propulsion). Sensors may directly or indirectly (e.g., via optical measurement) measure environmental conditions. Data may also be available from accelerometers or a flight computer/guidance, navigation, and control (GNC) system that can provide load and flight condition information. Data from sensors will likely be received at a wide range of frequencies, from tens of Hz to hundreds of kHz.

The goal of this scope is to synthesize such information over the full lifecycle of structural components into a predictive model that advises on component maintenance requirements and useful life estimates. Such methodologies should consider sensor noise, fault tolerance, robustness, and uncertainty quantification.

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:

For a Phase I effort, at a minimum, a report detailing the methodology for diagnostic and prognostic assessment of a structure using a diverse array of structural sensors is desired. In addition, a plan that describes the proof-of-concept demonstration and evaluation of the proposed SHM effectiveness for a structure is desired. The demonstration plans should identify sensors, test environment, test article concept, and the objectives/plan for evaluating the SHM methodology.

For a Phase II effort, the desired deliverable is to mature the technology through a demonstration of the SHM methodology, with relevant sensors, structures, and environments. Ideally, the deliverable would include 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 environmental testing, to work in a flight environment. This relevant environmental testing would satisfy NASA's technical readiness level expectations at the end of Phase II.
At the completion of Phase II and a $1M SBIR investment, there will be a strong pull from both NASA and non-NASA organizations to provide resources to demonstrate and mature promising sensor and data analysis methodologies on available ground- and flight-test opportunities.

State of the Art and Critical Gaps:

With the expected development of reusable hypersonic vehicles, there will be a critical need for advanced methodologies that synthesize data from a range of extreme environment sensors into integrated vehicle health management (IVHM) systems that will support vehicle flight exposure, component maintenance requirements, and life estimates.
Known gaps include the effective use of large-area distributed sensors in extreme high-speed environments to understand the condition of a hypersonic vehicle and predict the remaining life and capabilities of the vehicle structures.

Relevance / Science Traceability:

The technologies developed for this scope directly address the technical and capability challenges in ARMD AAVP in the areas of CST and HT projects and may also support NASA's high-enthalpy ground test facilities, including those within the AETC portfolio.

References:

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-208-2682; April-May 2008; https://ntrs.nasa.gov/citations/20080017096
2. https://www.nasa.gov/aeroresearch/programs/aavp
3. https://www.nasa.gov/aeroresearch/programs/aavp/cst
4. https://www.nasa.gov/aeroresearch/programs/aavp/ht
5. https://www.nasa.gov/aetc

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 the 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 meet the challenges presented by NASA’s 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 subtopic covers 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 technology 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.

For this year’s solicitation, areas of interest emphasizing flight test and measurement technologies will be focusing on digital data processing, telemetry, and optical sensing:

- High-efficiency, secure, digital telemetry techniques and/or systems to enable high-data rate and high-volume telemetry for flight test, including air-to-air and air-to-ground communication.
- Improved processing technologies that can perform low-latency, near-real-time telemetry processing that can utilize open-source operating system.
- Real-time integration of multiple data sources from onboard, off-board, satellite, and ground-based measurement equipment, including recording of data bus/avionics architectures.

- Optical-based measurement methods that capture data in various spectra for conducting quantitative in-flight boundary layer flow visualization and atmospheric modeling.
- Improved ruggedized, wide-bandwidth, wavelength-sweeping laser system design for in situ flight structural health monitoring to be operated in aircraft.

The emphasis here is for technology, preferably both flight hardware prototype(s) and software package(s), 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 FDC (Flight Demonstration and Capabilities) Project. 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, including 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 the A2.01 subtopic.

For technologies with space-only applications, please consider submitting to a related subtopic in the Space Technology Mission Directorate (STMD), as space-only technologies will be considered out of scope for the A2.01 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 generate a mid-term 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, the small business would deliver a prototype that includes beta-style or better hardware and/or software that is suitable to work in ground testing and can be proven, via relevant environment testing, to work in a flight environment. This relevant environment testing would satisfy NASA’s technical readiness level (TRL) 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 advanced telemetry techniques; intelligent internal state monitoring for air and space vehicles; techniques for studying sonic booms, including novel photography techniques; 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 the need for 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 various ARMD programs. FDC is seeking to enhance flight research and test capabilities necessary to address and achieve ARMD's strategic plan.

References:

- NASA's Quesst mission to reduce the loudness of a sonic boom and gather data on human responses to supersonic flight overhead: https://www.nasa.gov/X59
- NASA Armstrong Fact Sheet: NASA X-57 Maxwell: https://www.nasa.gov/X57/
- NASA Armstrong Fact Sheet: Fiber Optic Sensing System: https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-110-AFRC.html
- Schlieren Images Reveal Supersonic Shock Waves: https://www.nasa.gov/centers/armstrong/features/supersonic-shockwave-interaction.html
- NASA's Commercial Supersonic Technology (CST) Project: https://www.nasa.gov/aeroresearch/programs/aavp/cst
- NASA's Revolutionary Vertical Lift Technology (RVLT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/rvlt
- 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, wildfire and 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. Consider these three examples:

1. Remote missions utilizing one or more unmanned aircraft systems (UAS) have a need for autonomous planning algorithms that can coordinate and execute a mission with minimal human oversight.
2. Efforts to enable AAM and to integrate UAS into the National Airspace System (NAS) have a need for detect-and-avoid algorithms, sensor fusion techniques, robust trajectory planners, and contingency management systems.
3. Autonomous contingency management systems have a need for fault detection, diagnostics, and prognostics capabilities.

This subtopic is intended to address these needs with innovative and high-risk research, enabling greater use of autonomy in NASA research, civil aviation, and ultimately the emerging AAM market. In order to better address each research area, this subtopic will have rotating focus areas for each year.

The primary focus of the subtopic for this solicitation is cognition and multi-objective decision making. Any submission must show a strong relevance to this research area to be considered.

Specifically, NASA is seeking technologies (e.g., algorithms, sensor packages) that transform the raw data into actionable information and then make decisions based on this information. The raw data utilized should be key to the autonomous system's situational awareness, such as the environment during flight or other vehicles that could interact with the UAS. The technologies would then use the resulting information to create actions (such as a turning maneuver) that an autonomous UAS could follow.

Some examples of challenges and areas of interest include:

- Detect, recognize, and avoid in the National Airspace System (NAS) by utilizing multiple sensors. These technologies are needed to ensure safety of flight in dense environments such as a city and as the number of vehicles (manned and unmanned) in the airspace increases.
- In-flight trajectory/mission rerouting and planning. These technologies enable more fully autonomous systems that would be able to accomplish their missions or tasks while accounting for factors such as changes in the environment or interaction with other systems.
- Novel approaches to cognition and multi-objective decision making using an artificial-intelligence-based method such as machine learning are also encouraged.

Delivery of prototypes is expected by the end of Phase II. Prototype deliverables such as toolboxes, integrated hardware prototypes, training databases, or development/testing environments would allow for better possible infusion of the proposed technology into current and future NASA programs and projects.

It is important to note that any proposals for UAS aircraft development will not be considered.

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 10.2 Reasoning and Acting

Desired Deliverables of Phase I and Phase II:

- Analysis

- Prototype
- Hardware
- Software
- Research

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, and a plan to overcome the remaining barriers.
- 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.
- 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, and a plan to overcome the remaining barriers.
- 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 ensures 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, for the overall subtopic, the technologies that will be required to advance the state of the art are as follows:

- A certification process for complex nondeterministic algorithms.
- Prognostics, vehicle health, and sensor fusion algorithms.
- Decision-making and cooperative planning algorithms.
- Secure and robust communications.

For this solicitation, technologies needed to advance the state of the art are:

- Contingency decision-making algorithms.
- Advanced sensor packages that increase situational awareness.
- Decision-making algorithms that use advanced sensor packages to enable full autonomous operation.

Relevance / Science Traceability:
This subtopic is particularly relevant to the NASA Aeronautics Research Mission Directorate (ARMD) Strategic Thrust 6 (Assured Autonomy for Aviation Transformation) as well as Strategic Thrust 5 (In-Time System-Wide Safety Assurance).

- 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:

- Strategic Implementation Plan for NASA's ARMD: https://www.nasa.gov/aeroresearch/strategy
- 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
- UAS Integration in the NAS Project (concluded Sept 2020): https://www.nasa.gov/aeroresearch/programs/iasp/uas
- Enabling Autonomous Flight and Operations in the NAS Workshops: https://nari.arc.nasa.gov/aero-autonomy
- NASA Explores "Smart" Data for Autonomous World: https://www.nasa.gov/aeroresearch/nasa-explores-smart-data-for-autonomous-world
- Autonomous Systems Research at NASA's Armstrong Flight Research Center: https://www.nasa.gov/feature/autonomous-systems

Focus Area 20 Airspace Operations and Safety

This focus area includes technologies supporting 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 the 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 future air transportation system will include the integration of new types of vehicles such as unmanned vehicles, advanced subsonic aircraft, supersonic or commercial space vehicles; new types of emerging business models or operations such as urban air mobility/advanced 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 for Traditional Aviation Operations (SBIR)

Lead Center: ARC
Participating Center(s): LaRC

Scope Title: Advanced Air Traffic Management for Traditional Aviation Operations

Scope Description:
NASA has delivered advanced technologies to the Federal Aviation Administration (FAA) to improve the efficiency of operations in our National Airspace System (NAS), and we are working on capabilities to make NAS operations more efficient and sustainable. The FAA has recently developed a plan for modernization of the airspace, infrastructure, and safety assurance capabilities to transition to a more automated and information-centric system in the 2035 timeframe. This vision is called Info-Centric NAS. NASA is also working closely with the FAA and the aviation community to develop a vision and research roadmap for the future of aviation in the next 25 years and beyond: a concept called Sky for All, which seeks to develop an airspace that is scalable, accessible, safe,

sustainable, and resilient, enabling seamless access for all. As we look toward the future of aviation, the diversity, density, complexity, and volume of proposed operations necessitates a number of paradigm shifts to ensure system scalability and the evolution from trajectory-based operations to collaborative and highly automated operations.

