National Aeronautics and Space Administration
Small Business Innovation Research (SBIR) Phase I
Fiscal Year 2024 Solicitation

Proposal Package Due Date and Time:
March 11, 2024 - 5:00 p.m. ET

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Executive Summary

This solicitation sets the requirements for you, the offeror, to submit a proposal to NASA for Small Business Innovation Research (SBIR) Program Phase I projects in fiscal year (FY) 2024. Chapters 1-8 contain the objectives, deadlines, funding information, eligibility criteria, and instructions to submit a proposal package**.** Chapter 9 contains research and technology topics, categorized by focus areas and subtopics.

The NASA SBIR program supports small businesses to create innovative, disruptive technologies that benefit society and may be used in NASA programs and missions, other government agencies, and/or sold in commercial markets. Different from most investors, the NASA SBIR Program provides equity-free funding for early or "seed" stage research and development.

Important considerations:

Ensure you have the following registrations complete and up to date. If you are not registered, NASA recommends you start immediately.

- SAM.gov registration at https://sam.gov/. You must have a unique Entity Identifier (UEI)
- Registration with the SBIR Firm Registry at https://www.sbir.gov/registration

You must use the Proposal Submissions and Award Management System (ProSAMS) to submit a proposal package. ProSAMS requires firm registration and login and provides a secure connection. To access ProSAMS, go to https://prosams.nasa.gov/. Agencies must assess the security risks presented by offerors with financial ties or obligations to certain foreign countries. SBIR programs may not make awards to businesses with certain connections to foreign entities. See sections 1.1.1 Due Diligence Program to Assess Security Risks and 2.3.1 Disclosures of Foreign Affiliation or Relationships to Foreign Countries for additional details.

1. Program Description

1.1 Legislative Authority and Background

Congress created the Small Business Innovation Research (SBIR) program to support scientific excellence and technological innovation through the investment of federal research funds. The purpose of this investment is to build a strong national economy, strengthen the role of small business in meeting federal research and development needs, increase the commercial application of research results, and foster and encourage participation by socially and economically disadvantaged and women-owned small businesses.

The Small Business Administration (SBA) provides policy through the combined Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. The SBIR and STTR Extension Act of 2022 amended the Small Business Act *(15 U.S.C. 638*) to extend the SBIR and STTR programs until September 30, 2025.

1.1.1 Due Diligence Program to Assess Security Risks

The SBIR and STTR Extension Act of 2022 requires NASA, in coordination with the SBA, to establish and implement a due diligence program to assess security risks presented by offerors seeking a federally funded award. As noted above, the NASA SBIR/STTR Programs follow the policies and practices of the SBA SBIR/STTR Policy Directive. Revisions to the Policy Directive are in effect as of May 3, 2023, and can be viewed through the Federal Register Notice. This revision is incorporated into this solicitation, including Appendix III, "Disclosures of Foreign Affiliations or Relationships to Foreign Countries" as reflected in the Disclosures of Foreign Affiliations or Relationships to Foreign Countries form (see section 2.3.1).

In accordance with Section 4 of the SBIR and STTR Extension Act of 2022, NASA will review all proposals submitted in response to this solicitation to assess security risks presented by offerors seeking an SBIR or STTR award. NASA will use information provided by the offeror in response to the Disclosures of Foreign Affiliations or Relationships to Foreign Countries form and the proposal to conduct a risk-based due diligence review on the cybersecurity practices, patent analysis, employee analysis, and foreign ownership of a small business concern, including the financial ties and obligations (which shall include surety, equity, and debt obligations) of the offeror and its employees to a foreign country, foreign person, or foreign entity.

1.2 Purpose and Priorities

This solicitation sets the requirements for you, the offeror, to submit a proposal to NASA for Small Business Innovation Research (SBIR) Program Phase I projects in fiscal year (FY) 2024. **NASA will release its FY 2024 Phase I SBIR solicitation on January 9, 2024. You must submit completed proposal packages by Monday, March 11, 2024, 5:00 p.m. Eastern.**

The Space Technology Mission Directorate (STMD) directs implementation of the NASA SBIR and STTR programs. The NASA SBIR/STTR Program Management Office (PMO), hosted at the NASA Ames Research Center, operates the programs together with NASA mission directorates and centers. The NASA Shared Services Center (NSSC) manages SBIR and STTR procurements.

Each year NASA mission directorates, programs, and projects identify the research problems and technology needs that the SBIR program will solicit. The range of problems and technologies is broad, and the list of research subtopics varies from year to year to maintain alignment with current interests.

For details on the research subtopic descriptions by Technology Taxonomy, see chapter 9.

1.3 Three-Phase Program

NASA SBIR projects advance through three phases and are described in detail on the NASA SBIR/STTR website: https://sbir.nasa.gov/.

Phase I

Phase I projects should demonstrate technical feasibility of the proposed innovation and the potential for use in a NASA program or mission and/or the commercial market. 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.

Maximum value and period of performance (POP) for Phase I:

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

Phase II

Phase II proposals continue the research and development started in Phase I to bring the innovation closer to use in a NASA program or mission and/or the commercial market. Phase II requires a more detailed proposal of the technical effort and commercialization strategy. Only Phase I awardees are eligible to submit a Phase II proposal at the conclusion of the Phase I contract. NASA will publish a separate solicitation for 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

Phase I and II awards may not be sufficient in either dollars or time to prepare the project for government or commercial use. Therefore, NASA supports small businesses beyond Phase I and II awards with several Post Phase II initiatives. Please refer to the NASA SBIR/STTR website for eligibility, application deadlines, matching requirements and further information.

Phase III

SBIR awardees are eligible to receive sole-source Phase III contracts any time after award of their Phase I contracts. In Phase III, customers outside the SBIR and STTR programs—including NASA programs, other government agencies, or the private sector—fund the further development or use of innovative technologies, products, and services resulting from either a Phase I or Phase II award. Please refer to the NASA SBIR/STTR website for Phase III information.

1.4 Availability of Funds

NASA does not commit to fund any proposal or to make a specific number of awards. NASA may elect to make several or no awards in any specific research subtopic. NASA will determine the number of awards based on the level of appropriated funding provided to the program in FY 2024.

NASA will not accept more than 10 proposal packages from any one offeror. NASA does not plan to award more than five (5) SBIR contracts to any offeror. See sections 3.2 and chapter 4.

1.5 Eligibility Requirements

1.5.1 Small Business Concern (SBC)

You must submit a certification stating that the SBC meet the size, ownership, and other requirements of the SBIR program at the time of proposal package submission, award, and at any other time set forth in SBA's regulations at 13 CFR §§ 121.701-121.705. NASA encourages socially and economically disadvantaged and women-owned SBCs to propose.

1.5.2 SBC Size

You, combined with affiliates, must not have more than 500 employees.

1.5.3 SBIR Restrictions on Level of Small Business Participation

You must be the primary performer of the proposed research effort. To be awarded an SBIR Phase I contract, you must perform at least two-thirds or 67% of the effort, and subcontractors or consultants may perform up to one-third or 33% of the effort.

1.5.4 Place of Performance and American-made Products and Equipment

Congress intends that the Awardee of a Funding Agreement under the SBIR/STTR program should, when purchasing any equipment or a product with funds provided through the Funding Agreement, purchase only American-made equipment and products, to the extent possible, in keeping with the overall purposes of this program.

If a rare and unique circumstance exists (for example, if a supply, material, equipment, product, subcontractor/ consultant, or project requirement is not available in the United States), NASA requires you to provide justification by completing the Foreign Vendor Form. This form must be submitted within the Proposal Budget Form, see section 3.1.3.4. NASA will consider a deviation request during contract negotiation and either approve or decline before award.

If a foreign vendor is proposed, the Phase I contract may be delayed or not awarded.
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	Principal investigator must be primarily employed with the SBC
Employment Certification	For Phase I, the principal investigator must be primarily employed 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 PI employment time is spent in the employ of the SBC, based on a 40-hour workweek. NASA considers a 19.9-hour or more workweek elsewhere to conflict with this rule.
Co-PIs	Not allowed
Deviation Request	NASA will review any deviation requests during negotiation and either approve or decline before award.
Misrepresentation of Qualifications	If you mispresent qualifications, NASA will decline the proposal package or terminate the contract.
Substitution of PIs	To substitute PIs, you must request approval from NASA after award

1.5.6 Restrictions on Venture-Capital-Owned Businesses

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 to this 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 as defined in 1.5.1. Include in the proposal package a copy or summary of the joint venture or partnership agreement that includes, at a minimum, a statement of how the workload will be distributed, managed, and charged. See definitions for Joint Ventures along with examples at 13 CFR 121.103(h).

1.5.8 Required Benchmark Transition Rate

More experienced firms (SBCs with 21 or more Phase I awards) must meet performance benchmark requirements to continue participating in SBIR and STTR programs. The purpose of these benchmarks is to ensure that Phase I offerors that have won multiple prior SBIR and STTR awards are progressing towards commercialization. SBA will notify companies failing the benchmarks as well as the relevant officials at participating agencies like NASA.

Please refer to https://www.sbir.gov/performance-benchmarks for more information.

1.6 NASA Technology Available (TAV) for SBIR Use

You may use technology developed by NASA, or Technology Available (TAV), on SBIR projects. NASA has over 1,400 patents available for licensing, including many patents related to sensors and materials, and over 1,000 available software applications/tools in the Portfolio and Software Catalog via the NASA Technology Transfer Portal, http://technology.nasa.gov.

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 you intend 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. Awardees will request the SUA from the appropriate NASA Center Software Release Authority (SRA) after contract award.

1.6.2 Use of NASA Patent

If you intend to use a NASA patent, you must apply for a nonexclusive, royalty-free evaluation license prior to submitting a proposal. After you have identified a patent to license in the NASA patent portfolio (http://technology.nasa.gov), click the link on the patent webpage ("Apply Now to License this Technology") to NASA's Automated Licensing System (ATLAS) to finalize your license with the appropriate field center technology transfer office. You must provide the completed evaluation license application with the proposal following the directions in section 3.1.3.7.

The evaluation license will automatically terminate at the end of the SBIR contract. License applications are treated in accordance with federal patent licensing regulations 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.

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. This is a time-consuming process and therefore, NASA does not recommend it for Phase I projects.

1.7 I-Corps™

NASA partners with the National Science Foundation (NSF) to give Phase I awardees the opportunity to participate in the NSF Innovation Corps (I-Corps™) program. I-Corps enables you to conduct customer discovery to learn your customers' needs, to obtain a better understanding of your company's value proposition, and to develop an outline of a business plan for moving forward. 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. For more information on the NASA I-Corps program, visit the NASA SBIR/STTR website.

If you are selected for Phase I contract negotiations, you will be provided the opportunity to opt into and participate in the NASA SBIR/STTR I-Corps program as indicated in section 3.1.3.9.

The amount of funding is up to $10,000 to support participation in the shortened I-Corps version for SBIR awardees. I-Corps awards will be made separately with a modification to the Phase I contract.

1.8 Technical and Business Assistance (TABA)

Under the Small Business Act, you may request a Technical and Business Assistance (TABA) supplement up to $6,500 above the award amount of the Phase I contract. At Phase II, you may request a TABA supplement up to $50,000. If your project is selected for award and the TABA supplement is authorized by NASA, you must use the TABA supplement to contract with one or more vendors to receive services to assist in:

- Making better technical decisions concerning this SBIR project
- Solving technical problems that arise during the conduct of this SBIR project
- Minimizing technical risks associated with this SBIR project
- Commercializing new products and processes resulting from this SBIR project

TABA may include, for example:

- Access to a network of non-NASA scientists and engineers
- Assistance with product sales
- Intellectual property (IP) protections
- Market research
- Market validation
- Development of regulatory and manufacturing plans
- Access to technical and business literature available through online databases

TABA vendors may include private commercialization assistance or business development service providers, public-private partnerships, other entrepreneurial support organizations (ESOs), and attorneys or other IP or licensing professionals. TABA funds may not be used to fund activities conducted internally by the small business awardee.