This subtopic is intended to spur or accelerate the development of new air traffic management concepts, techniques, tools, and technologies that will improve the efficiency, capacity, and/or environmental compatibility of "conventional" civil aviation operations in the NAS—commercial airline operations that most of the American public has contact with today.

Proposals should target current-day operations, near-term future operations (circa 2035), or far-term future operations (circa 2045). For perspective on operations in the latter timeframes, proposers may consider the FAA's "Info-Centric NAS" vision for 2035 and NASA's "Sky for All" vision for 2045.

Areas of interest include, but are not limited to:

- Airspace services or capabilities that are scalable and adaptation-independent using advanced methods such as machine learning or artificial intelligence.
- Digital routing and rerouting around weather and constrained airspace resources using ground-based or cockpit-based systems.
- Advanced tools or methods that enable or accelerate the transition to safe, end-to-end trajectory-based operations (TBO) for domestic and oceanic airspace.
- Capabilities that facilitate the scalable integration of autonomous or remotely piloted cargo aircraft (i.e., large unmanned aircraft systems (UAS)) into the conventional NAS structure using conventional (or similar) procedures, including teaming collaborations between the human operator and the autonomous agent/technology for operations involving a remote pilot (during near-term and far-term operations).

Proposals that focus on any of the following areas will not be considered, as they are outside the scope of this subtopic: small UAS operations, advanced air mobility (AAM) operations, electric vertical-takeoff-and-landing (eVTOL) aircraft operations, Class E airspace operations, and Upper Class E airspace operations.

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 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 aviation 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 AOSP and have resulted in successful technology transfer to external stakeholders (including the FAA and the air transportation industry).

References:
NASA Airspace Operations and Safety Program website: https://www.nasa.gov/aeroresearch/programs/aosp
FAA's "Info-Centric NAS" Vision: https://www.faa.gov/about/office_org/headquarters_offices/ang/icn
NASA's "Sky for All" website: https://nari.arc.nasa.gov/skyforall/

A3.02: Advanced Air Traffic Management for Nontraditional Airspace Operations (SBIR)

Lead Center: **ARC**
Participating Center(s): **LaRC**

Subtopic Introduction:
NASA's Aeronautics Research Mission Directorate (ARMD) has 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, referred to as "UAS Traffic Management" (UTM). This work is being adapted to safely and efficiently integrate larger Advanced Air Mobility (AAM) vehicles and operations with existing operations and mission types. NASA is exploring airspace operations incorporating novel aviation operations, including AAM and unmanned vehicles occurring in all airspaces. NASA’s research to enable unmanned vehicles to be safely and fully integrated into the airspace leverages capabilities of a service-based architecture such as that developed for UTM. This has led to new procedures, equipage, operating requirements, and policy recommendations to enable widespread, harmonized, and equitable execution of diverse unmanned missions ranging from urban air taxi to regional cargo delivery and public good missions such as emergency response operations.

Scope Title: Nontraditional Aviation Operations for Advanced Air Mobility (AAM)

Scope Description:
This scope is focused on 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 AAM services will be rejected.
This subtopic seeks proposals with application to AAM including:

- Service-based architecture designs that enable greater scalability of AAM 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 ultra-high 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 vehicle operations (such as electric vertical takeoff and landing).
- Bridging the gap between current-day operations and future operations with state-of-the-art concepts, technologies, and critical gaps as it pertains to teaming collaborations between the human operator and the autonomous agent/technology in current and future National Airspace System (NAS) operations.
    - Increased human-autonomy teaming is needed to accommodate the increasing demand, complexity, and diversity of air transportation missions and operations.

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. However, proposals focused exclusively on cybersecurity will be rejected.

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 (ARMD Thrust 1 Goal) as well as developing autonomy applications for aviation (as under ARMD Thrust 6) that are specifically applicable to AAM operations and address postpandemic 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 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:

Current state of the art: NASA has been researching advanced air transportation concepts and technologies to improve the viability and scalability of AAM operations in the National Airspace System (NAS).

Critical gaps: Significant challenges remain to fully develop the AAM airspace concept of operations, including:

- Integrating air transportation technologies across different domains and operators.
- Providing comprehensive, strategic scheduling and traffic management technologies.
- Enabling concepts that will allow for scaling demand and complexity of operations.

This subtopic is focused on airspace operations for the AAM concept only. Proposals must have clear application to AAM airspace operations. Proposals that focus on AAM vehicle capabilities or onboard vehicle technologies or systems will be rejected. Proposals that are specific to other nontraditional operations (e.g., space traffic management, automated air cargo, UTM, and ultra-high-altitude operations) without clear application to AAM will be rejected.

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 AAM concepts and technologies and scale them up to meet the needs of everyday travelers. The technologies may also leverage new autonomy/artificial intelligence/data science methods and approaches.

References:

- https://www.nasa.gov/aeroresearch/programs/aosp
- https://www.nasa.gov/aeroresearch/strategy

Scope Title: Nontraditional Aviation Operations for Wildfire Response

Scope Description:

In the United States, wildfires are becoming increasingly severe and costly in terms of acreage burned, property damaged, 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's history of contributions to wildfire and other disaster management includes remote sensing, instrumentation, mapping, data fusion, and prediction. More recently, the NASA 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 adapted to safely and efficiently integrate larger Advanced Air Mobility (AAM) 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 smoke-jumpers 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 these:

- 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.

- 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 strategic planning capabilities to collect, process, and disseminate information that enables persistent monitoring of wildland fire conditions (e.g., satellites, conventional aircraft, and UAS).
- Provide strategic planning and tracking capabilities to enable the most effective use of ground crews, ground equipment, and aircraft during operations (e.g., both at a single incident and across multiple incidents).
- Provide strategic planning capabilities that support multimission planning to support efficient mission assignments to support concurrent operations (e.g., air attack and search and rescue).
- Provide an extension to the UTM network that considers the unique needs and characteristics of wildfire disaster situations (e.g., nonconnected environments) and the response to combat them.
- Increase the throughput of available communications, reduce the latency of data transfer, provide interoperability with existing communication solutions, and provide a reliable network for the use of UAS, other aviation assets, and emergency responders on the ground.
- Provide a mobile position, navigation, and timing solution to support automated operations (e.g., automated precision water drops) in Global Positioning System- (GPS-) degraded environments (e.g., mountainous canyons).
- Provide wildland fire prediction, airspace coordination, and resource tracking for a common operating picture for situational awareness that supports various stakeholders in the incident command structure (e.g., incident commander, air tactical group supervisor, aircraft dispatch, UAS pilot, etc.).
- 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 R&D 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 the wildfire fighting environment. Advanced tools and techniques are required to address the following gaps:

- Existing airspace management process is very manual and slow.
- Awareness of aircraft operations is 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; in some cases, fire season is 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.

On June 30, 2021, 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 sectors 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:

- https://www.nasa.gov/aeroresearch/programs/aosp
- https://www.nasa.gov/aeroresearch/strategy

A3.03: Future Aviation Systems Safety (SBIR)

Lead Center: ARC
Participating Center(s): LaRC

Subtopic Introduction:
The System-Wide Safety (SWS) Project within the Airspace Operations and Safety Program (AOSP) is developing an In-Time Aviation Safety Management System (IASMS), a scalable and distributed system approach to address aviation safety needs. IASMS services, functions, and capabilities (SFCs) are structured to “Monitor—Assess—Mitigate” operational safety risks. 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, an area of high interest is methods for monitoring, assessing, and mitigating cybersecurity vulnerabilities and attacks. Innovative approaches and methods that can be easily incorporated into the IASMS are sought those monitor/assess/mitigate vulnerabilities before they can be exploited by malicious actors. Proposals that lack a technology/function that can be integrated into the concept of IASMS will be rejected.

This subtopic seeks innovative proposals addressing one of the following three scopes:

- In-Time Aviation Safety Management System Services, Functions, and Capabilities.
- Verification and Validation (V&V) Technologies for Assurance of Autonomy for Operational Systems.
- Technologies for Monitoring, Assessing, and Mitigating Cybersecurity Vulnerabilities and Attacks.

Scope Title: In-Time Aviation Safety Management System (IASMS) Services, Functions, and Capabilities

Scope Description:

In alignment with Aeronautics Research Mission Directorate (ARMD) Strategic Thrust 5, In-Time System-Wide Safety Assurance, AOSP's SWS Project is developing an IASMS, a scalable and distributed system approach to address aviation safety needs. IASMS services, functions, and capabilities (SFCs) are structured to "Monitor—Assess—Mitigate" operational safety risks. 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. 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 IASMS will be rejected. Proposals are sought whose technologies can be integrated into IASMS:

- Address safety-critical risks identified for beyond-visual-line-of-sight operations in small and large unmanned aircraft systems (UAS), such as:
    - Flight outside of approved airspace.
    - Unsafe proximity to people/property.
    - Critical system failure (including loss of command-and-control link, loss of or degraded Global Positioning System (GPS) coverage, loss of power, and engine failure).
    - Loss of control (i.e., outside envelope or flight control system failure).
- Supporting safety prognostic decision-support tools, automation, techniques, strategies, and protocols:
    - Support real-time safety assurance (including in-time monitoring of safety requirements).
    - Consider operational context as well as operator state, traits, and intent.
    - Integrated prevention, mitigation, and recovery plans with information uncertainty and system dynamics in small and large UAS and trajectory-based operations environment.
    - Enable transition from a dedicated pilot in command or operator for each aircraft (as required per current regulations) to single-pilot operations.
    - Enable efficient management of multiple unmanned and Advanced Air Mobility (AAM)/Urban Air Mobility (UAM) aircraft in civil operations.
- Develop, apply, and assure IASMS services, functions, and/or capabilities to emergency response missions using aerospace vehicle operations. Operations may include 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. In particular, new technologies are sought that address AOSP SWS Project efforts to develop an IASMS.
- 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. AOSP is addressing this challenge with a major area of focus on In-Time System-Wide Safety Assurance (ISSA)/IASMS.