For information on how to request a TABA supplement at Phase I, please see section 3.1.3.8, Request for Use of Technical and Business Assistance Funds. NASA does not guarantee approval of requests for a TABA supplement. Awardees who receive a TABA supplement must deliver a description of services obtained, and results at completion of their Phase I contract. For reference, see https://www.sbir.gov/node/2088581.

1.9 Small Business Administration (SBA) Applicant Resources

The SBA works with several local partners of various organizational types to train and support potential SBIR/STTR applicants around the country from proposal assistance to SAM registration, and commercialization support to industry connections. To find local assistance visit: https://www.sbir.gov/local-assistance.
To find out more information on the specific types of SBA federal resources available, visit: https://www.sbir.gov/resources.

1.10 Fraud, Waste and Abuse and False Statements

Fraud is "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."

NASA reserves the right to decline any proposal packages that include plagiarism and false claims. Further, 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 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

1.11 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 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

In accordance with NFS 1852.215-84, the ombudsman does not participate in any way with the evaluation of proposal packages, the source selection process, or the adjudication of formal contract disputes. Therefore, before consulting with the ombudsman, you must first address your concerns, issues, disagreements, and/or recommendations to the Contracting Officer for resolution. The process set forth in this solicitation provision (and described at NFS 1852.215-84) does not change your right to file a bid protest or the period in which to timely file a protest.

1.12 General Information

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

To ensure fairness, NASA will not answer questions about the intent and/or content of research subtopics in this solicitation during the open solicitation period.

If you have questions requesting clarification of proposal package instructions and administrative matters, refer to the NASA SBIR/STTR website or contact the NASA SBIR/STTR Helpdesk. **The Helpdesk will not guarantee a timely answer to questions received after March 4, 2024, at 5:00 p.m. ET.**

1. NASA SBIR/STTR Website: http://sbir.nasa.gov
2. Helpdesk:
    a. Email: agency-sbir@mail.nasa.gov
    b. You must provide the name and telephone number of the person to contact, the organization name and address, and the specific questions or requests.

1.13 Definitions

NASA strongly encourages you to review the list of definitions 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.

2. Registrations, Certifications and Other Information

2.1 Small Business Administration (SBA) Company Registry

You must register with SBA's Company Registry and update your commercialization status. See https://www.sbir.gov/registration. You must provide your unique SBC Control ID (assigned by SBA upon completion of the Company Registry registration) and upload a PDF copy of the SBA Company Registry registration with the Firm Certification From.

2.2 System for Award Management (SAM) Registration

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. You may obtain information on SAM registration and annual confirmation requirements at https://sam.gov/content/home or by calling 866-606-8220.

You must start the registration process with SAM prior to submitting a proposal package. To be eligible for SBIR awards, you must have an active SAM registration under North American Industry Classification System (NAICS) code 541713 or 541715 at the time of proposal selection.

If you do not have an active SAM registration at the time of proposal selection, you will be ineligible for award. If you have started the registration process but did not complete the registration by the time of proposal selection, you will be ineligible for award.

If you are not registered, you should consider applying for registration immediately upon receipt of this solicitation. Typically, SAM registration and updates to SAM registration take several weeks. NASA recommends to list Purpose of Registration as "All Awards" on your SAM Registration.

2.3 Certifications

You must complete the Firm and Proposal Certifications by answering "Yes" or "No" to certifications as applicable in the Proposal Submissions and Award Management System (ProSAMS). Carefully read each of the certification statements. The Federal Government relies on the information to determine whether you are eligible for a SBIR program award. ProSAMS requires firm registration and login. To access ProSAMS, go to https://prosams.nasa.gov.

NASA uses a similar certification 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 invoice certifications and as a condition for payment, a life cycle certification shall be completed in ProSAMS. The life cycle certification 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 you may not meet certain eligibility requirements for award, they may request you provide clarification or supporting documentation. If the Contracting Officer still believes you are not eligible, you must file a size protest with the SBA, who will determine eligibility.

2.3.1 Disclosures of Foreign Affiliation or Relationships to Foreign Countries

You must complete the “Disclosures of Foreign Affiliations or Relationships to Foreign Countries” form as part of your proposal submission. Even if you do not have any foreign relationships, you must complete this form to represent that such relationships do not exist. If you do not submit this form, NASA will decline your proposal during the administrative screening process, and it will not be evaluated. Foreign involvement or investment does not independently disqualify you but failing to disclose such affiliations or relationships may result in denial of an award.

The disclosures require the following information:

(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 five-year period preceding submission of the proposal; and
(G) any foreign entity, offshore entity, or entity outside the United States related to the small business concern.

After reviewing the above listed disclosures, and if determined appropriate by NASA, the program may ask you to provide true copies of any 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 in effect during the five-year period before proposal submission.

During award, you must regularly report to NASA any changes to a required disclosure.

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

SAM contains required certifications that you may access at https://www.acquisition.gov/browsefar as part of the required registration (see FAR 4.1102). You must complete these certifications to be eligible for award. You must provide representations and certifications electronically via the website and update the representations and certifications as necessary, and at least annually, to keep them current, accurate, and complete. NASA will not enter any contract if you do not comply with these requirements.

In addition, you will need to be aware of the clauses that will be included in the contract if selected for a contract. For a complete list of FAR and NASA clauses see Appendix C.

2.5 Software Development Standards

If you are proposing projects involving the development of software, you may be required to comply with 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

NASA requires a protocol approved by a NASA review board if proposed work includes human or animal subjects. **Due to the complexity of the approval process, NASA does not allow use of human and/or animal subjects for Phase I projects.** For additional information, contact the NASA SBIR/STTR Program Office at agency-sbir@mail.nasa.gov. Reference 14 CFR 1230 and 1232.

2.7 Flight Safety Standards

If you are proposing projects involving the delivery of a spacecraft, you must comply with NASA Procedural Requirements (NPR) 8079.1, NASA Spacecraft Conjunction Analysis and Collision Avoidance for Space Environment Protection, available online at https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=8079&s=1.

2.8 HSPD-12

If your project is selected for award and requires access to federally controlled facilities or access to a federal information system (a*s defined in FAR 2.101(b)(2)*) for 6 consecutive months or more, you must apply for and receive appropriate Personal Identify Verification (PIV) credentials.

FAR clause 52.204-9, Personal Identity Verification of Contractor Personnel, states in part that the contractor must ensure that individuals needing such access provide the personal background and biographical information requested by NASA. See https://nvlpubs.nist.gov/nistpubs/FIPS/NIST.FIPS.201-3.pdf.

3. Proposal Preparation Instructions and Requirements

3.1 Requirements to Submit a Phase I Proposal Package

3.1.1 General Requirements

NASA will be using ProSAMS for the submission of these proposal packages. This solicitation guides firms through the steps for submitting a complete proposal package. All submissions will be completed through the secure ProSAMS URL and most communication between NASA and the firm is through email. To access ProSAMS, go to https://prosams.nasa.gov.

Proposal packages contain a Technical Proposal as described in section 3.1.3.5 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 missions and/or programs, commercial markets, and other potential markets and customers.

Be thoughtful in selecting a subtopic to ensure the proposal is responsive to the subtopic. **NASA will not move a proposal between subtopics or programs.**

Classified Information

NASA will decline any proposal package that contains classified information.

3.1.2 Format Requirements

NASA administratively screens all elements of a proposal package for compliance with format requirements. At its discretion, NASA may decline any proposal package or disregard specific proposal content that exceeds the stated limits when adjusted to comply with format requirements.

Required Page Limits and Suggested Page Lengths

A Phase I technical proposal—all 10 parts including all graphics and table of contents—must not exceed a total of 19 standard letter size (8.5- by 11-inch or 21.6- by 27.9-cm) pages.

NASA will not accept technical proposal uploads with any page(s) over the 19-page limit. The additional forms required for proposal package submission do not count against the 19-page limit.

As a guideline to help you address each part of the technical proposal within the 19-page limit, NASA suggests a page length for each of the 10 parts.

Technical Proposal Part	**Suggested Number of Pages**
Part 1: Table of Contents	0.5 pages

Part 2: Identification and Significance of Innovation	5 pages
Part 3: Technical Objectives	1 page
Part 4: Work Plan	5 pages
Part 5: Related R/R&D	1 page
Part 6: Key Personnel and Bibliography of Directly Related Work	2.5 pages
Part 7: The Market Opportunity	1 page
Part 8: Facilities/Equipment	1 page
Part 9: Subcontractors and Consultants	1 page
Part 10: Related, Essentially Equivalent, and Duplicate Proposals and Award	1 page

Margins

Use 1.0-inch (2.5 cm) margins.

Type Size

Use type size 10 point or larger for text or tables, except as legends on reduced drawings.

Header/Footer Requirements

Include the SBC name, proposal number, and project title in the header on each page of the proposal. Include the page number and proprietary legend (see section 3.4), if applicable in the footer on each page of the proposal. You may use margins for header/footer information.

Project Title

The proposal project title must be concise and descriptive of the proposed effort. Do not use the NASA research subtopic title, acronyms, or words like "development of" or "study of."

3.1.3 Proposal Package

Each proposal package must 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, 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 NASA Technology Available (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)
    a. Firm Information
    b. Firm Certifications
    c. Audit Information
    d. Disclosures of Foreign Affiliations or Relationships to Foreign Countries Audit Information
    e. Prior Awards Addendum

   f. Commercial Metrics Report (CMR)

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: https://submissions.gsfc.nasa.gov/submissions/learning-support/firm-templates.

What Not to Include

NASA will not consider the following items during evaluation:

- Letters of interest, support, or funding commitment
- Technical papers
- Product samples
- Videos
- Slides
- PowerPoint slide decks
- Other ancillary items

However, all submitted content other than the required forms designated in 1-11 above will count against the proposal page limit.

3.1.3.1 Proposal Contact Information Form

You must provide complete information for each contact person and submit the form as required. **Contact Information is public information and may be disclosed.**

3.1.3.2 Proposal Certifications Form

You must provide complete information for each question in the form and certify its accuracy as required.

3.1.3.3 Proposal Summary Form

You must provide complete information for each section of the form as required. **The Proposal Summary, including the technical abstract, is public information and may be disclosed.**

3.1.3.4 Proposal Budget Form

You must complete the Proposal Budget form following the instructions provided. See 5.5 Profit or Fee and 5.6 Cost Sharing. The total requested funding for the Phase I effort must not exceed $150,000 or $156,500 (if requesting $6,500 for Technical and Business Assistance (TABA), see section 1.8 and 3.1.3.8 for more information on the TABA opportunity).

All proposed cost is supported with documentation, such as a quote, previous purchase order, published price lists, etc. **NASA is not responsible for any monies you expend for proposal preparation and submission.**

In addition, you must submit the following information in the Proposal Budget form, as applicable:

- **Use of a Foreign Vendor.** If you are requesting to purchase products and equipment from a foreign vendor, you must complete the Foreign Vendor Form (see section 1.5.4 for more information).
- **Use of Government Resources.** If you plan to use government resources (such as, services, equipment, facilities, laboratories, etc.), as described in Part 8 of the technical proposal instructions, you must provide the following:
    1. Statement, signed by the appropriate Federal department or agency official, verifying that the resources are available during the proposed period of performance, authorizing their use, and if applicable, including the associated cost.
    2. Signed letter on your company letterhead explaining why your SBIR research project requires the use of government resources. Include data that verifies the absence of non-federal facilities or personnel capable of supporting the research effort, and, if applicable, the associated cost estimate.