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, extracting relevant information from diverse data sources, and identifying anomalous behaviors to help predict hazardous events and evaluate safety risk. This subtopic contributes technologies toward those objectives.

References:

https://www.nasa.gov/aeroresearch/programs/aosp

Scope Title: Verification and Validation (V&V) Technologies for Assurance of Autonomy for Operational Systems

Scope Description:

In alignment with ARMD Strategic Thrust 5, In-Time System-Wide Safety Assurance, AOSP's SWS Project is developing an IASMS, a scalable and distributed system approach to address aviation safety needs. IASMS services, functions, and capabilities (SFCs) are structured to “Monitor—Assess—Mitigate” operational safety risks. 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. New methodologies for V&V of these capabilities are needed to ensure safe operations within the National Airspace System (NAS). Proposals that lack a technology/function that can be integrated into the concept of IASMS will be rejected.

Proposals are sought whose technologies can be integrated into IASMS:

- Address safety-critical risks identified in beyond-visual-line-of-sight operations in small and large UAS, such as:
  - Flight outside of approved airspace.
  - Unsafe proximity to people/property.

    - Critical system failure (including loss of command-and-control link, loss of or degraded GPS, loss of power, and engine failure).
    - Loss of control (i.e., outside envelope or flight control system failure).
- Supporting safety prognostic decision support tools, automation, techniques, strategies, and protocols:
    - Support real-time safety assurance (including in-time monitoring of safety requirements).
    - Consider operational context, as well as operator state, traits, and intent.
    - Integrated prevention, mitigation, and recovery plans with information uncertainty and system dynamics in small and large UAS and trajectory-based operations environment.
    - Enable transition from a dedicated pilot in command or operator for each aircraft (as required per current regulations) to single-pilot operations.
    - Enable efficient management of multiple unmanned and AAM aircraft in civil operations.
    - Assure safety of air traffic applications through V&V tools and techniques used during certification and throughout the product life cycle.

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. In particular, new technologies are sought that address AOSP SWS Project efforts to develop an IASMS.
- 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. AOSP is addressing this challenge with a major area of focus on ISSA/IASMS.

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 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, extracting relevant information from diverse data sources, and identifying anomalous behaviors to help predict hazardous events and evaluate safety risk. This subtopic contributes technologies toward those objectives.

References:
https://www.nasa.gov/aeroresearch/programs/aosp

Scope Title: Technologies for Monitoring, Assessing, and Mitigating Cybersecurity Vulnerabilities and Attacks

Scope Description:
In alignment with the ARMD's Strategic Thrust #5, In-Time System Wide Safety Assurance, AOSP's SWS Project is developing an In-Time Aviation Safety Management System (IASMS), a scalable and distributed system approach to address aviation safety needs. IASMS services, functions, and capabilities (SFCs) are structured to "Monitor—Assess—Mitigate" operational safety risks. 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. Due to the increasingly digital transformation of the airspace system and nature of the IASMS, an 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. Proposals that lack a technology/function that can be integrated into the concept of IASMS will be rejected.

Proposals are sought whose technologies can be integrated into IASMS where potential cybersecurity or cyber-physical attack can affect any or all operations within UAS airspace system.

- Research and development of ISSA objectives:
    - Detect and identify system-wide safety anomalies, precursors, and margins.
    - Automatic remediation actions to restore sufficient network or application services to support mission essential functions.
    - Develop safety-data-focused architecture, data exchange model, and data collection mechanisms.
    - Enable simulations to investigate flight risks.

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. In particular, new technologies are sought that address AOSP SWS Project efforts to develop an IASMS.
- 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. AOSP is addressing this challenge with a major area of focus on ISSA/IASMS.

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 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, extracting relevant information from diverse data sources, and identifying anomalous behaviors to help predict hazardous events and evaluate safety risk. This subtopic contributes technologies toward those objectives.

References:
https://www.nasa.gov/aeroresearch/programs/aosp

A3.05: Advanced Air Mobility (AAM) Integration (SBIR)

Lead Center: HQ
Participating Center(s): LaRC

Subtopic Introduction:
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 (RAM), low-altitude mobility (LAM) (e.g., 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 composed of three pillars: vehicle, airspace, and community. The specific scopes within this subtopic are intended to be crosscutting and focused on technologies and capabilities that will benefit stakeholders within all three pillars.

Scope Title: Advancing Lidars for Use for AAM Operations

Scope Description:
Measurement of wind and turbulence is likely to be critical in realizing the proliferation of safe and efficient AAM. These measurements are needed in the AAM flight environment of the atmospheric boundary layer, where there is currently a gap in weather observations. Required capabilities are for wind profiles (wind vector vs. altitude) resolutions better than 1 m/s of speed, 5° of direction, and less than 5 m in vertical altitude increment. In addition, profiles of turbulence (quantified such as by turbulence kinetic energy, eddy dissipation rate, or structures) are needed. Since these wind parameters can be short-lived or spatially small, measurements are required with integration times on the order of seconds. Many research-grade studies and demonstrations have shown the capability of coherent Doppler wind lidar to make the needed measurements. However, existing wind lidar technology is bulky, expensive, and complex. Solutions are thus sought for improving the performance, size, weight, power, and cost of coherent Doppler wind lidar.

Both ground-based and airborne wind lidars are of interest. Ground-based implementations would be used at vertiport locations to monitor conditions aloft of wind and turbulence. Airborne wind lidars, with the lidar attached to a vehicle in flight, would be used to offer look-ahead measurements of wind and turbulence for possible avoidance or active-control mitigation actions. In either ground or airborne applications, laser eye safety is a critical requirement.

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:
- Research
- Prototype
- Hardware

Desired Deliverables Description:
Phase I deliverables should include an instrument system-level design and/or simulation study. In addition, a laboratory demonstration would be desirable for a critical component or subsystem that forms the crux of the system-level design. Phase II deliverables would progress to a system-level instrument for field testing of wind and turbulence measurements.

State of the Art and Critical Gaps:
Critical gaps in technology include:
- Ground-based, upward-looking wind lidar system for profiling wind and turbulence of cost less than currently available commercial systems. Alternatively, lidars are of interest with performance exceeding current commercial systems in range capability out to 10-km distance in typical North American wintertime atmospheric boundary layer conditions.
- Airborne wind lidar systems of size, weight, and power amenable to attachment to a variety of AAM vehicle types. A capability for wind measurements to at least 100 m of distance ahead of the aircraft is needed.

Relevance / Science Traceability:

Next generation lidars will directly benefit the safety, scalability, and ability to incorporate automation within the AAM system.

References:

[1] National Research Council, Laser Radar: Progress and Opportunities in Active Electro-Optical Sensing (National Academies Press, Washington, DC, 2014). www.nap.edu/catalog/18733.html
[2] Button, Keith. "Weather Woes." Aerospace America, AIAA: https://aerospaceamerica.aiaa.org/features/weather-woes/

Scope Title: Weather Measurement Network Design Tool

Scope Description:

Weather requirements for safe, efficient, and scalable AAM operations include the collection, translation, and usage of weather information exchanged between entities. As the lower-altitude air-mobility airspace where AAM operations occur is a highly dynamic environment in which conditions vary rapidly, both spatially and temporally, weather conditions will at times be an impactful and even significant hazard. Adequate weather information away from airports and in challenging environments (e.g., urban areas) is necessary to ensure conditions are captured in a timely and cost-effective way and that the conditions fall within regulatory and safety constraints. The specific weather information requirements (e.g., resolution, accuracy, precision, and refresh rate) for different parameters (e.g., temperature, wind speed, wind shear, icing, turbulence, and pressure) is highly dependent on vehicle specifications and type certification; vertiport location and configuration; and airspace procedure design, density of operations, and other factors. To address this dependency, the current draft of the ASTM Weather Supplemental Data Service Provider (SDSP) standard has categorized weather measurements into three tiers. Similar to Instrument Landing Systems (ILS) categories, weather measurements with the greatest accuracy are Tier 3, followed by Tier 2, and sensors able to make less-accurate measurements would provide Tier 1 information.

To effectively provide weather measurements to support AAM operations, sensors not only need to be accurate, but they also need to be cost effective. Sensor assessment factors include:

- Number and types of measurements the sensor takes
- Accuracy
- Performance (e.g., temperature range -5° to 110° F)
- Range
- Latency
- Reliability
- Self-test capability
- Number of operational constraints
- Cost (purchase and operations)
- Density to adequately cover an area considering siting limitations and micro-weather diversity and geography
- Life expectancy
- Data transmission path
- Dependencies (power, internet, and computing power to process data to determine measurement)
- In situ sensing (generally most accurate), remote sensing (less precise), derived (cameras)
- Physical size and weight

Proposals under this scope shall propose a phased effort to provide a capability to design scalable, robust, and tailored weather-sensing networks. Phase I efforts would consist of two complementary efforts. The first would be to develop a catalog of available AAM sensors and technologies utilizing the sensor factors above. Part of this catalog would include hypothetical sensors/technologies and their parameters necessary to provide weather measurements for UAM Maturity Level 4 (UML-4)* operations in multiple environments. The other Phase I effort would be to develop the architecture and identify the needed data sources for a tool that could design a weather-sensing network composed of the real and hypothetical sensors. This tool could provide results tailored for specific localities and missions (e.g., RAM or LAM). The tool would also provide expected performance of the system over geographic areas (e.g., Tier 3 in areas of expected high density AAM traffic or Tier 2 in areas of less traffic density). The tool would also provide the expected cost and other parameters (e.g., the need for reliable wireless data networks).