  Due to the complexity and length of time for the approval process, NASA strongly discourages you from requesting the use of government resources during the performance of a Phase I. Approval for the use of government resources for a Phase I technical proposal requires a strong justification at the time of submission and will require approval by the Contracting Officer during negotiations if selected for award.
- **Use of Subcontractors and Consultants.** You may establish business arrangements with other entities or individuals to perform some of the proposed R/R&D effort, within the limits in section 1.5 and below. Subcontractors' and consultants' work must also be performed in the United States (see section 1.5.4 for more information).

  If you propose using subcontractors or consultants, you must submit the following:
    1. List of consultants by name with the number of hours and hourly costs identified for each consultant.
    2. Subcontractor budget that aligns with your Proposal Budget form and includes direct labor, other direct costs, and profit, as well as indirect rate agreements.
    3. A letter of commitment for each subcontractor and/or consultant, dated and signed by the appropriate person with contact information.
        a. If a university is proposed as a subcontractor, the signed letter must be on the university letterhead from the Office of Sponsored Programs.
        b. If an independent consultant is proposed, the signed letter must not be on university letterhead.

  The proposed subcontracted business arrangements, including consultants, must not exceed 33 percent of the research and/or analytical work. To calculate this percentage, divide the total cost of the proposed subcontracting effort including applicable indirect rates such as overhead and G&A by the total price proposed less profit.

Percentage of subcontracting effort = (Subcontractor cost + G&A) / (Total price – Profit)

Example:	Total price including 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%**

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

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

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, NASA strongly discourages travel during the Phase I contract. If the purpose of the meeting cannot be accomplished via videoconference or teleconference, you must justify the trip in the proposal budget form. The Contracting Officer and Technical Monitor will review travel requests to determine if they are necessary to complete the proposed effort.

3.1.3.5 Technical Proposal

The technical proposal must contain all 10 parts in order, number, and title as listed below. NASA will decline any proposal package that does not have all 10 parts and it will not be evaluated. If a part is not applicable to your proposed effort, you must include the part and mark it "Not applicable." Do not include any budget data in the technical proposal.

Part 1: Table of Contents (Suggested page limit – 0.5 page and counts toward the 19-page limit)
Begin the technical proposal with a brief table of contents indicating the page numbers of each of the parts of the technical proposal).

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.

If you plan to use NASA TAV including Intellectual Property (IP), you must describe planned developments with the IP. Add the NASA Evaluation License Application as an attachment in the Proposal Certifications form (see section 1.6).

Part 4: Work Plan (Suggested page limit – 5 pages)
Include a detailed plan to meet the Phase I technical objectives. The plan must include:

- Detailed task descriptions, that is, what will be done, where it will be done, and the methods you will use to do it
- Schedules
- Resource allocations
- Estimated task hours for each key personnel that match hours reported in the Proposal Budget Form
- Planned accomplishments (including project milestones)
- If the offeror is a joint venture or limited partnership, a statement of how the workload will be distributed, managed, and charged

Part 5: Related R/R&D (Suggested page limit – 1 page)
Describe significant existing R/R&D that is directly related to the technical proposal including any conducted by the PI or by the company. Describe how it relates to the proposed effort and any planned coordination with outside sources. You must demonstrate awareness of key recent R/R&D conducted by others in the specific subject area. Include any pertinent references or publications.

Part 6: Key Personnel and Bibliography of Directly Related Work (Suggested page limit – 2.5 pages)
Identify all 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, you may summarize the most relevant experience or publications.

The PI is key to the success of the effort. The following applies:

- **Functions:** The PI plans and directs the project, leading it technically and making substantial personal contributions during its implementation. The PI also serves as the primary contact with NASA on the project and ensures that work proceeds according to contract agreements. Competent management of PI functions is essential to project success. You must 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:** You must clearly present the qualifications and capabilities of the proposed PI and the basis for PI selection. NASA has the sole right to accept or decline a PI based on factors such as education, experience, demonstrated ability and competence, and any other evidence related to the specific assignment.
- **Eligibility:** You must establish and confirm the eligibility of the PI and indicate if existing projects and other proposals recently submitted or planned commit the time of the PI concurrently with this proposed project. NASA will decline your proposal if you try to circumvent the restriction on PIs working more than half time for an academic or a nonprofit organization by substituting an ineligible PI.

Part 7: The Market Opportunity (Suggested page limit – 1 page)
Describe the potential commercialization approach for the innovation by addressing the following:

- The potential economic benefits associated with your innovation.
- The potential customers and basic go-to-market strategy.
- The potential risks in bringing your innovation to market.

The SBIR program is mandated to move funded innovations into federal and private sector commercial markets. Companies that address market opportunities early are better positioned to apply for and receive follow-on SBIR contracts, and to commercialize their innovations. **NASA encourages you to use TABA and I-Corps, to help you address market opportunities. See sections 3.1.3.8 for how to request TABA and 3.1.3.9 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. You must justify any proposed equipment purchase. **When purchasing equipment or a product under the SBIR contract, you should purchase only American-made products or equipment.**

Although use of government-furnished laboratory equipment, facilities, or services (collectively, “government resources”) is strongly discouraged in Phase I proposals, describe in this part why the use of such government resources is necessary and not reasonably available from the private sector if applicable. See sections 3.1.3.4 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.

If you plan to use a federal laboratory/facility during a follow-on Phase II contract, please state this intent in your Phase I proposal.

Part 9: Subcontractors and Consultants (Suggested page limit – 1 page)
Describe all subcontracting or other business arrangements, including who they are with and for what expertise, functions, services, and number of hours. You must ensure that all organizations and individuals are available for the time periods proposed. The narrative description of subcontractors and consultants in the technical proposal should support the proposed approach and documentation in the Proposal Budget form, section 3.1.3.4.

Part 10: Related, Essentially Equivalent, and Duplicate Proposals and Awards (Suggested page limit – 1 page)
WARNING: It is illegal to enter into multiple funding agreements for essentially equivalent work. While you may submit similar or identical proposals to multiple solicitations, it is risky. You must notify the agencies in advance and resolve the matter prior to award.

If you choose to submit identical proposals or proposals containing a significant amount of essentially equivalent work under other federal program solicitations, you must include a statement in each proposal containing:

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.

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).

3.1.3.6 Briefing Chart

The 1-page briefing chart is required to assist in the ranking of technical proposals prior to selection. Summarize on the provided electronic form:

- Identification and Significance of Innovation
- Technical Objectives and Proposed Deliverables
- NASA Applications
- Non-NASA Applications
- Graphic

The briefing chart is public information and may be disclosed. Do not include proprietary information or International Traffic in Arms Regulation (ITAR)-restricted data. For more information on ITAR see https://www.sbir.gov/tutorials/itar/.

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

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

3.1.3.8 Request for Technical and Business Assistance (TABA) Supplement at Phase I

NASA encourages you to request the TABA supplement of up to $6,500 at Phase I. You will choose your own TABA vendor. NASA cannot direct you to any specific TABA vendor or website. See Section 1.8.

NASA encourages you to use the limited amount of $6,500 Phase I TABA funds for:

1. Development of a Phase II TABA Needs Assessment – If you plan to request a TABA supplement at Phase II, you should secure a TABA vendor at Phase I 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 you would need if the project was selected for a future Phase II award. Phase II TABA supplements may be up to $50,000.

2. Development of a Phase II Commercialization and Business Plan – If you are planning to submit a future proposal for Phase II funding, you will be required to submit a commercialization and business plan that meets the requirements of that future Phase II solicitation. NASA encourages you to use a Phase I TABA supplement to secure a TABA vendor to help develop the commercialization and business plan. The goal of the commercialization and business plan is to allow NASA to evaluate your ability to commercialize the innovation and provide a level of confidence regarding your future and financial viability.

If you request the Phase I TABA supplement, you must do so in the proposal package submission. You are not required to request TABA at Phase I. TABA at Phase II eligibility is not dependent on Phase I TABA participation.

TABA Vendor Information - The TABA request must provide the following information for each vendor according to the directions found in the Budget forms in ProSAMS:

- Contact information of the vendor (name, address, phone number, website)
- Description of vendor(s) expertise and knowledge of providing the desired technical and business assistance services
- Itemized list of services and costs the TABA vendor will provide (vendor quote)
- 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.

All TABA vendors must be legal businesses 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 as incomplete and will not review the TABA request or provide TABA approval under the award.

The TABA supplement is 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. NASA will not consider requests for TABA funding outside of the Phase I period of performance or after a proposal package submission.

3.1.3.9 I-Corps Interest Form

You will complete a short I-Corps interest form as part of your proposal package submission. NASA uses this form to determine the level of interest from Phase I offerors to participate in the NASA I-Corps program. See section 1.7.

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. NASA will provide directions for completing the proposal including due dates, training dates, and available funding by email. NASA 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.

3.1.3.10 SBC Level Forms

You must complete all SBC level forms electronically within ProSAMS. The SBC level forms do not count toward the 19-page limit for the technical proposal. To access ProSAMS, go to https://prosams.nasa.gov.

A. **Firm Information**

You must complete the SBC identifying information once to be applicable across all proposals submitted to this solicitation.

B. **Firm Certifications**

You must complete the Firm Certifications section of by answering “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.

C. **Audit Information**

Although you are not required to have an approved accounting system, it is easier for NASA to determine that your rates are fair and reasonable if you have an approved accounting system. To assist NASA, you must complete the questions in the Audit Information form regarding your 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 you must also complete. If you have 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 uses this Audit Information to assist with negotiations if the proposal package is selected for award. The Contracting Officer will advise you what is required to determine reasonable cost and/or rates in the event the Audit Information is not adequate.

D. **Disclosures of Foreign Affiliations or Relationships to Foreign Countries**

Each offeror is required to complete the Disclosures of Foreign Affiliations or Relationships to Foreign Countries form as required in ProSAMS. See section 2.3.1 for additional information on these disclosures. You must answer “Yes” or “No” as applicable and provide the requested information related to each “yes” response.
Please note that even if you do not have any foreign relationships, you must complete the "Disclosures of Foreign Affiliations or Relationships to Foreign Countries form" to represent that such relationships do not exist. Failure to complete and include this form will result in the declination of your application during the administrative screening

E. **Prior Awards Addendum**

If you have 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 you have received any SBIR or STTR Phase II awards, even if fewer than 15 in the last 5 years, NASA still recommends that you complete this form as the information will be useful to you when completing the Commercialization Metrics Report (CMR).

F. **Commercialization Metrics Report (CMR)**

NASA uses a commercialization report/data-gathering process to track the overall commercialization success of its SBIR and STTR programs. You must complete the Commercialization Metrics Report or update an existing report if applicable, via https://www.sbir.gov/ (the report is available in the "My Dashboard" section of your company's sbir.gov profile) as part of the proposal package submissions process. 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 you have 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 report will also ask you to provide financial, sales, and ownership information, as well as any commercialization success you have had because of SBIR or STTR awards. You must update this information annually during proposal package submission via ProSAMS.

CMR input is kept confidential and will not be made public except in broad aggregate, with no company-specific attribution. Do not submit password protected documents.

3.2 Multiple Proposal Submissions

Each proposal must be based on a unique innovation, limited in scope to just one subtopic, and submitted only under that one subtopic within each program. You may not submit more than 10 proposals to the SBIR program. You may submit more than one unique proposal to the same subtopic; however, you must not submit the same (or substantially equivalent) proposal to more than one subtopic. If you submit substantially equivalent proposals to several subtopics, NASA may decline all such proposals.