Phase II efforts would be to build a prototype of the tool for a specific regional or statewide RAM instantiation and to enhance the catalog with additional real and hypothetical sensors/technologies necessary to make the resulting weather-measurement system cost effective and robust.

*UML-4 defined: UML-4 is characterized by medium total traffic levels, medium-complexity operations, and reliance on collaborative and responsible automation. UML-4 is anticipated to be enabled following several key regulatory changes that significantly increase the reliability of UAM transportation and its scalability. These regulatory changes would extend UAM operations into instrument meteorological conditions (IMC) and reduce the specialized skills and associated training needed by human pilots and controllers as high-assurance automated systems are trusted to perform selected safety-critical functions. At UML-4, UAM is expected to be practical in many U.S. metropolitan areas, not just areas with predominately visual meteorological conditions (VMC) weather. In addition, increasing economies of scale are expected to make UAM accessible and attractive to a significant percentage of the public for travel between high-density, origin-destination pairs (e.g., commercial airport to business district).

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 11.5 Mission Architecture, Systems Analysis and Concept Development

Desired Deliverables of Phase I and Phase II:

- Prototype
- Analysis
- Research
- Software

Desired Deliverables Description:

Phase I would provide the catalog of the sensors and the proposed architecture of the tool documenting the data sources needed, tradeoffs capable within the tool, and ability of the tool to address one or multiple AAM mission types.

Phase II would provide a prototype of the tool and a catalog updated with additional sensors.

State of the Art and Critical Gaps:

Weather Measurement Sensor/Technology Catalog: Current "catalog" does not exist. There are lists of available types of sensors (e.g., anemometers) but no comprehensive source that includes multiple parameters of those sensors, including costs and dependencies that could be utilized to design a network with desired performance at an acceptable cost. This catalog would also be useful to identify sensor and technology gaps for research and future SBIRs.

Weather network design tool: Several initial tools exist that are focused on weather-measurement networks to support small, unmanned aircraft system (sUAS)* operations. This effort would provide an opportunity to develop/expand those tools to RAM and UAM along with incorporating the concept of tiered weather measurement accuracy that's being incorporated into the draft UAS Weather SDSP standard.

*FAA 107-2 Advisory Circular definitions:
4.2.6 Small Unmanned Aircraft (UA). A UA weighing less than 55 pounds, including everything that is onboard or otherwise attached to the aircraft, and can be flown without the possibility of direct human intervention from within or on the aircraft.
4.2.7 Small Unmanned Aircraft System (sUAS). A small UA and its associated elements (including communication links and the components that control the small UA) that are required for the safe and efficient operation of the small UA in the National Airspace System (NAS).

Relevance / Science Traceability:

Airspace Operations and Safety Program (AOSP) - Air Traffic Management - eXploration (ATM-X), AAM, and System-Wide Safety (SWS) for use of sample datasets derived from proposed and/or actually built networks to support validation of airspace decision-support tools, airspace and aircraft automation capabilities, and to support development and validation of In-time Aviation Safety Management System (IASMS) tools.

Transformative Aeronautics Concepts Program (TACP) - Convergent Aeronautics Solutions (CAS) catalog will inform with gaps in sensor technologies and areas for potential future CAS projects.

Advanced Air Vehicles Program (AAVP) - Revolutionary Vertical Lift Technology (RVLT) could utilize sample datasets to inform future work in the areas of ride quality and weather-tolerant aircraft.

References:

[1] Patterson, M. P. “Advanced Air Mobility (AAM): An Overview and Brief History,” Transportation Engineering and Safety Conference, 10 Dec 2021. https://ntrs.nasa.gov/citations/20210024608
[2] Hill, B. P., et al. UAM Vision Concept of Operations (ConOps) UAM Maturity Level (UML) 4, 2020. https://ntrs.nasa.gov/citations/20205011091
[3] Antcliff, K., et al. Regional Air Mobility: Leveraging Our National Investments to Energize the American Travel Experience, 2021. https://ntrs.nasa.gov/citations/20210014033
[4] Federal Aviation Administration (FAA). “Unmanned Aircraft Systems (UAS) Traffic Management (UTM) Concept of Operations v2.0: Foundational Principles,” 2020. https://www.faa.gov/sites/faa.gov/files/2022-08/UTM_ConOps_v2.pdf
[5] Levitt, I., et al. (2021). “UAM Airspace Research Roadmap.” NASA/TM-20210019876. NASA, Washington D.C. https://ntrs.nasa.gov/citations/20210019876
[6] Goodrich, K. H., and Theodore, C. R. “Description of the NASA Urban Air Mobility Maturity Level (UML) Scale,” AIAA Scitech 2021 Forum, AIAA 2021-1627. https://doi.org/10.2514/6.2021-1627
[7] NASA AAM Ecosystem Working Groups meetings and recordings. https://nari.arc.nasa.gov/aam-portal/

Scope Title: Enabling AAM Vehicle-to-Vehicle (V2V) Communications – Testbed

Scope Description:

The potential advantages of V2V communications have been widely recognized. The safety benefits enabled by V2V are called out in NASA’s Airspace Research Roadmap. Currently, many unknowns surround the implementation of V2V, including across standards, technologies, procedures, and policy perspective. As such, this area is viewed to have higher risk and a longer return on investment (ROI) compared with other areas within AAM. Consequently, this is an area potentially suited for a small business to have a significant near-term impact, allowing them not only to build a strong foundation in the area of V2V, but also to leverage that foundation to support entities building V2V capabilities in the future.

The expected Phase I effort would be to design a V2V communications testbed, and the Phase II effort would be to build a working prototype of this testbed.

The proposed effort can be focused on either sUAS or passenger-carrying-size electric vertical takeoff and landing (eVTOL), and the proposal should demonstrate the proposer’s thorough familiarity with the current standards efforts in this area. At least two standards organizations are working in this area: Institute of Electrical and

Electronics Engineers (IEEE) Working Groups 1920.1 (Aerial Communications and Networking) and 1920.2 (Vehicle-to-Vehicle Communications for Unmanned Aircraft Systems), and potentially the Radio Technical Commission for Aeronautics (RTCA) AAM Surveillance Spectrum ad hoc Working Group. The proposer should also demonstrate in the proposal familiarity with and the intent to leverage other relevant V2V efforts (e.g., ground vehicles, robotics, and medical equipment).

Phase I specifics

The Phase I effort should result in a design and documented requirements of a V2V testbed. The design developed during the course of this effort should consider equipment, location(s), and architecture(s) required to meet the potential requirements of:

- Standards organizations working to develop standards necessary to enable V2V.
- Federal Aviation Administration (FAA) V2V-related research.
- NASA's airspace projects' V2V-related research.
- NASA's aviation safety project's In-time Aviation Safety Management System (IASMS) research enabled by V2V capabilities.
- NASA's automation research being considered for testing as part of the National Campaign's Integration of Automated Systems (IAS) testing.
- At least two potential vehicle operators (sUAS and/or eVTOL).
- At least one avionics manufacturer.
- At least three V2V academic subject matter experts.

The design should also consider costs (e.g., to build, operate, maintain, and evolve), portability (e.g., the ability to provide services in different locations), spectrum permissions, security, versatility (e.g., reconfigurable avionics or ability to simulate or incorporate the testbed into actual flight demonstrations), and opportunities for early commercialization.

Phase II specifics

The Phase II effort to build the working prototype should consider:

- Near-term commercialization opportunities from the potential stakeholders interviewed during Phase I.
- Opportunities to support standards development and research and reduce ecosystem ROI timeline.
- Partnering with at least one vehicle operator to exercise prototype testbed.
- Documenting which of the requirements identified in Phase I are achievable in the prototype testbed and those that would require further enhancement in a matured testbed.

Expected TRL or TRL Range at completion of the Project: 1 to 3

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
- Analysis
- Research
- Hardware
- Software

Desired Deliverables Description:

The Phase I effort under this SBIR would be to design a V2V communications testbed, and the Phase II effort would be to build a working prototype of this testbed. More detail can be found in the scope description.

State of the Art and Critical Gaps:

Advances are being made in this area in the fields of ground vehicles, robotics, and medical devices. While these efforts incorporate safety critical aspects, none are likely to combine those associated with aviation including passenger carrying flights over nonparticipating people and land, spectrum limitations and potential interference, stringent regulatory requirements for equipment and procedures, and the importance of ecosystem stakeholder support in the development of standards.

The safety, efficiency, and scalability improvements possible with the implementation of V2V communications make this capability critical to achieving UML-4 operations.

Current standards efforts are leveraging the advances mentioned, but the timeline for the ROI in this area still puts it beyond that of larger companies. Additionally, the technical and regulatory uncertainty also increase the risk for this investment. The development and validation of standards will require sharing of some information that could be considered competition sensitive. A communications testbed requires resources and equipment challenging to obtain for resource-constrained entities. Lastly, to be truly impactful, some level of the results achieved during tests will need to be made available to standards bodies to obtain ecosystem stakeholder buy-in and validation of those standards.

Relevance/Science Traceability:

This effort would potentially support the efforts of ARMD's ATM-X, AAM, and SWS projects. It could also inform the Sky4All effort along with efforts currently being considered such as support to firefighting operations.

The effort as described is a current gap in Aeronautics Research Mission Directorate (ARMD) Communications, Navigation and Surveillance (CNS) research portfolio, and having a testbed in the 2024 and out timeframe would greatly benefit multiple research efforts.

References:

[1] Patterson, M. P. “Advanced Air Mobility (AAM): An Overview and Brief History,” Transportation Engineering and Safety Conference, 10 Dec 2021. https://ntrs.nasa.gov/citations/20210024608

[2] Hill, B. P., et al. UAM Vision Concept of Operations (ConOps) UAM Maturity Level (UML) 4, 2020. https://ntrs.nasa.gov/citations/20205011091

[3] Antcliff, K., et al. Regional Air Mobility: Leveraging Our National Investments to Energize the American Travel Experience, 2021. https://ntrs.nasa.gov/citations/20210014033

[4] Federal Aviation Administration (FAA). “Unmanned Aircraft Systems (UAS) Traffic Management (UTM) Concept of Operations v2.0: Foundational Principles,” 2020. https://www.faa.gov/sites/faa.gov/files/2022-08/UTM_ConOps_v2.pdf

[5] Levitt, I., et al. (2021). “UAM Airspace Research Roadmap.” NASA/TM-20210019876. NASA, Washington, D.C. https://ntrs.nasa.gov/citations/20210019876 and https://nari.arc.nasa.gov/uam-research-roadmap

[6] Goodrich, K. H., and Theodore, C. R. “Description of the NASA Urban Air Mobility Maturity Level (UML) Scale,” AIAA Scitech 2021 Forum, AIAA 2021-1627. https://doi.org/10.2514/6.2021-1627

[7] NASA AAM Ecosystem Working Groups meetings and recordings, specifically Sept. 21, 2021, and April 19, 2022. https://nari.arc.nasa.gov/aam-portal/

[8] Chakrabarty, Anjan, et al. (2020)."Vehicle to Vehicle (V2V) Communication for Collision Avoidance for Multi-Copters Flying in UTM -TCL4." https://ntrs.nasa.gov/api/citations/20200001198/downloads/20200001198.pdf

[9] Reliable, Secure, and Scalable Communications, Navigation, and Surveillance (CNS) Options for Urban Air Mobility (UAM). https://ntrs.nasa.gov/api/citations/20205006661/downloads/UAM%20CNS%20Final%20Report%2080GRC019D0017%20with%20App%20A%20B%20C%20v2.pdf

[10] Data Communications Considerations and Approaches for the Future, GAMA EPIC Data Communications Ad-hoc Committee Whitepaper, Version 1.0, March 2021.

https://gama.aero/documents/epic-whitepaper-data-communications-and-approaches-for-the-future-version-1-0-april-2020
[11] Wing, David, et al. "Applicability of Digital Flight to the Operations of Self-Piloted Unmanned Aircraft Systems in the National Airspace System."
https://ntrs.nasa.gov/api/citations/20210025961/downloads/NASA-TM-20210025961.pdf

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 spacecrafts 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 lower cost, 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 as well as, 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 novel integrated communications and navigation devices for use well beyond Earth, with improved power management and robust tolerance of the harsher thermal and radiation environment of deep space. 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 missions. 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 the autonomous operation of spacecraft or for the 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:
•https://www.nasa.gov/directorates/spacetech/small_spacecraft/index.html
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: Integrated Deep Space Navigation and Communications

Scope Description:
Communications and navigation technologies for small spacecraft beyond low Earth orbit (LEO) 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 envisioned science missions within the decadal surveys and contribute to the success of human exploration missions, including construction of the lunar communications architecture [Ref. 12]. Primary applications include data relay from lunar surface to surface, data relay to Earth, and navigational aids to surface and orbiting users. Considerations for technology and capability extension to the Martian domain and other deep space applications are also solicited. Distributing these capabilities across multiple small satellites may be necessary because of limited size, weight, and power (SWaP), but also to enhance coverage.

NASA is seeking efforts to develop relative and absolute navigation systems and technologies that are integrated with the small spacecraft's communication system. Depending on the integration approach, the navigation system may share radio-frequency (RF) or optical components, digital processing components, and/or a distributed implementation across the small satellite cluster. Synergies should allow for a significant reduction in SWaP when compared to each SmallSat employing an independent navigation system. Having 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 and contribute to the success of Artemis human exploration missions.

Multiple small spacecraft operating in coordinated orbital geometries or performing relative stationkeeping 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 navigation 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 stationkeeping/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 rangefinding 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. Improvements in 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. Most 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.
Solutions can operate anywhere in the electromagnetic spectrum; 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 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 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, with the Iris transponder being SOA. 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. Additional SOA information is found in Reference 10. 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.
- 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. SOA 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. 8]. NASA is also partnering with universities for use of surface-feature-based navigation and timing [Ref. 9].

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 DSM concept 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, Commercial Lunar Payload Services (CLPS); human exploration (Artemis) landing site and resource surveys; and communications 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] National Telecommunications and Information Administration Frequency Allocation Chart: https://www.ntia.doc.gov/files/ntia/publications/january_2016_spectrum_wall_chart.pdf
[5] National Telecommunications and Information Administration Tables of Frequency Allocations: https://www.ntia.doc.gov/legacy/osmhome/alloctbl/alloctbl.html
[6] NASA Spectrum Policy and Guidance for Small Satellite Missions: http://www.nasa.gov/directorates/heo/scan/spectrum/policy_and_guidance.html
[7] NASA Space Communications and Navigation: https://www.nasa.gov/directorates/heo/scan/services/overview/index.html
[8] Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE): https://www.nasa.gov/directorates/spacetech/small_spacecraft/capstone
[9] On-Orbit Demonstration of Surface Feature-Based Navigation and Timing: https://www.nasa.gov/feature/ames/nasa-selects-universities-for-collaborative-development
[10] State of the Art Small Spacecraft Technology Report: https://www.nasa.gov/smallsat-institute/sst-soa
[11] Potential Program Users:

- https://www.nasa.gov/topics/moon-to-mars
- https://www.nasa.gov/content/commercial-lunar-payload-services

[12] LunaNet: https://www.nasa.gov/feature/goddard/2021/lunanet-empowering-artemis-with-communications-and-navigation-interoperability

Z8.09: Small Spacecraft Transfer Stage Development (SBIR)

Lead Center: MSFC
Participating Center(s): 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 in order 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 50 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 >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 support services, such as communications relay and/or PNT, post spacecraft deployment. Proposer to outline the performance and duration these support services can achieve for applicable orbital environments, but it is envisaged that at a minimum:
    - The transfer stage is compatible with the Deep Space Network (DSN), or equivalent asset, for communications and tracking, and its estimated position can be determined at values in line with the current state of the art for the target destination. Transfer stage should be able to relay at least 100 MB/week of data using "store and forward" techniques.
    - The transfer stage is able to provide any deployed SmallSat with PNT data such that its relative position to the transfer stage can be established autonomously aboard either vehicle to prevent loss of spacecraft tracking, following deployment without direct communication with Earth assets. In addition or alternatively, if the transfer stage can be repurposed post-deployment to provide longer term communications relay and Global Navigation Satellite System (GNSS)-like PNT services to the deployed SmallSat, that is also of high interest to the subtopic.
    - The transfer stage is able to communicate with any deployed SmallSat at ≥1 kbps in S-, X-, or Ka-band for crosslinks of mission-critical data using Delay/Disruption Tolerant Networking (DTN) protocols, when acting as a communications relay between the SmallSat and Earth.

3. Enable small-cargo delivery and inspections to support on-orbit servicing, assembly, and manufacturing platforms.
4. Examine the use of lower toxicity propellant alternatives to increase system safety for transport, ground handling, and launch operations.

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. 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. 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. Efforts leading to Phase II delivery of an integrated system that could be either 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, stationkeeping, 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 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 near-Earth orbit (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.

References:

- Small Spacecraft Technology Program. https://www.nasa.gov/directorates/spacetech/small_spacecraft/index.html
- Small Spacecraft Technology Report. State of the Art of Small Spacecraft Technology | NASA.
- Lunar Flashlight Mission Overview. What is Lunar Flashlight? | NASA
- CAPSTONE Mission Overview. What is CAPSTONE? | NASA
- Moonbeam Mission Overview. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180007439.pdf
- Report on Sustainable Lunar Infrastructure. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170012214.pdf
- Air Force Eagle Program Overview. https://www.kirtland.af.mil/Portals/52/documents/EAGLE-factsheet.pdf

- Air Force Eagle Mission Article. https://www.c4isrnet.com/c2-comms/satellites/2018/04/16/air-force-launches-experiment-to-boost-satellite-communications/
- Example SST: Rocket Lab Photon. Satellite Solutions | Rocket Lab (rocketlabusa.com)
- Example SST: Bradford Green Prop Systems. Bradford ECAPS - High Performance Green Propulsion Thrusters
- Example SST: AR Green Prop Systems. Green Propulsion | Aerojet Rocketdyne
- Example SST: AR Cubesat Systems. https://www.rocket.com/sites/default/files/documents/CubeSat%20Mod%20Prop2sided.pdf
- Example SST: NG ESPAStar. https://www.northropgrumman.com/wp-content/uploads/DS-23-ESPAStar.pdf
- Deep Space Network (DSN) handbook. https://deepspace.jpl.nasa.gov/dsndocs/810-005/
- Space Frequency Coordination Group (SFCG) handbook. https://www.sfcgonline.org/Resources/default.aspx
- NASA Delay/Disruption Tolerant Networking (DTN). http://www.nasa.gov/content/dtn

Z8.13: Space Debris Prevention for Small Spacecraft (SBIR)

Lead Center: MSFC
Participating Center(s): ARC

Subtopic Introduction:
The rise in individual small spacecraft launches, which also includes increased deployment of small spacecraft swarms, is contributing to congestion in low Earth orbit (LEO) as well as a rapidly increasing population in higher orbit regimes. Between 2012 and 2019, the number of small spacecraft launches increased 5x, with ~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 about the increasing space debris and operational control in a highly congested space (space traffic management) 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]. Several 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 [Ref. 5], as well as significant strain on the current space traffic management architectures to prevent such scenarios [Ref. 6].