3.3 Understanding the Patent Landscape

You 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.

3.4 Proprietary Information in the Proposal Submission

Limit proprietary information to only that information that is essential to your proposal.

Information contained in unsuccessful proposals remains your property. The Federal Government may, however, retain copies of all proposals. Public release of information in any proposal submitted will be subject to existing statutory and regulatory requirements. If proprietary information is provided 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 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 you wish to protect:

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

3.5 Release of Certain Proposal Information

In submitting a proposal, you agree 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 your property, and NASA will protect it from public disclosure to the extent permitted by law, including requests submitted under the Freedom of Information Act (FOIA).

4. Method of Selection and Evaluation Criteria

4.1 Phase I Selection Process and Evaluation Criteria

NASA conducts a multi-stage review process of all proposal packages:

1. Administrative review for compliance with Chapters 3 and 6 of the solicitation
2. Initial screening for responsiveness to the subtopic
3. Technical evaluation 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
4. Price evaluation
5. Scoring and weighting to determine rating
6. Prioritization
7. Selection
8. Determination of cost/price reasonableness and responsibility

Do not assume that evaluators are acquainted with your company, key individuals, or with any experiments or other information. NASA will judge each proposal on its own merit and will not conduct any tradeoff analyses between or among competed proposals.

4.1.1 Administrative Review

NASA will review all proposal packages received by the published deadline to determine if the proposal package meets the requirements found in chapters 3 and 6. NASA may decline and not evaluate a proposal package that is not compliant with the requirements in chapters 3 and 6. NASA will notify you of its decision to eliminate the proposal package from consideration and the reason(s) for the decision.

4.1.2 Technical Responsiveness

NASA will screen proposal packages that pass the administrative review to determine technical responsiveness to the subtopic of this solicitation. Proposal packages that are not responsive to the subtopic will be declined and not evaluated. NASA will notify you of its decision to eliminate the proposal package from consideration and the reason(s) for the decision. **Ensure your technical proposal is responsive to the subtopic. NASA will NOT evaluate a technical proposal under a subtopic other than the one you select.**

4.1.3 Technical Evaluation Criteria

NASA will evaluate proposal packages that comply with administrative requirements and are technically responsive to the subtopic of this solicitation. Subject matter experts will determine the most promising technical and scientific approaches, based on the following criteria:

Factor 1: Scientific/Technical Merit and Feasibility

NASA will evaluate the proposed effort 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.
- 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 equipment 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 3.1.3.4 and part 8 of the technical proposal), will be evaluated for reasonableness.

Factor 3: Effectiveness of the Proposed Work Plan
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 whether the offeror's proposal has demonstrated a knowledge of the potential economic benefits of the innovation, potential customers including NASA mission programs, other government agency programs, and/or non-government markets and strategies to reach them, as well as risks associated with this approach. If known, offerors may 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, NASA will evaluate the budget proposal form to determine whether the 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

NASA will score factors 1, 2, and 3 numerically. Factor 1 is worth 50 points. 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. NASA will assign factor 4 an adjectival rating (Excellent, Very Good, Good, Fair, or Poor).

The most highly rated proposals are eligible for prioritization. To determine the most highly rated 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). 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, and/or geographic distribution when making recommendations.

4.4 Selection

The SSO makes the final decisions to determine the proposals that will enter contract negotiations. The SSO may consider the additional programmatic balance factors identified in Section 4.3 along with the technical merit and commercial potential.

After the SSO selection has been finalized, NASA will post the list of proposals selected for negotiation on the NASA SBIR/STTR website. All SBCs selected by the SSO will receive a formal notification letter. NASA will evaluate each proposal selected for negotiation 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.

4.5 I-Corps Evaluation Process

For awardees that submit an I-Corps proposal pursuant to sections 1.7 and 3.1.3.9, NASA will provide a programmatic assessment 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 demonstrates that there is potential for commercialization in both NASA and commercial markets.

Based on the assessment of the above criteria the NASA SBIR/STTR PMO will provide a recommendation to the SSO of I-Corps proposals to receive funding. The SSO will make the final selections. NASA anticipates selecting approximately 28 SBIR SBCs 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 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 3.1.3.8 and informs the Contracting Officer of the final determination to allow TABA funding under the contract. NASA will notify you of the approval or denial of TABA funding prior to TABA award.

During this review, NASA will consider:

- If the awardee proposes to 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 contact information.
- The vendor(s) expertise and knowledge in providing the desired technical and business assistance services
- Costs in the vendor quote(s) and whether they are reflected in the budget forms
- Proposed plans to submit a deliverable summarizing the outcome of the TABA services with expected supporting information.
- Any evidence of Fraud, Waste and Abuse.

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 proposal package. In deciding to obtain an outside evaluation, NASA will 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. Outside evaluators will certify that the information (data) contained in the proposal package is for evaluation purposes and will not be further disclosed.

4.7.2 Non-NASA Access to Confidential Business Information

In the conduct of proposal package processing and potential contract administration, NASA may need to provide access to the 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, NASA will send a notification to the designated small business representative identified in the proposal package according to the processes described below.

Due to the competitive nature of the program and limited funding, recommendations to fund or not fund a proposal package are final. NASA will not reconsider selection decisions or provide additional information regarding the final decision. Offerors are encouraged to use the written feedback to understand the outcome and review of their 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 proposal package.

1. At the time of the public selection announcement, NASA will send an email to the designated small business representative indicating the outcome of the 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 agency-sbir@mail.nasa.gov. **Due to the sensitivity of this feedback, NASA will only provide feedback to the designated small business representative and not to any other parties.**

5. Considerations for Contracting and Additional Information

5.1 Requirements for Negotiations

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 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 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 C). 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. **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.

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

5.1.1 Requirements for Contracting

Awardees are required to make certain legal commitments through acceptance of numerous clauses in their Phase I contracts. This list is not a complete list of clauses to be included in Phase I contracts and is not the specific wording of such clauses. Copies of complete terms and conditions are available by following the links in appendix C.

(1) Standards of Work. Work performed under the contract must conform to high professional standards.
(2) Inspection. Work performed under the contract 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 contract.
(4) Default. The Federal Government may terminate the contract if the contractor fails to perform the work contracted.
(5) Termination for Convenience. The contract 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 contract 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 contract.
(12) Covenant Against Contingent Fees. No person or agency has been employed to solicit or secure the contract 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 contract 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 contract.
(15) American Made Equipment and Products. When purchasing equipment or a product under the SBIR/STTR contract, purchase only American-made items whenever possible.

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 Evaluated	Number of SBIR Phase I Awards	Percentage of SBIR Phase I Awards
2023	1,311	250	19.0%
2022	1,392	280	20.1%
2021	1,503	305	20.2%

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 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 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. 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 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.

You must provide to NASA all technical reports and other deliverables required by the contract. These reports must document progress made on the project and activities required for completion. Periodic certification for payment is required as stated in the contract. You must submit a final report 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 you receive the TABA supplement, your Phase I contract requires TABA deliverables that summarize the outcome of the TABA services. NASA bases reimbursement for TABA on delivery of a TABA final report at the end of the contract period of performance.

5.4 Payment Schedule

The exact payment terms are included in the contract. Invoices are submitted electronically through the Department of Treasury's Invoice Processing Platform (IPP). If you are approved to receive the TABA supplement under a Phase I award, you will be reimbursed for TABA expenses. You must submit TABA vendor invoices for reimbursement per the payment schedule in section 3.1.3.8. NASA will not reimburse any amounts incurred over the TABA funding amount that NASA approved prior to award.

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 proposal packages under this program solicitation; however, cost sharing is not required. Cost sharing will not be an evaluation factor in consideration of your 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 must 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 SBA SBIR/STTR Policy Directive provided in section 1.1 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

Awardees must certify with every invoice that they have not previously been paid nor are 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 you submit certain organizational, management, personnel, and financial information to establish contractor responsibility. 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. Proposal packages requiring waivers must include an explanation of why the waiver is appropriate. NASA will provide your 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 3.1.3.4 of the solicitation. **NASA facilities qualify as federal laboratories.**

Support Agreements for Use of Government Resources

All offerors selected for award who require and receive approval from the SBIR Program Executive for the use of any federal facility must, 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. 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) 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 is responsible for any costs associated with services, equipment, or facilities provided by NASA or another Federal department or agency, and such costs will not increase the price of this contract.

5.14 Agency Recovery Authority and Ongoing Reporting

In accordance with Section 5 of the SBIR and STTR Extension Act of 2022, the NASA will –

1) require a small business concern receiving an award under its SBIR program to repay all amounts received from the Federal agency under the award if—
    (A) the small business concern makes a material misstatement that the Federal agency determines poses a risk to national security; or
    (B) there is a change in ownership, change to entity structure, or other substantial change in circumstances of the small business concern that the Federal agency determines poses a risk to national security; and
2) require a small business concern receiving an award under its SBIR program to regularly report to the Federal agency and the SBA throughout the duration of the award on—
    (A) any change to a disclosure required under subparagraphs (A) through (G) of section 2.3.1 above.
    (B) any material misstatement made under section 5.14 paragraph (A) above; and
    (C) any change described in section 5.14 paragraph (B) above.

6. Submission of Proposals

6.1 How to Apply for SBIR Phase I

NASA uses electronically supported business processes for the SBIR program. You must have internet access and an email address. NASA will not accept paper submissions.

To apply for a NASA SBIR Phase I contract, you must follow the steps found below.

6.1.1 Electronic Submission Requirements via the ProSAMS

NASA uses ProSAMS for the submission of these proposal packages. ProSAMS requires firm registration and login. To access ProSAMS, go to https://prosams.nasa.gov/.

NASA recommends that an authorized small business representative be the person to register the firm and complete the required firm level forms. They will be the only person allowed to edit the firm level forms.

For successful submission of a complete proposal package, you must complete all required and applicable forms, and upload the required documents per the submission requirements indicated in ProSAMS.

6.1.2 Deadline for Phase I Proposal Package

NASA must receive your proposal package for Phase I no later than 5:00 p.m. ET on Monday, March 11, 2024, via ProSAMS.

You are responsible for ensuring that all files constituting the proposal package are uploaded and endorsed prior to the deadline. **If a proposal package is not received by the 5:00 p.m. ET deadline, NASA will determine the proposal package to be incomplete and will not evaluate it.** Start the submission process early to allow sufficient time to upload the complete proposal package. If you wait to submit a proposal package near the deadline, you are at risk of not completing the required uploads and endorsements by the required deadline and NASA may decline the proposal package.

6.1.3 Proposal Package Submission

Upload all components of a proposal package using the Proposal Submissions module in ProSAMS. The designated business representative and principal investigator must endorse the proposal package. All transactions via ProSAMS are encrypted for security purposes.

Do not submit security/password-protected PDF files, as reviewers may not be able to open and read these files. NASA will decline proposal packages containing security/password-protected PDF files and they will not be evaluated.

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

You may upload a 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. Embedded animation or video, as well as reference technical papers for “further reading,” will not be considered for evaluation. **NASA may decline a proposal package that is missing the final endorsements.**

6.1.4 Acknowledgment of a Proposal Package Receipt

NASA will acknowledge receipt of an electronically submitted proposal package by sending an email to the designated Business Official's email address as provided on the proposal package cover sheet. **If you do not receive a proposal package acknowledgment after submission, immediately contact the NASA SBIR/STTR Program Support Office at agency-sbir@mail.nasa.gov.**

6.1.5 Withdrawal of Proposal Packages

Prior to the close of submissions, you may withdraw proposal packages. To withdraw a proposal package after the deadline, the designated small business representative must send written notification via email to agency-sbir@mail.nasa.gov.