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 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.

Scope Title: Onboard Devices for Deorbit and/or Disposal of Single Spacecraft

Scope Description:
Objective: Develop low size, weight, power, and cost (SWaP-C) active and/or passive onboard devices for deorbit and/or disposal of single spacecraft while also efficiently and effectively minimizing the probability of new orbital debris creation during the deorbit or disposal mission phase.

While the challenges posed by space debris and the management of large constellations within that environment are 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. Furthermore, the active deorbit and/or disposal device technologies based upon fueled propulsion systems that make use of nontoxic fuels, "green propellants," are desirable technologies to reduce complexity in the spacecraft vehicle integration process, to maximize launch opportunities, and to encourage a “greener” space domain. In particular, deorbit/disposal technologies that enable even higher orbits than currently possible are desired. Further, technologies that actively or passively enable deorbit or disposal are desired, with consideration of potential risk for creation of new additional debris—that is, technologies that provide active or passive management 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. Last, 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 and have been developed, demonstrated, and even commercialized/sold for mission use. However, capability needs to continue to grow, especially for higher orbital applications with considerations to minimize the risk of new debris creation during the disposal phase of mission, as well as for more controlled deorbit and disposal. This subtopic, in the context of SmallSats, is of high importance to the Small Spacecraft Technology (SST) Program, the Agency, and the Nation in helping avoid a world that lives under the threat of the Kessler syndrome (i.e., exponential, catastrophic production of debris in orbit). Previous instances of this subtopic were focused on drag sails, but more investment is needed to help build and expand the ecosystem to include other onboard deorbit and disposal devices, as well as swarm/constellation management technologies, to help mitigate the risks (including considerations minimizing the probability of new space debris creation during the disposal phase of the mission) raised by the anticipated launch of many thousands more satellites in the years to come, most of which will be SmallSats.

Relevance / Science Traceability:

With increased use of higher orbital regimes by small spacecraft and regulatory attention on short- and 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.

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. Process for Limiting Orbital Debris. 2012. https://standards.nasa.gov/standard/nasa/nasa-std-871914
8. NASA State of the Art of Small Spacecraft Technology. 2020. https://www.nasa.gov/smallsat-institute/sst-soa-2020

Scope Title: Autonomous Space Traffic Management Technologies for Small Spacecraft Swarms and Constellations

Scope Description:

Objective: Develop technological solutions for enhanced autonomous space traffic management that relate to the safe operations of SmallSat swarms and constellations, with the aim of reducing the strain on current space traffic management architectures.

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 the generation of orbital debris as a result of collisions 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" [Ref. 4] and therefore was not acted upon, with the impact identified only 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 an 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 stationkeeping 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 Corporation, 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. https://www.nasa.gov/press-release/nasa-spacex-sign-joint-spaceflight-safety-agreement
8. 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 Space Operations Mission Directorate (SOMD) provides mission-critical space operations services to both NASA customers and 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 SOMD 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 the following goal:
Enabling the development of advanced manufacturing technologies and materials that benefit from the use of the unique microgravity 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:

- In Space Production Applications | NASA: https://www.nasa.gov/mission_pages/station/in-space-production-applications
- Space Station Research & Technology: https://www.nasa.gov/mission_pages/station/research/experiments/explorer

H8.01: Low-Earth Orbit Platform and Microgravity Utilization for Terrestrial Applications (SBIR)

Lead Center: ARC
Participating Center(s): JSC, LaRC, MSFC

Scope Title: Use of the ISS to Foster Commercialization of LEO Space

Scope Description:
The NASA In-Space Production Applications (InSPA) portfolio invests in U.S. entities to develop, demonstrate, and master in-space production of goods and materials (including biomaterials) that target important terrestrial markets and lead to the creation of new markets and industries in space. InSPA is a collaboration between NASA and the International Space Station (ISS) National Laboratory to encourage use of the ISS and future low Earth orbit (LEO) platforms that follow the ISS to advance NASA's objective to maintain and strengthen the United States' leadership of in-space manufacturing and production.

This subtopic supports the InSPA Project goals to: (1) serve U.S. national interests by developing materials and technologies that strengthen industry leadership and improve national security; (2) provide benefits to humanity by developing products that significantly improve the quality of life on Earth; and (3) accelerate development of the space economy in LEO by stimulating demand for scalable and sustainable non-NASA utilization of future commercial LEO destinations.

This subtopic seeks proposals that leverage the unique capabilities of the ISS to develop and test new technologies that will lead to in-space manufacturing of advanced materials and products for use on Earth. Proposals should clearly describe how development of its technologies and products will benefit from the space environment to produce advanced materials and products to a level of quality and performance superior to that which is possible on Earth. In addition, the value of the application, the market size, and the role space plays in developing a better product should be clearly presented. The intent is to transition the results of this subtopic into customer-scale, in-space manufacturing products to achieve U.S. Government objectives for developing the LEO economy.

Of specific interest are proposals that plan to develop valuable terrestrial applications that could lead to commercial markets in LEO. The emphasis is on producing goods or materials in space that are superior to what can be achieved on Earth and serve important national needs, benefit humanity, or lead to sustainable markets. Use of the ISS should facilitate validation of these applications and enable development of a product at reduced cost to attract significant capital and lead to growth of new and emerging LEO commercial markets in the following areas: advanced materials and biomanufacturing.

Proposals that can be implemented on the ISS within 4 years from first funds to first flight are highly encouraged to apply. Proposers with little or no flight experience are encouraged to contact the operator of the ISS National Laboratory—the Center for the Advancement of Science in Space (CASIS)—to discuss the practicalities of implementing their concept. Many first-time fliers have succeeded in flying their manufacturing or production prototypes on the ISS over the past 5 years. A high percentage of InSPA Small Business Innovation Research (SBIR) awards going back to 2016 have already flown at least once, and often more than once, on the ISS. In addition, proposed production strategies should be appropriate for the crewed vehicle and fit within the accommodations and constraints of the ISS National Laboratory.
For further information on InSPA goals and opportunities, please visit
https://www.nasa.gov/mission_pages/station/in-space-production-applications

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 the commercial LEO 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 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:

- NASA LEO Economy Strategy: https://cms.nasa.gov/leo-economy/low-earth-orbit-economy and Opportunities to Stimulate Demand | NASA
- Space Station Research & Technology at: https://www.nasa.gov/mission_pages/station/research/experiments/explorer
- 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.

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 extreme environments. Fine dust can foul mechanisms, alter thermal properties, obscure optical systems, abrade textiles, and scratch surfaces. 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 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. Specific extreme environment innovations being sought in this solicitation will be outlined in the subtopic descriptions.

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 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. The properties of the lunar dust, although not fully understood at this time, vary markedly from sources of internally generated dust. For example, particles are known to have a broad size distribution, with sizes in the fine and ultrafine range (<100 nm). They are also irregularly shaped and jagged, with abrasive properties that can damage mechanisms and equipment. There is also the chance that the airborne dust particles could maintain surface charge and be reactive in the Environmental Control and Life Support System (ECLSS) environment. Air quality in the larger living areas (e.g., habitats) 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, crew time spent on cleaning should be minimal. Filtration and separation systems should therefore be as maintenance free as possible, and potentially regenerable, to avoid the cost of flying spares and consumables.

Currently on the International Space Station (ISS), astronauts must weekly vacuum protective screens covering filters to remove larger particles and lint fibers 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. Based on the level of lunar dust contamination, even these 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. Miniaturized aerosol instruments should therefore 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 re-entrained 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) with an initial (clean filter) pressure drop not to exceed 125 Pa and a maximum or end-of-life pressure not to exceed 250 Pa. The system needs to meet requirements for both lunar dust and spacecraft cabin dust (derived from materials in the spacecraft, 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 High Efficiency Particulate Air (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, and its proper storage and disposal.

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, or preferably over the duration of a multi-year mission. 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:

Exploration Systems Development Mission Directorate (ESDMD) and Life Support Systems (LSS) can use this technology. It is absolutely necessary for Artemis and for any dusty planetary destination.

References:

- NASA. NASA Space Flight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health, NASA-STD-3001, Volume 2, Revision B, 2019-09-09.
- NASA. Human Landing System EVA Compatibility IRD, EVA-EXP-0070 (DRAFT), September 23, 2019.
- Agui, Juan; Vijayakumar, R.; and Perry, Jay. Particulate Filtration Design Considerations for Crewed Spacecraft Life Support Systems. 46th International Conference on Environmental Systems, 2016.
- Apollo 17 Technical Crew Debriefing, page 20-12, NASA Manned Spacecraft Center, January 4, 1973, MSC-07631.

Z13.05: Components for Extreme Environments (SBIR)

Lead Center: KSC

Participating Center(s): GRC, JSC, LaRC

Subtopic Introduction:

NASA seeks new technologies to enable sustainable lunar surface operations by developing components capable of operating and surviving in extreme environments. Scalable mechanisms that can operate in cold and dusty environments without active (powered) heating and dust mitigation and human-rated spacecraft components that can freeze and thaw without suffering damage or performance degradation are two examples. Pressurized habitats and rovers operating at the lunar South Pole will be subjected to environmental temperatures as low as -213 °C (-351 °F), and proposals should discuss how the technology will enhance or replace the current state of the art (SOA) technologies and techniques. This solicitation specifically targets proposals for new technologies and methods that clearly address one of the following areas:

- Mechanisms for Extreme Environments
- Freeze-Tolerant Radiators and Heat Exchangers
- Freeze-Tolerant Water Containers

These areas are considered of equal priority, and no award preference is expected for one area over another.