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), must 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 must 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:
https://www.nasa.gov/budgets-plans-and-reports/
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 Technology, Policy, and Strategy	
2020 NASA Technology Taxonomy	https://www.nasa.gov/otps/2020-nasa-technology-taxonomy/

NASA Mission Directorates	
Aeronautics Research Mission Directorate (ARMD)	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 Mission Directorate (SMD)	http://nasascience.nasa.gov
Space Technology Mission Directorate (STMD)	https://www.nasa.gov/space-technology-mission-directorate/

NASA Centers	
Ames Research Center (ARC)	https://www.nasa.gov/ames/
Armstrong Flight Research Center (AFRC)	https://www.nasa.gov/armstrong/
Glenn Research Center (GRC)	https://www.nasa.gov/glenn/
Goddard Space Flight Center (GSFC)	https://www.nasa.gov/goddard/
Jet Propulsion Laboratory (JPL)	https://www.jpl.nasa.gov/
Johnson Space Center (JSC)	https://www.nasa.gov/johnson/
Kennedy Space Center (KSC)	https://www.nasa.gov/kennedy/
Langley Research Center (LaRC)	https://www.nasa.gov/langley/
Marshall Space Flight Center (MSFC)	https://www.nasa.gov/marshall/
Stennis Space Center (SSC)	https://www.nasa.gov/stennis/
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 use to learn about the program and to get help for developing a 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 https://www.sbir.gov/about 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

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 proposal package, use the following checklist:

- ☐ The technical proposal and innovation are submitted for one subtopic only.
- ☐ The entire proposal package is submitted consistent with the requirements outlined in chapter 3.
  - ☐ Proposal Contact Information
  - ☐ Proposal Certifications
  - ☐ Proposal Summary
  - ☐ Proposal Budget
    - ☐ Including letters of commitment for government resources and subcontractors/ consultants (if applicable)
    - ☐ Foreign Vendor form (if applicable)
  - ☐ Technical Proposal including all 10 parts in order as stated in section 3.1.3.5.
  - ☐ Briefing Chart
  - ☐ NASA Evaluation License Application, only if TAV is being proposed
  - ☐ I-Corps Interest Form
  - ☐ Technical and Business Assistance (TABA) Request, if applicable
  - ☐ SBC-Level Forms completed once for all proposal packages submitted to a single solicitation
    - ☐ SBC Certifications
    - ☐ Audit Information
    - ☐ Prior Awards Addendum
    - ☐ Commercialization Metrics Report (CMR)
    - ☐ Disclosure of Foreign Affiliations
- ☐ The technical proposal does not exceed a total of 19 standard 8.5- by 11-inch pages with one-inch margins and follows the format requirements (section 3.1.2).
- ☐ All required letters/documentation are included.
  - ☐ A letter of commitment from the appropriate government official if the research effort requires use of government resources (sections 3.1.3.4 and 5.13).
  - ☐ Letters of commitment from subcontractors/consultants.
  - ☐ 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.
  - ☐ NASA Evaluation License Application if proposing the use of NASA technology (TAV).
  - ☐ Supporting documentation of budgeted costs.
- ☐ Proposed funding for the technical effort does not exceed $150,000 (section 1.3), and if requesting TABA, the cost for TABA does not exceed $6,500 (sections 1.8 and 3.1.3.8).
- ☐ Proposed project duration does not exceed six (6) months (section 1.3).
- ☐ Confirm you received an acknowledgement of submission email before 5:00 p.m. ET on March 11, 2024 (section 6.1.4).

9. Research Subtopics for SBIR

Introduction

The SBIR subtopics are organized by NASA's Technology Taxonomy and thus identify subtopics where your research and development capabilities may be a good match. The 2020 NASA Technology Taxonomy reflects a shift to a structure that aligns technology areas based on technical disciplines.

In addition, there are some SBIR subtopics that may be closely aligned with the NASA STTR program. Consider both programs when planning to apply. To find the current NASA SBIR and STTR solicitations, visit the NASA SBIR/STTR website.

NASA uses the same subtopic numbering convention for the SBIR program each year:

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)

Think of the subtopic lead mission directorates and lead/participating centers as potential customers for your technical proposals. Multiple mission directorates and centers may have interests across the subtopics within a Technology Taxonomy area.

Related subtopic pointers are identified in some subtopic headers to assist you with identifying other subtopics that seek related technologies for different customers or applications. As stated in chapter 3, NASA will not accept the same (or substantially equivalent) proposal packages to more than one subtopic. It is your responsibility to select which subtopic to propose to.

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TX01: Propulsion Systems

This area covers technologies for chemical and non-chemical propulsion systems or their related ancillary systems for propulsion, space launch propulsion, or in-space propulsion applications.

A1.02 Quiet Performance - Propulsion Noise (SBIR)

Related Subtopic Pointers: T1.15

Lead Center: GRC
Participating Center(s): LaRC

Subtopic Introduction:
The subtopic is aimed at enabling the design of environmentally acceptable aircraft through the development of tools and technologies for predicting, diagnosing, and mitigating the noise impact of commercial aircraft operations on communities near and around airports. Noise continues to be a limiting factor on the growth of the nation's air transportation system. Reductions in aircraft noise could lead to wider community acceptance and increased potential for air traffic growth on a global scale.

Scope Title: Propulsion Noise

Scope Description:

Innovative methods and technologies are necessary for the design and development of efficient and environmentally acceptable aircraft. The impact of aircraft noise on communities near and around airports is the predominant limiting factor on the growth of the nation's air transportation system. Reductions in aircraft noise could lead to wider community acceptance, lower airline operating costs where noise quotas or fees are employed, and increased potential for air traffic growth on a global scale. In support of the Advanced Air Vehicles Program (AAVP), Integrated Aviation Systems Program (IASP), and Transformative Aeronautics Concepts Program (TACP), improvements in noise prediction, diagnostics, and reduction are needed for subsonic and supersonic aircraft. Specifically, innovations in the following areas are solicited:

Prediction:

- High-fidelity fan broadband noise prediction capability.
- Models/codes for prediction of installed noise for fans and/or open rotors.
- Robust models for inlet and exhaust noise from multistage fans.

Diagnostics:

- Tools/technologies for quantitative characterization of fan in-duct broadband noise in terms of its spatial and temporal content.
- Phased array and acoustical holography tools and/or techniques to measure realistic propulsion noise sources in challenging test environments.

Reduction:

- Liners capable of appreciable sound absorption over at least two octaves.
- Low-noise propulsor concepts that are significantly quieter than the current generation of fans and open rotors.
- Concepts for mitigating the effects of distorted inflow on propulsor noise (ducted or unducted).

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

Primary Technology Taxonomy:

- Level 1: TX 01 Propulsion Systems
- Level 2: TX 01.3 Aero Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Tools and technologies that enable prediction, diagnostics, and reduction of propulsion noise, at the component or system level, for subsonic and supersonic aircraft. Clear definition of path(s) for commercialization and infusion of these technologies.

Phase I deliverables can include:

- Demonstration of models/codes for predicting propulsor noise using available model test problems.
- Demonstration of advanced noise diagnostic tools/techniques using canonical or virtual test problems.
- Proof-of-concept demonstration of propulsion noise reduction concepts or technologies in laboratory environment.

Phase II deliverables can include:

- Models/codes that accurately predict propulsor noise for realistic fans and open rotors.
- Matured advanced noise diagnostic tools/techniques applicable to realistic propulsors in relevant test environments (e.g., wind tunnels).
- Maturation of propulsion noise reduction concepts or technologies to realistic propulsion components, subsystems, or systems.

State of the Art and Critical Gaps:

Efficient high-fidelity prediction tools that enable timely evaluations of various engine architectures and operating conditions are lacking. Availability of such tools is essential at the design stage or for system-level assessment. Accurate and robust diagnostic tools for source identification and characterization do not exist for most of the important propulsion noise sources such as fans, combustors, and turbines. State-of-the-art technologies for propulsion noise reduction are generally passive and tend to be designed for a specific operating condition. Adaptive materials and mechanisms that can modify their acoustic performance based on the noise state of the engine are highly desirable. New prediction tools, diagnostic capabilities, and noise-reduction technologies would enable development of quieter propulsion systems.

Relevance / Science Traceability:

AAVP: The Advanced Air Transport Technology (AATT) and Commercial Supersonic Technology (CST) Projects would benefit from more accurate, efficient, and robust propulsion noise prediction and diagnostics, and from reduction tools and technologies. These could lead to quieter propulsion systems that can help reduce the aircraft noise footprint at takeoff and landing. New engine architectures and new airframe-engine integration concepts could also benefit from an infusion of new tools and technologies to assess their acoustic performance in early design stages.

TACP: The Transformational Tools and Technologies (TTT) Project would benefit from tool developments to enhance the ability for considering acoustic requirements 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 application in numerous vehicle classes in the AAVP portfolio, including subsonic and supersonic transports, as well as vertical lift vehicles.

References:

1. AAVP - Advanced Air Transport Technology (AATT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/aatt
2. AAVP - Commercial Supersonic Technology (CST) Project: https://www.nasa.gov/aeroresearch/programs/aavp/cst
3. TACP - Transformational Tools and Technologies (TTT) Project: https://www.nasa.gov/aeroresearch/programs/tacp/ttt

A1.03 Low Emissions/Clean Power - Environmentally Responsible Propulsion (SBIR)

Related Subtopic Pointers: T1.15
Lead Center: GRC
Participating Center(s): LaRC

Subtopic Introduction:

Innovative tools and technologies are required to address several challenges to improving combustor operability and durability and minimizing the impact of aircraft emissions on human health and the environment. Overcoming these challenges is important to both next-generation subsonic aircraft and potential future high-speed commercial aircraft. Particulate matter emissions from aircraft gas turbine engines, consisting primarily of ultrafine soot, contribute to adverse health and climate impacts, and new international standards on nonvolatile particulate matter emissions started in 2023. Next-generation single-aisle aircraft are pushing towards smaller engine cores and higher overall pressure ratios, leading to challenges in combustor cooling design. Future high-speed (supersonic) aircraft also face significant combustor cooling challenges due to the need for maximizing the air available to combust with the fuel (to provide ultra-low emissions of oxides of nitrogen that mitigate ozone depletion at stratospheric cruise altitudes) while operating at the harshest thermal condition during long-duration cruise. Conventional gas turbine engines operating at higher overall pressure ratios and future hybrid-electric or high-speed aircraft concepts that use the fuel as a heat sink may experience fuel injection behavior outside of current understanding and modeling capabilities. Aviation goals to reduce climate impacts from aviation will drive increased use of blending ratios of sustainable aviation fuels.

Scope Title: Environmentally Responsible Propulsion Aircraft—Combustor Tools and Technologies

Scope Description:

Innovative tools and technologies are required to address several challenges to improving combustor operability and durability and minimizing the impact of aircraft emissions on human health and the environment. Overcoming these challenges is important to both next-generation subsonic aircraft and potential future high-speed commercial aircraft. Particulate matter emissions from aircraft gas turbine engines, consisting primarily of ultrafine soot, contribute to adverse health and climate impacts, and new international standards on nonvolatile particulate matter emissions started in 2023. Next-generation single-aisle aircraft are pushing towards smaller engine cores and higher overall pressure ratios, leading to challenges in combustor cooling design. Future high-speed (supersonic) aircraft also face significant combustor cooling challenges due to the need for maximizing the air available to combust with the fuel (to provide ultra-low emissions of oxides of nitrogen that mitigate ozone depletion at stratospheric cruise altitudes) while operating at the harshest thermal condition during long-duration cruise. Conventional gas turbine engines operating at higher overall pressure ratios and future hybrid-electric or high-speed aircraft concepts that use the fuel as a heat sink may experience fuel injection behavior outside of current understanding and modeling capabilities. Aviation goals to reduce climate impacts from aviation will drive increased use of blending ratios of sustainable aviation fuels.

To address these challenges, innovations in the following specific areas are solicited:

- Nonintrusive optical techniques to measure near-wall velocities, temperature, and/or turbulence variables for experiments with liquid-spray injection operating over a range of pressures (1 atm to at least 30 atm).
- Tools and technologies to improve combustor durability and optimize cooling in the combustor for smaller core subsonic applications and/or long-duration cruise supersonic applications.
- Approaches that tightly couple convection, conduction, and radiation heat transfer in a computationally efficient manner applicable to time-accurate, eddy-resolving simulations of combustion flows with liquid-spray injection.
- Fuel-sensitive soot-precursor chemistry models applicable to Jet-A and various blending ratios of Jet-A with sustainable aviation fuels.
- For multicomponent hydrocarbon fuels (conventional jet fuel and sustainable aviation fuels), models for the transition from two-phase (liquid-vapor regime with surface tension) behavior to a single-phase behavior (where no surface tension exists) that may be encountered for fuels injected into high-pressure and high-temperature combustor chamber conditions, and/or for heated fuels.

Development of measurement techniques for characterizing aircraft engine particle emissions in the 10- to 200-nm particle diameter size range and their interactions with contrails and contrail-cirrus clouds. Complete instrument systems are desired, including features such as remote/unattended operation and data acquisition and minimum size, weight, and power consumption. Instrument prototypes as a deliverable in Phase II proposals and/or field demonstrations are encouraged. Desired measurement capabilities include:

- Size-dependent number and mass concentrations at 1-Hz time resolution that differentiate volatile/nonvolatile particles or elemental/organic carbon fractions, consistent with the measurement definitions given by the standard SAE ARP6320A (https://www.sae.org/standards/content/arp6320a/). Note that the ARP is referenced only for measurement referencing and terminology; this subtopic seeks proposals for research-grade instruments that go significantly beyond the current state of the art and the baseline measurement requirements of the ARP.
- Speciated organic, sulfate, and nitrate mass concentrations of particles in the 3- to 30-nm diameter size range. Techniques for differentiating sub-30-nm-diameter organic aerosol formed from engine oil versus fuel combustion are particularly desired.
- Open-path, aircraft cloud probes suitable for measuring the number and size distribution of near-field small contrail ice crystals down to a nominal 0.1- to 0.3-µm diameter lower size limit.

- Aircraft-mounted water vapor, dew point, or relative humidity probe with a small enough size, weight, and power footprint that it would be suitable for integration on a commercial aircraft. Instrument should be optimized for upper tropospheric ambient measurements (nominally 20-ppm minimum sensitivity for water vapor, -40 to -70 °C static air temperature, 150- to 300-mbar static air pressure).
- Aircraft-mounted temperature probe suitable for measuring static air temperature with accuracy at or better than 0.1 °C under upper tropospheric flight conditions. Measurements carried out at high sample line pressures relevant for sector combustor studies and low pressures relevant for flight studies.

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

Primary Technology Taxonomy:

- Level 1: TX 01 Propulsion Systems
- Level 2: TX 01.3 Aero Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Software
- Hardware

Desired Deliverables Description:

Computer simulation software to predict the best and most effective combustor configurations will be a major deliverable. Sensor development for monitoring engine emissions would be another deliverable. Phase I should successfully demonstrate fabrication/testing of a laboratory breadboard system, overcoming a major system or subsystem technical hurdle, or foundational work that lays the groundwork for the Phase II work plan, which should be summarized in the Phase I report.
Phase II deliverables such as instrument prototypes and/or field demonstrations are highly encouraged.

State of the Art and Critical Gaps:

Combustion involves multiphase, multicomponent fuel, turbulent, unsteady, 3D, reacting flows, where much of the physics of the processes are not completely understood. Computational fluid dynamics (CFD) codes used for combustion do not currently have the predictive capability that is typically found for nonreacting flows. Low-emissions combustion concepts require very rapid mixing of the fuel and air with a minimum pressure loss to achieve complete combustion in the smallest volume. Areas of specific interest where research is solicited include:

- Development of laser-based diagnostics for quantitative spatially and temporally resolved measurements of fuel/air ratio in reacting flows at elevated pressure.
- Development of optical techniques for soot measurement and characterization for combustor flametube and sector tests (nonprevaporized liquid combustion, fuel Jet-A, pressures 3 to 80 atm; flame temperatures up to 2,250 K, soot diameters on the order of 10 to 100 nm)
- Development of ultrasensitive instruments for determining the size-dependent mass of combustion-generated particle emissions.

- Low-emissions combustor concepts for small, high-pressure engine cores.

Relevance / Science Traceability:

Aeronautics Research Mission Directorate (ARMD), Transformational Tools and Technologies (TTT), Advanced Air Vehicles Program (AAVP).
Achieving low emissions and finding new pathways to cleaner power are critical for the development of future air vehicles. Vehicles for subsonic and supersonic flight regimes will be required to operate on a variety of certified aircraft fuels and emit extremely low amounts of gaseous and particulate emissions to satisfy increasingly stringent emissions regulations. Future vehicles will be more fuel efficient, which will result in smaller engine cores operating at higher pressures. Future combustors will also likely employ lean-burn concepts, which are more susceptible to combustion instabilities.

Infusion/Commercial Potential: These developments will impact future aircraft engine combustor designs (lower emissions, improved operability, control of instabilities) and may have commercial applications in other gas-turbine-based industries, such as power generation and industrial burners. The modeling and results can be and will be employed in current and future hydrocarbon rocket engine designs (improving combustion efficiency, ignition, stability, etc.).

References:

1. Advanced Air Vehicles Program—Advanced Air Transport Technology (AATT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/aatt
2. Advanced Air Vehicles Program—Commercial Supersonic Technology (CST) Project: https://www.nasa.gov/aeroresearch/programs/aavp/cst
3. Transformative Aeronautics Concepts Program—Transformational Tools and Technologies (TTT) Project: https://www.nasa.gov/aeroresearch/programs/tacp/ttt
4. NASA Glenn Combustor Facilities: https://www1.grc.nasa.gov/facilities/erb/combustor/
5. NASA Langley Aerosol Research Group: https://science-data.larc.nasa.gov/large/aeronautics.html
6. Procedure for the Continuous Sampling and Measurement of Non-Volatile Particulate Matter Emissions from Aircraft Turbine Engines (ARP6320): https://www.sae.org/standards/content/arp6320/\

A1.04 Electrified Aircraft Propulsion (SBIR)

Related Subtopic Pointers: T1.15
Lead Center: GRC
Participating Center(s): AFRC, LaRC

Subtopic Introduction:

NASA and industry studies have shown that Electrified Aircraft Propulsion (EAP) concepts can reduce energy use, carbon and nitrogen oxide emissions, and direct operating costs, resulting in benefits for both the public and the airline operators. EAP technology is currently a big investment within ARMD. Within its Strategic Implementation Plan (SIP), research in EAP directly supports Mega Driver 2 (Affordability, Sustainability and Energy Use) and Strategic Thrust 3 (Ultra-Efficient Subsonic Transport). The Integrated Aviation Systems Program (IASP) has an entire flight project dedicated to electrification (Electrified Powertrain Flight Demonstration Project or EPFD). It can even be said that all ARMD programs have some significant investment in EAP.

However, EAP is a difficult technical area. Several areas still need to be researched before they are implemented on electrified or hybrid-electric aircraft.

In terms of commercialization and potential marketability, the electric aircraft market was estimated to be $99 million in 2018 and has been forecasted to grow to as much as $178 billion by 2040.

Scope Title: Energy Storage for Electrified Aircraft Propulsion (EAP)

Scope Description:

Technical proposals are sought for the development of energy storage systems that will be required for aircraft using turboelectric, hybrid-electric, or all-electric power generation as part of the propulsion system. This subtopic is targeted towards megawatt-class vehicles. **Proposals that do not address the needs and targets specifically called out in the solicitation will not be considered.**
Specifically, novel developments are sought in these areas:

- Energy storage systems with specific energy >400 Wh/kg at the system level under continuous 2C rate discharge conditions are required. If component- or cell-level advancements are proposed, a path must be shown towards the stated system-level metrics. Combination/hybrid energy storage systems (e.g., battery + supercapacitor) that meet the system-level metrics are acceptable.
- In addition to meeting the system-level metrics, materials or strategies to promote rapid charging, high temperature operation up to 100 °C, novel system designs incorporating passive thermal management, and novel battery designs to passively prevent the propagation of thermal runaway from cell to cell are also desirable.
- This subtopic seeks energy solutions in the Technology Readiness Level (TRL) 3-5 range that are appropriate for near-term applications.

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

Primary Technology Taxonomy:

- **Level 1:** TX 01 Propulsion Systems
- **Level 2:** TX 01.3 Aero Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

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.

Phase I Deliverables

1. Demonstrate a design that can obtain a specific energy of >400 Whr/kg at the system level under continuous 2C rate discharge.
2. Demonstrate a design that can promote rapid charging, operates at high temperatures up to 100 °C, and incorporates passive thermal management to prevent the propagation of thermal runaway.
3. Reports (Tests, Final).

Phase II Deliverables:

1. Prototype of Phase I design with the performance parameters established in Phase I.
2. Reports (Tests, Quarterly, Final).

State of the Art and Critical Gaps:

All of the areas described under the scope of the subtopic are critical gaps/needs in the area of EAP. Batteries have been proposed for powering electric aircraft, either as standalone systems or hybridized with other power-generation systems. The key challenge to battery-powered propulsion systems for aviation is to increase battery-specific energy. Fuel cells convert the chemical energy in a fuel into electrical power without any combustion. The exhaust from fuel cells is totally carbon-free if hydrogen is used as the fuel in a hybrid-electric concept. The ability of an aircraft to manage heat will be a limiting factor for the high-power electrical power systems needed for turboelectric propulsion. The thermal management system itself will require electrical power to operate, and that power demand will need to be accounted for along with the demands of other nonpropulsive (secondary) power systems.

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 post-2035: The prevalence of small-aircraft fleets with electrified propulsion will provide improved economics, performance, safety, and environmental impact, while growth in fleet operations of large aircraft with cleaner, more efficient alternative propulsion systems will substantially contribute to carbon reduction.

Projects working in the vehicle aspects of EAP include:

- Advanced Air Vehicles Program (AAVP)/Advanced Air Transport Technology (AATT) Project.
- Integrated Aviation Systems Program (IASP)/Flight Demonstrations and Capabilities (FDC) Project.
- AAVP/Revolutionary Vertical Lift Technology (RVLT) Project.
- Transformative Aeronautics Concepts Program (TACP)/Convergent Aeronautics Solutions (CAS) Project.
- TACP/Transformational Tools and Technologies (TTT) Project.