Scope Title: Mechanisms for Extreme Environments

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 extreme environments. The Apollo missions and other lunar exploration have identified significant extreme environment-related problems that will challenge future mission success.

Mechanisms in extreme environments must function in the presence of lunar regolith and charged dust, micrometeoroids, extreme temperature variations, plasma, high-energy cosmic rays and other ionizing radiation, solar ultraviolet (UV) and other electromagnetic (EM) radiation, changing gravitational conditions, and other electrically induced 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 extreme environments and will have little to no maintenance.

New environmentally hardened mechanism technologies also need to be scalable from small exploration-type devices moving a few grams of materials, to larger scale equipment used for materials handling and transport for in-situ resource utilization (ISRU) activities with the capability to move hundreds of kilograms of materials.
This scope seeks scalable mechanism technologies that can function in these environments, including:

- 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 extreme 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 ISRU (sample tools, dust cleaning, landing gear, pointing actuator).
- Materials handling and transportation components (hoist, lift, pallet, pick and place, common transport interface, etc.).
- Implements for regolith moving, digging, pushing, transporting, compacting, and for construction work with regolith in general.

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) (-396 °F).
- 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 cold- and 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, scaled, 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 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 are needed. 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.
- Lubrication required for mobility freezes at operational temperatures.
- 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:
Developing mechanisms for extreme environments will be one of the biggest challenges for operation on the lunar surface for the Artemis program.

References:
Dust Mitigation Gap Assessment Report, International Space Exploration Coordination Group (ISECG): https://www.globalspaceexploration.org/wordpress/docs/Dust%20Mitigation%20Gap%20Assessment%20Report.pdf

Scope Title: Freeze-Tolerant Radiators and Heat Exchangers

Scope Description:
Proposals are sought to develop freeze-tolerant radiators and heat exchangers that can freeze and thaw without suffering damage or performance degradation on human-rated spacecraft on the lunar surface. Current ground rules and assumptions (GRAs) for lunar pressurized habitats include 1) Single-phase nontoxic external and internal active thermal control system (ATCS) coolant loops; 2) Heat exchangers and deployable radiators operating at turbulent flow to remove and reject heat; 3) Operate near the lunar South Pole and survive the lunar nights (lasting up to 14 days), where environmental temperatures can drop below the freezing point of heritage and candidate ATCS coolants (e.g., ammonia, water, Freon, HFE 7200) and as low as -213 °C (-351 °F); and 4) Total heat loads varying between 2 and 15 kW, or 6,824 to 51,182 BTU/hr.

Based on these GRAs, the risk of loss of mission (LOM) due to rupturing radiator and heat exchanger coolant tubes because of freeze-thaw cycles is high, and the development of freeze-tolerant radiators and heat exchangers is necessary to reduce this risk and reduce heater power during Artemis missions.
Specifically, developments in radiators and heat exchangers are sought in these areas:

- Lightweight, corrosion-resistant, freeze-tolerant metallic coolant tubes ranging from 0.127 to 3.81 cm (0.05 to 1.5 in.) inner diameter, 51 to 304 cm (20 to 120 in.) long, and operating under turbulent flow conditions.
- Lightweight, high-strength, corrosion-resistant, freeze-tolerant nonmetallic flexible coolant tubes ranging from 0.127 to 3.81 cm (0.05 to 1.5 in.) inner diameter, 51 to 304 cm (20 to 120 in.) long, and operating under turbulent flow conditions.
- Radiators and exchangers with variable thermal resistance that can temporarily eliminate or reduce heat rejection. Examples include, but are not limited to, low-power (less than 1 kW) devices that are capable of suctioning, temporary storing, then refilling the coolant to and from a radiator or heat exchanger and variable emissivity devices or materials (e.g., louvers, thermochromic and electrochromic coatings).

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

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:

Phase I Deliverables: A proof-of-concept or breadboard demonstrating technical feasibility and operability in a laboratory environment, and a report that includes analytical and model simulations in a relevant environment and heat loads to answer critical questions focused on reducing the risk of freezing radiators or heat exchangers. In addition, the report shall include recommendations for brassboard or prototype development during Phase II.

Phase II Deliverables: Delivery of a brassboard or prototype with a goal of achieving TRL 5 or 6, and laboratory testing demonstrating operability over the range of expected environmental conditions and heat loads. A report shall be written that includes functional, performance, analytical and test results; an evaluation of the technology's maturity level (i.e., TRL); risk of proceeding with the development; and a well-developed flight demonstration and infusion plan.

State of the Art and Critical Gaps:

SOA ATCS on human-rated spacecraft like the Apollo Service Module (SM) and International Space Station (ISS) used mechanically pumped, single-phase coolant to collect, transport, and reject heat, and the components that are most vulnerable to rupturing due to freeze-thaw cycles are the radiators and heat exchangers because they are exposed to the environment. The Apollo SM radiators were designed to partially stagnate, and only the coolant tubes, not the manifolds, in the ISS radiators were designed to withstand the high-pressure transients induced by freeze-thaw cycles. This requires small inner diameters (0.18 cm or 0.07 in.) metallic (Inconel or stainless steel) coolant tubes with thick walls (0.32 cm or 0.125 in.) outer diameters), optimal spacing between tubes, and turbulent flow. Bigger inner diameters may be required for future radiators to enhance hydraulic and thermal performance but increasing the outer diameter to enable freeze tolerance will increase the mass and counter the thermal performance. Similarly, the Apollo SM and ISS heat exchangers used metallic coolant tubes with large inner diameters (2.5 cm or 1 in.) and thin walls to achieve high heat transfer coefficients but increasing the outer diameter for freeze tolerance will impact thermal performance. Inconel and stainless-steel coolant tubes were used in these systems for their higher thermal conductivity, corrosion resistance, and strength for micrometeoroid and orbital debris (MMOD) protection but consequently limit freeze protection. Therefore, nonmetallic flexible coolant tubes that are corrosion resistant with high strength are also desired to enable freeze tolerance while meeting thermal and hydraulic requirements. There are no SoA ATCSs that can vary the thermal resistance of a radiator or heat exchanger to temporarily eliminate or reduce heat rejection, but this capability is desired to enable freeze tolerance.

Relevance / Science Traceability:

Pressurized habitats or rovers stationed near the lunar South Pole for future Artemis missions will be exposed to extremely cold environmental temperatures as low as -213 °C (-351 °F) during lunar nights (up to 14 days), which are below the freezing point of heritage or candidate ATCS coolants (e.g., ammonia, water, Freon, HFE 7200). Preliminary analysis results of the conceptual lunar Surface Habitat ATCS architecture showed significant heater power (up to 4 kW or 13,648 BTU/hr) is required to prevent the coolant from freezing and maintain operations. Thus, freeze-tolerant radiators and heat exchangers are needed to reduce heater power, avoid rupturing the coolant tubes, and reduce the risk of loss of mission (LOM).

References:

- Babiak, S., Evans, B., Naville, D., Schunk, G., "Conceptual Thermal Control System Design for a Lunar Surface Habitat," Thermal Fluids & Analysis Workshop (TFAWS), August 24-26, 2021.

- Binns, D., Hager, P., "Thermal design challenges for lunar ISRU payloads," 50th International Conference on Environmental Systems (ICES), July 12-15, 2021.
- Samonski, F.H., Jr., Tucker, E.M., “Apollo experience report: Command and service module environmental control system,” NASA Technical Note (TN) D-6718, March 1, 1972.
- International Space Station (ISS) Active Thermal Control System (ATCS) Overview. https://www.nasa.gov/pdf/473486main_iss_atcs_overview.pdf

Scope Title: Freeze-Tolerant Water Containers

Scope Description:
Proposals are sought to develop flexible, freeze-tolerant water containers that can survive the extremely cold environmental temperatures at unpressurized and pressurized conditions on the lunar surface. Water recovered from in situ devices may be contained in bags that are subjected to an unpressurized environment on the lunar surface and will be exposed to temperatures from -213 to 127 °C (-351 to 260 °F). The water containers may be brought inside a pressurized habitat or rover at atmospheric conditions, then processed and treated to produce potable water for contingency use. Therefore, the containers need to withstand pressure and thermal cycles, prevent the water from freezing while on the lunar surface, and be flexible so they can shrink when empty to reduce volume and expand when full; full to empty container ratio >100:1 and maximum water mass of 250 kg (555 lbm).

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

Desired Deliverables Description:
Phase I Deliverables: A proof-of-concept or breadboard demonstrating technical feasibility and operability in a laboratory environment, and a report that includes analytical and model simulations in a relevant environment. In addition, the report shall include recommendations for brassboard or prototype development during Phase II.
Phase II Deliverables: Delivery of a brassboard or prototype with a goal of achieving TRL 5 or 6, and laboratory testing demonstrating operability over the range of expected environmental conditions and water volume. A report shall be written that includes functional, performance, and analytical test results; an evaluation of the technology’s maturity level (i.e., TRL); risk of proceeding with the development; and a well-developed flight demonstration and infusion plan.

State of the Art and Critical Gaps:
SOA contingency water containers (CWCs) used on the space shuttle and the International Space Station (ISS) were designed to be stored in an atmospheric environment and were not rated for the vacuum conditions, pressure cycles, and extreme environmental temperatures expected at the lunar South Pole. Current containers have a reasonable water mass to empty volume ratio of 25:1, and the internal space on the ISS and space shuttle constrained the maximum water mass to 45 kg (99 lbm). Critical gaps are the flexible, freeze-tolerant water

containers for unpressurized and pressurized conditions at temperatures ranging from -213 to 127 °C (-351 to 260 °F); full to empty container ratio >100:1; and maximum water mass of 250 kg (555 lbm).