References:

1. EAP is called out as a key part of Thrust 3 in the ARMD Strategic Implementation Plan: https://www.nasa.gov/wp-content/uploads/2021/04/sip-2023-final-508.pdf
2. Overview of NASA's EAP Research for Large Subsonic Aircraft: https://ntrs.nasa.gov/search.jsp?R=20170006235
3. NASA X-57 Project: https://www.nasa.gov/aeroresearch/X-57/technical/index.html
4. “High Efficiency Megawatt Motor Preliminary Design,” Jansen et al.: https://ntrs.nasa.gov/citations/20190029589

Scope Title: Fuel Cell Development for Electrified Aircraft Propulsion

Scope Description:

Technical proposals are sought for the development of fuel cell systems that will be required for aircraft using turboelectric, hybrid-electric, or all-electric power generation as part of the propulsion system. This subtopic is targeted towards megawatt-class vehicles. **Proposals that do not address the needs and targets specifically called out in the solicitation will not be considered.**
Specifically, novel developments are sought in these areas:

- Fuel Cell Improvements in Power Density and Stability. Characterize existing fuel cell electrolyte technologies at scales of ≥25 cm^2 and develop new cell configuration (MEA and flow field) to maintain a cell-level power density of ≥0.8 W/cm^2 for ≥15 min consecutively.
- Also looking to demonstrate performance stability with ≤10 µV/h degradation over at least 250 h at peak power density.

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

Primary Technology Taxonomy:

- Level 1: TX 01 Propulsion Systems
- Level 2: TX 01.3 Aero Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

- Software

Desired Deliverables Description:

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.

Phase I Deliverables:

1. Demonstrate cell-level power density of ≥0.80 W/cm^2 for ≥15 min consecutively.
2. Demonstrate performance stability with ≤10 µV/h degradation over at least 250 h at peak power density.
3. Reports (Tests, Final)

Phase II Deliverables:

1. Demonstrate cell-level power density of ≥0.88 W/cm^2 for ≥15 min consecutively.
2. Demonstrate performance stability with ≤8 µV/h degradation over at least 250 h at peak power density.
3. Subscale stack prototype.
4. Reports (Test, Quarterly, Final).

State of the Art and Critical Gaps:

All of the areas described under the scope of the subtopic are critical gaps/needs in the area of EAP. Batteries have been proposed for powering electric aircraft, either as standalone systems or hybridized with other power generation systems. The key challenge to battery-powered propulsion systems for aviation is to increase battery-specific energy. Fuel cells convert the chemical energy in a fuel into electrical power without any combustion. The exhaust from fuel cells is totally carbon-free if hydrogen is used as the fuel in a hybrid-electric concept. The ability of an aircraft to manage heat will be a limiting factor for the high-power electrical power systems needed for turboelectric propulsion. The thermal management system itself will require electrical power to operate, and that power demand will need to be accounted for along with the demands of other nonpropulsive (secondary) power systems. 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:

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- 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 post-2035: The prevalence of small-aircraft fleets with electrified propulsion will provide improved economics, performance, safety, and environmental impact, while growth in fleet operations of large aircraft with cleaner, more efficient alternative propulsion systems will substantially contribute to carbon reduction.

Projects working in the vehicle aspects of EAP include:

- Advanced Air Vehicles Program (AAVP)/Advanced Air Transport Technology (AATT) Project.
- Integrated Aviation Systems Program (IASP)/Flight Demonstrations and Capabilities (FDC) Project.
- AAVP/Revolutionary Vertical Lift Technology (RVLT) Project.
- Transformative Aeronautics Concepts Program (TACP)/Convergent Aeronautics Solutions (CAS) Project.
- TACP/Transformational Tools and Technologies (TTT) Project.

References:

1. EAP is called out as a key part of Thrust 3 in the ARMD Strategic Implementation Plan: https://www.nasa.gov/wp-content/uploads/2021/04/sip-2023-final-508.pdf
2. Overview of NASA's EAP Research for Large Subsonic Aircraft: https://ntrs.nasa.gov/search.jsp?R=20170006235
3. NASA X-57 Project: https://www.nasa.gov/aeroresearch/X-57/technical/index.html
4. “High Efficiency Megawatt Motor Preliminary Design,” Jansen et al.: https://ntrs.nasa.gov/citations/20190029589

Scope Title: Fuel Cell Thermal Management Concepts for Electrified Aircraft Propulsion

Scope Description:

Technical proposals are sought for the development of advanced Fuel Cell-level thermal management systems that will be required for aircraft using turboelectric, hybrid-electric, or all-electric power generation as part of the propulsion system. This subtopic is targeted towards megawatt-class vehicles. **Proposals that do not address the needs and targets specifically called out in the solicitation will not be considered.**
Specifically, novel developments are sought in these areas:

- Advanced Fuel Cell-Level Thermal Management. Develop fuel cell flow fields of ≥1 m^2 that support fuel cell operation, minimizing in-plane thermal gradients to ≤10 Δ ºC/m when exposed to a uniform thermal load of ≥10 kW/m^2. This requirement is in addition to the standard mechanical and chemical requirements of a flow field plate for use in planar fuel cell stacks.

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

Primary Technology Taxonomy:

- Level 1: TX 01 Propulsion Systems
- Level 2: TX 01.3 Aero Propulsion

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

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.

Phase I Deliverables:

1. Demonstrate in-plane thermal gradients to $\leq 10\ \Delta$ ºC/m at peak thermal loads of ≥ 10 kW/m^2.
2. Reports (Tests, Final).

Phase II Deliverables:

1. Demonstrate in-plane thermal gradients to $\leq 10\ \Delta$ºC/m at peak thermal loads of ≥ 15 kW/m^2.
2. Sub-scale stack prototype.
3. Reports (Test, Quarterly, Final).

State of the Art and Critical Gaps:

All of the areas described under the scope of the subtopic are critical gaps/needs in the area of EAP. Batteries have been proposed for powering electric aircraft, either as standalone systems or hybridized with other power generation systems. The key challenge to battery-powered propulsion systems for aviation is to increase battery specific energy. Fuel cells convert the chemical energy in a fuel into electrical power without any combustion. The exhaust from fuel cells is totally carbon-free if hydrogen is used as the fuel in a hybrid-electric concept. The ability of an aircraft to manage heat will be a limiting factor for the high-power electrical power systems needed for turboelectric propulsion. The thermal management system itself will require electrical power to operate, and that power demand will need to be accounted for along with the demands of other nonpropulsive (secondary) power systems. 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 post-2035: The prevalence of small-aircraft fleets with electrified propulsion will provide improved economics, performance, safety, and environmental impact, while growth in fleet operations of large aircraft with cleaner, more efficient alternative propulsion systems will substantially contribute to carbon reduction.

Projects working in the vehicle aspects of EAP include:

- Advanced Air Vehicles Program (AAVP)/Advanced Air Transport Technology (AATT) Project.
- Integrated Aviation Systems Program (IASP)/Flight Demonstrations and Capabilities (FDC) Project.
- AAVP/Revolutionary Vertical Lift Technology (RVLT) Project.
- Transformative Aeronautics Concepts Program (TACP)/Convergent Aeronautics Solutions (CAS) Project.
- TACP/Transformational Tools and Technologies (TTT) Project.

References:

1. EAP is called out as a key part of Thrust 3 in the ARMD Strategic Implementation Plan: https://www.nasa.gov/wp-content/uploads/2021/04/sip-2023-final-508.pdf
2. Overview of NASA's EAP Research for Large Subsonic Aircraft: https://ntrs.nasa.gov/search.jsp?R=20170006235
3. NASA X-57 Project: https://www.nasa.gov/aeroresearch/X-57/technical/index.html
4. High Efficiency Megawatt Motor Preliminary Design," Jansen et al.: https://ntrs.nasa.gov/citations/20190029589

A1.09 Zero-Emissions Technologies for Aircraft (SBIR)

Related Subtopic Pointers: T1.15
Lead Center: GRC
Participating Center(s):

Subtopic Introduction:

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 the 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-emissions 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. One example of such a 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 wingspan 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 primarily to power 150-kW generator), power at 150 kW total, individual converters at 40 kW, 10 kW operating on a DC power bus, and thermal management from pumped liquid cooling loops with a worst-case hot temperature of 60 °C.

Scope Title: Energy Conversion for Aircraft, Cryogenic Fuel Management, and Thermal Management

Scope Description:

This SBIR subtopic is open to any ideas that lead to aircraft with zero emissions or highly reduced emissions. 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.

Proposals that emphasize physical prototypes in Phase I or would be planned for Phase II are especially desirable.

We are focused on some specific areas this year:

1. Turbofan technologies demonstrated on a small turbofan engine in the 500-lb thrust class. Preferred implementations are those in which a significant fraction (>65%) of the power generated is produced as electrical power 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:

- Combined cycles (topping, bottoming, other), as well as novel cycles.
- Integration concepts of combustor and turbine for improved overall and component performance.
- 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 will be considered,
- Solid oxide/turbine fuel cell combinations.
- Heat exchangers with waste heat recovery performance that results in aircraft-level benefits.

2. Technologies to make cryogenic fuels practical on an aircraft such as, but not limited to, liquid hydrogen and liquid natural gas.

- Tank technologies that address weight, boiloff, aircraft loads, safety requirements, and transport and refueling requirements at airports.
- Cryogenic pump technologies that address the requirements for cryogenic fuel distribution on aircraft and loading/unloading of cryogenic fuels into tanks.
- On-ground airport cryogenic management technologies.

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 on 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:

The TRL of power extraction from both shafts of a turbofan is still low 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 applications and the cost of them must come down. Cryogenic tanks and pumps need to be made more reliable, less expensive, and lighter in weight. The thermal management systems must be made efficient, reliable, and light in weight. Most of these items require a system approach to optimization and a focus on longer, more rugged applications, as well as the ability to keep costs 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 previously.

Potential advocates include 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-O'Connor (Electrified Powertrain Flight Demonstration (EPFD) Project Manager), and Ralph Jansen.

References:

1. NASA ARMD Strategic Implementation Plan: https://www.nasa.gov/wp-content/uploads/2021/04/sip-2023-final-508.pdf
2. NASA Aeronautics Research: https://www.nasa.gov/aeroresearch
3. NASA Aeronautics Sustainable Aviation: https://www.nasa.gov/aeroresearch/sustainable-aviation
4. Electrified Aircraft Propulsion: https://www1.grc.nasa.gov/aeronautics/eap/
5. NASA Aims for Climate-Friendly Aviation: https://www.nasa.gov/aeroresearch/nasa-aims-for-climate-friendly-aviation
6. Subsonic Single Aft Engine (SUSAN) Aircraft: https://www1.grc.nasa.gov/aeronautics/eap/airplane-concepts/susan/
7. Subsonic Single Aft Engine (SUSAN) Transport Aircraft Concept and Trade Space Exploration: https://arc.aiaa.org/doi/pdf/10.2514/6.2022-2179

Z10.05 : Rotating Detonation Rocket Engine Nozzles and Instrumentation (SBIR)

Related Subtopic Pointers: T1.15

Lead Center: MSFC
Participating Center(s): GRC

Subtopic Introduction:

Rotating detonation rocket engines (RDREs) are a promising rocket concept that could provide higher thermodynamic performance in a smaller package than traditional chemical rocket engines. The annular combustion chamber of an RDRE typically contains multiple co-rotating detonation waves that generate a composite wave-passing frequency of 10 kHz or more. The resulting combustor flow-field pressure, temperature, and velocity varies significantly in both space and time. To achieve the performance potential of this concept, it is necessary to develop components capable of achieving high performance despite the flow oscillations. Additionally, it is desired that the components (combustor, nozzle, manifolds) be no longer or heavier than the state-of-the-art components for steady flow rockets. In some cases, the unsteady gas-dynamic flow field may allow for considerably shorter and lighter components to be developed with acceptable performance. Also, advanced instrumentation concepts are needed to aid the evaluation of the performance of these components that can make time-resolved measurements with a frequency response at or above 100 kHz. This subtopic is focused on the development of one key component, a high-area-ratio nozzle (HARN) for vacuum applications, and either a high-frequency wall heat transfer point sensor (preferred) or a high-frequency wall temperature point sensor capable of surviving multiple firings in an RDRE combustor.