Relevance / Science Traceability:

NASA is developing in situ water retrieval technologies to excavate or drill into regolith-based water deposits from various regions on the lunar surface, then transport, store, and process into potable water, propellant, fuel cell reactants, and life support consumables for Artemis missions.

References:

1. Carter, Layne et al., “Status of ISS Water Management and Recovery,” 49th International Conference on Environmental Systems (ICES), July 7-11, 2019.
2. Tobias, Barry et al., “International Space Station Water Balance Operations,” 41st International Conference on Environmental Systems (ICES), 2011.
3. 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
4. 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.
5. Schultz, P.H., Hermalyn, B., Colaprete, A., Ennico, K., Shirley, M., Marshall, W.S., “The LCROSS cratering experiment,” Science, 330, 2010, pp. 468-472.

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 validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in	Documented test performance demonstrating agreement with analytical predictions. Documented

		environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	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 missions and goals and are possible areas for SBIR funded SBCs 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.

Commercial Lunar Payload Services (CLPS) - NASA is working with several American companies to deliver science and technology to the lunar surface through the CLPS initiative.

Flight Opportunities (Flight Opps) – This NASA program 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. Offerors are encouraged to consult with the Flight Opportunities team and their resources for any technology development that benefits from microgravity testing.

International Space Station (ISS) - 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 of potential transition and infusion opportunities available to each subtopic. Offerors should think of this as a starting point; however, offerors are encouraged to consider these opportunities and their resources for advancing technology development under any of the subtopics.

NASA is not placing any priority on subtopics or awards that fall under these specific opportunities, but rather this is to assist in future planning. 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			
Z10.03	Space Nuclear Propulsion		Yes			

Subtopic #	Subtopic Title	Climate	Moon to Mars	CLPS	Flight Opps	ISS
Z10.04	Materials, Processes, and Technologies for Advancing In-Space Electric Propulsion Thrusters		Yes			
Focus Area 2 Power, Energy and Storage						
S13.07	Energy Storage for Extreme Environments		Yes	Yes		
S16.01	Photovoltaic Power Generation and Conversion		Yes	Yes		
S16.02	Dynamic Power Conversion		Yes	Yes		
Z1.05	Lunar and Planetary Surface Power Management and Distribution	Yes	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		
Z5.08	Integrated Mission Planning and Execution for Autonomous Robotic Systems		Yes	Yes		
Focus Area 4 Robotic Systems for Space Exploration						
S13.01	Robotic Mobility, Manipulation and Sampling		Yes	Yes		
Z5.06	Servicing and Assembly Applications		Yes			
Z5.07	Autonomous Robotic Manipulation, Utilization, and Maintenance		Yes	Yes		
Focus Area 5 Communications and Navigation						
H9.01	Long-Range Optical Telecommunications		Yes		Yes	
H9.03	Flight Dynamics and Navigation Technologies		Yes	Yes	Yes	
H9.08	Lunar 3GPP Technologies		Yes	Yes	Yes	
S16.03	Guidance, Navigation, and Control					
Focus Area 6 Life Support and Habitation Systems						
H3.10	Microbial Monitoring of Spacecraft Environments: Automated Sample Preparation for Sequencing-Based Monitoring	Yes	Yes	Yes	Yes	Yes
H4.08	Anti-Fog Solutions for Spacesuit Helmet		Yes		Yes	Yes
Focus Area 7 Human Research and Health Maintenance						
H12.05	Autonomous Medical Operations		Yes	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						
S11.01	Lidar Remote-Sensing Technologies	Yes	Yes			
S11.02	Technologies for Active Microwave Remote Sensing	Yes	Yes			
S11.03	Technologies for Passive Microwave Remote Sensing	Yes				
S11.04	Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter	Yes				

Subtopic #	Subtopic Title	Climate	Moon to Mars	CLPS	Flight Opps	ISS
S11.05	Suborbital Instruments and Sensor Systems for Earth Science Measurements	Yes			Yes	
S12.06	Detector Technologies for Ultraviolet (UV), X-Ray, and Gamma-Ray Instruments					
S13.05	In Situ Instruments and Instrument Components for Planetary Science		Yes	Yes		
S14.02	In Situ Particles and Fields and Remote-Sensing Enabling Technologies for Heliophysics Instruments					
S15.02	In Situ Sample Preparation and Analysis for Biological and Physical Sciences in a Microgravity Environment					Yes
S16.07	Cryogenic Systems for Sensors and Detectors		Yes	Yes		
S16.08	Atomic Quantum Sensor and Clocks					
Focus Area 10 Advanced Telescope Technologies						
S12.01	Exoplanet Detection and Characterization Technologies					
S12.02	Precision Deployable Optical Structures and Metrology					
S12.03	Advanced Optical Systems and Fabrication/Testing/Control Technologies for Extended-Ultraviolet/Optical to Mid/Far-Infrared Telescopes					
S12.04	X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics					
Focus Area 11 Spacecraft and Platform Subsystems						
S13.03	Extreme Environments Technology		Yes	Yes		
S13.04	Contamination Control and Planetary Protection		Yes	Yes		
Z2.02	High-Performance Space Computing Technology		Yes			Yes
Focus Area 12 Entry, Descent, and Landing Systems						
Z7.01	Entry, Descent, and Landing Flight Sensors and Ground-Testing Technologies		Yes	Yes		
Z7.03	Entry and Descent System Technologies		Yes			
Z7.04	Landing Systems Technologies		Yes	Yes		
Focus Area 13 Information Technologies for Science Data						
S14.01	Space Weather Research-to-Operations-to-Research (R2O2R) Technology Development and Commercial Applications					
S17.01	Technologies for Large-Scale Numerical Simulation					
S17.02	Integrated Campaign and System Modeling	Yes	Yes			
S17.04	Application of Artificial Intelligence for Science Modeling and Instrumentation	Yes				
Focus Area 15 Materials Research, Advanced Manufacturing, Structures, and Assembly						
H5.01	Lunar Surface 50 kW-Class Solar Array Structures		Yes	Yes		
H5.05	Inflatable Softgoods for Next Generation Habitation Systems	Yes		Yes	Yes	

Subtopic #	Subtopic Title	Climate	Moon to Mars	CLPS	Flight Opps	ISS
Z4.05	Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis		Yes			
Z4.07	Advanced Materials and Manufacturing for In-Space Operations		Yes	Yes		
Z14.02	Extraterrestrial Surface Construction		Yes	Yes		
Focus Area 16 Ground & Launch Processing						
H10.01	Advanced Propulsion Systems Ground Test Technology		Yes			
H10.02	Autonomous Operations Technologies for Ground and Launch Systems		Yes	Yes	Yes	
Focus Area 17 Thermal Management Systems						
Z2.01	Spacecraft Thermal Management		Yes			
Focus Area 18 Air Vehicle Technology						
A1.02	Quiet Performance - Airframe Noise	Yes				
A1.04	Electrified Aircraft Propulsion	Yes				
A1.05	Computational Tools and Methods					
A1.06	Electric Vertical Take-Off and Landing (eVTOL) Vehicle Technologies for Weather Tolerant Operations					
A1.08	Aeronautics Ground Test and Measurement Technologies: Sensors and Diagnostic Systems for High-Speed Flows					
A1.09	Zero-Emissions Technologies for Aircraft	Yes				
A1.10	Structural Sensors for Health Monitoring of Hypersonic Vehicles					
Focus Area 19 Integrated Flight Systems						
A2.01	Flight Test and Measurement Technologies					
A2.02	Enabling Aircraft Autonomy					
Focus Area 20 Airspace Operations and Safety						
A2.03	Advanced Air Mobility (AAM) Integration					
A3.01	Advanced Air Traffic Management for Traditional Aviation Operations	Yes				
A3.02	Advanced Air Traffic Management for Nontraditional Airspace Operations	Yes				
A3.03	Future Aviation Systems Safety					
Focus Area 21 Small Spacecraft Technologies						
Z8.02	Communications and Navigation for Distributed Small Spacecraft Beyond Low Earth Orbit (LEO)		Yes			
Z8.09	Small Spacecraft Transfer Stage Development		Yes			
Z8.13	Space Debris Prevention for Small Spacecraft					
Focus Area 22 Low Earth Orbit Platform Utilization and Microgravity Research						

Subtopic #	Subtopic Title	Climate	Moon to Mars	CLPS	Flight Opps	ISS
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						
Z13.02	Components for Extreme Environments		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 provisions, clauses, regulations, and certifications that apply to Phase I submissions and contracts. Each provision, 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. Additional contract clauses may apply at time of award.

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) Provisions and Clauses

52.203-18 PROHIBITION ON CONTRACTING WITH ENTITIES THAT REQUIRE CERTAIN INTERNAL CONFIDENTIALITY AGREEMENTS OR STATEMENTS-REPRESENTATION

52.203-19 PROHIBITION ON REQUIRING CERTAIN INTERNAL CONFIDENTIALITY AGREEMENTS OR STATEMENTS.

52.204-7 SYSTEM FOR AWARD MANAGEMENT.

52.204-8 ANNUAL REPRESENTATIONS AND CERTIFICATIONS (DEVIATION 20-02B)

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.

52.219-6 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)

52.225-1 BUY AMERICAN-SUPPLIES (NOV 2021)

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 Provisions and Clauses

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 PROGRAM. (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.

1852.227-11 PATENT RIGHTS – OWNERSHIP BY THE CONTRACTOR.

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