Scope Title: High-Area-Ratio Rotating Detonation Rocket Engine Nozzle for In-Space Applications

Scope Description

Innovative designs by which RDRE combustion products can be optimally expanded to produce near-ideal thrust at minimum hardware mass/length are desired. A typical RDRE nozzle has an aerospike-like plug nozzle attached to the center body and an outer cowl or expansion contour. It is not currently understood how to optimally expand the flow from an RDRE combustor given the oscillatory exhaust flow field. Studies purely on high-area-ratio aerospike nozzles alone are not of interest. In addition to the expansion section described previously, novel methods for chamber and subsequent throat design are of interest. It is well known that an abrupt area contraction can cause a deleterious impact to the detonation's stability, thus causing a decrease in detonative performance, which is likely to cause a decrease in global engine performance and operability. Further investments into geometries that do not hinder detonation performance but also increase specific impulse (I_{sp}) are desired. Relevant in-space propellant combinations and operating conditions are required.

Phase I requires the use of computational fluid dynamics (CFD) modeling or equivalent analysis/experimental work that explicitly identifies trends in loss minimization and thrust maximization, in addition to attempts that reduce overall hardware mass and length requirements. The primary goal is to better understand how to design a coupled chamber and nozzle configuration for RDREs that will produce maximum thrust at minimum nozzle length in a vacuum environment.

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

Primary Technology Taxonomy:

- Level 1: TX 01 Propulsion Systems
- Level 2: TX 01.4 Advanced Propulsion

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Performance trends from a parameterized set of 2D/3D computational combustor/nozzle models should be delivered. Information from any validation calculations or computational tests of effects of grid density/structure, turbulence, viscosity, boundary layer resolution, heat transfer, etc., should be included in addition to the actual combustor nozzle modeling results. Baseline CFD models of reference steady-flow rocket combustor/nozzle sets should also be included for comparison.

Finally, prototype hardware tested at altitude/vacuum conditions will be required in Phase II to demonstrate how engine performance compares with computational results. Hardware that prioritizes mass and length savings as well as performance improvement for an RDRE compared to a traditional liquid rocket engine at the same operating conditions is preferred.

Key performance parameters are system I_{sp}, mass reduction, and length reduction compared to a baseline engine.

State of the Art and Critical Gaps:

There is currently no established method for designing HARNs for RDREs. Traditional rocket nozzle design methods, such as the method of characteristics for minimum-length bell nozzles, have been applied in some cases, while simple constant cone angle nozzles have been used in other cases. It is theorized that RDRE nozzles could be designed at the identical area ratio but at a reduced total length due to the ability of RDRE exhaust flow to stay attached to expansion surfaces at expansion angles where steady flow would separate from the wall.

Relevance / Science Traceability:

This subtopic is aligned with current Space Technology Mission Directorate priorities. A vacuum geometry in-space propulsion system directly enables space missions requiring high I_{sp}. Missions to the Moon, Mars, and other planetary bodies within the solar system would directly benefit from this technology. Programs such as Space Launch System (SLS), Human Landing System (HLS), and Commercial Lunar Payload Services (CLPS) lander missions would directly benefit from the technology because it extends and enables capabilities not currently possible with traditional rocket engines, both in terms of propulsive performance and reduced mass and length.

References:

1. K. Goto, J. Nishimura, A. Kawasaki, K. Matsuoka, J. Kasahara, A. Matsuo, I. Funaki, D. Nakata, M. Uchiumi, and K. Higashino, “Propulsive performance and heating environment of rotating detonation engine with various nozzles,” J. Propuls. Power, vol. 35, no. 1, pp. 213–223, 2019.
2. S. Yetao, L. Meng, and W. Jianping, “Continuous detonation engine and effects of different types of nozzle on its propulsion performance,” Chinese J. Aeronaut., vol. 23, no. 6, pp. 647–652, 2010.

3. M. Fotia, T. A. Kaemming, J. Hoke, and F. Schauer, “Study of the experimental performance of a rotating detonation engine with nozzled exhaust flow,” in 53rd AIAA Aerospace Sciences Meeting, 2015, p. 631.
4. T. Smith, A. Pavli, and K. Kacynski, “Comparison of theoretical and experimental thrust performance of a 1030:1 area ratio rocket nozzle at a chamber pressure of 2413 kN/sq m (350 psia),” in 23rd Joint Propulsion Conference, 1987, p. 2069.
5. S. Yungster, D. Paxson, K. Miki, H.D. Perkins, “Computational Fluid Dynamic Optimization of an Experimental Rotating Detonation Rocket Engine Nozzle,” AIAA 2022-4107, June 2022.

Scope Title: Rotating Detonation Rocket Engine Wall Sensors

Scope Description:

Rotating detonation rocket engines (RDREs) are a promising rocket concept that could provide higher thermodynamic performance in a smaller package than traditional chemical rocket engines. One key element required to design such engines is an understanding of the temperature and heat flux conditions at the combustor wall. Given that the flow field fluctuates in time and space from 3,000 to 12,000 times per second, these measurements would ideally be of sufficient frequency response so as to capture the phenomena at a single point as a function of time during a detonation wave passage. However, even a time average of these parameters would be useful for anchoring numerical models of the near-wall flow field. Although calorimetry measurements have been made for a number of engines, these measurements are made over a region of the combustor and do not provide sufficient spatial fidelity to validate computational models.

This subtopic element is intended to promote the development of point measurement sensors for wall heat flux or temperature capable of operating at RDRE combustor temperatures and pressures for short durations (2 to 10 s) with a frequency response in excess of 100 kHz. Such sensors would be very valuable for NASA for use in a number of combustor devices with high-frequency oscillations in addition to RDREs. This capability currently does not exist. Data from such sensors would allow designers to properly design combustors using accurate values for design heat flux and temperature as a function of time. Such sensors would be a marketable commodity in and of themselves for use in a variety of applications, not just RDREs. These applications would include munitions, gas turbines, and ramjets/scramjets. For NASA, the data from such sensors would be invaluable for developing flight-weight RDRE designs.

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

Primary Technology Taxonomy:

- Level 1:TX 01 Propulsion Systems
- Level 2:TX 01.4 Advanced Propulsion

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Analysis

Desired Deliverables Description:

For Phase I, a detailed design of the proposed sensor(s), along with supporting analysis showing that the design requirements could be met by the design approach used.

For Phase II, a prototype should be manufactured and tested initially in a known environment, such as a shock tube or detonation tube. Final testing should take place within a running RDRE.

A sensor that provides a time average of heat flux or temperature at a single location is acceptable but not preferred.

State of the Art and Critical Gaps:

Currently, there is no heat transfer gauge or temperature sensor that can be used to assess the impact of the detonative flow on the combustor wall. Calorimetry data is expensive to obtain and not localized enough for use in model development and validation.

Relevance / Science Traceability:

This work is highly relevant to NASA's interest in developing RDREs for NASA missions and for the space transportation community as a whole. Additional utility for defense applications is expected.

References:

1. Gifford, D. Hubble, C. Pullins, T. Diller, and S. Huxtable, “Durable Heat Flux Sensor for Extreme Temperature and Heat Flux Environments,” Journal of Thermophysics and Heat Transfer, Vol. 24, No. 1, January–March 2010, pp. 69-76.
2. F. Ladeinde, H. Oh, and S. Jacobs, “Supersonic combustion heat flux in a rotating detonation engine,” Acta Astronautica, Vol. 203, February 2023, pp. 226-245.

Z5.06 Servicing and Assembly Applications (SBIR)

Related Subtopic Pointers: T1.15
Lead Center: GSFC
Participating Center(s): ARC, JPL, KSC, LaRC

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. This subtopic addresses key servicing and assembly gaps in the Space Technology Mission Directorate (STMD) roadmap.

Scope Title: Optimized Interfaces for Science Instrument and Spacecraft Servicing and Assembly

Scope Description:

NASA requests novel conceptual designs for interfaces for in-space or surface robotic servicing and assembly, as well as science instrument upgrade. Development of minimized mass and volume robotic connections that provide increased capability for electrical, thermal, power, fluid transfer, and installation of science instruments or modules is highly desirable.

For surface science instrument interfaces, reductions in mass and volume for electrical and power connections will enable increased science opportunities. The current state of the art for dust-compliant electrical and power interfaces challenges instrument designs with packaging constraints that limit instrument volume for near-term systems. SMD is soliciting proposals for deployed instruments for Artemis manned missions, and reductions in mass and volume are needed to comply with astronaut handling requirements. A modular approach for swapping instruments or providing supplemental power enabled by innovations in key interfaces that is achievable in astronaut and rover enabled deployments is needed for sustainable Artemis and future Mars missions.

For in-space instrument and spacecraft interfaces, development of robotic connections that enable instrument swap and/or dedicated interfaces for outfitting of unplanned components has substantial benefits for multiple platform concepts. System evaluation of interface designs that include mechanical, thermal, and electrical connections is needed. Upgrade of instruments requires interfaces with sufficient power and flexibility to survive during replacement activities.

Development of robotic technologies for instruments, spacecraft assembly interfaces, and outfitting addresses gaps in robotics, autonomy, assembly, and servicing.

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 04.6 Robotics Integration

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 interface.
- Concept for low-cost flight demonstration.

Phase II deliverables include:

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

State of the Art and Critical Gaps:

The current state of the art for surface science instrument interfaces is low-TRL concepts for dust-compliant electrical connectors and wireless charging interfaces. Current concepts require reductions in mass and volume to enable implementation in a wide variety of applications. Improvements in interface design enable increased science opportunities enabled by robotic rovers and assisted by human astronauts. The current state of the art for in-space interfaces for in-space assembly is primarily International Space Station interfaces. A system-level approach for future systems should include in-space assembly and servicing as options in the architecture trades. Design of interfaces that enable upgrades and modernization is highly desirable and addresses many STMD gaps in the areas of robotics, assembly, and increased autonomy.

Relevance / Science Traceability:

NASA missions to provide science for Artemis are challenged by mass and volume constraints. Dust-compliant interfaces for power and data interfaces do not exist in the smaller form factor required for astronaut-handled modules.

NASA is studying mission concepts for assembly of spacecraft components in space, and upgrade of science instruments on spacecraft.

References:

On-Orbit Satellite Servicing Study Project Report. October 2010. https://sspd.gsfc.nasa.gov/images/NASA_Satellite%20Servicing_Project_Report_0511.pdf

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Scope Title: Venting of Storable Fluid Systems Near Sensitive Space Systems

Scope Description:

Venting of storable fluid systems into a microgravity vacuum near sensitive spacecraft assemblies and components is required for future in-space fluid transfer operations. Technical solutions to one or all of the following technological in-space fluid venting gaps are requested:

- Near-continuous, liquid-free microgravity venting from a propellant management device (PMD)-style propellant tank. These PMD tanks are not the positive displacement variety (e.g., diaphragm, bladder, or bellows type). 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 (monomethyl-hydrazine (MMH) and nitrogen tetroxide (NTO)) to multiple two-phase commodity in-space replenishment efforts on other storable fluids (such as green propellants) and nonstorable fluids (such as cryogenics).
- A device (or multiple commodity-specific devices) that enables liquid venting of hypergolic and other typical in-space fuels and oxidizers (such as ASCENT (Advanced Spacecraft Energetic

Non-Toxic) propellant, peroxide, or others) that includes decomposition, minimal thrust and impulse, controllable/predictable plumes, and minimal contamination concentration levels. The goal of this device is to minimize or eliminate the risk of harm to surrounding materials/components on the spacecraft as a result of exposure to the vented fluid.
- User-friendly modeling techniques and solutions that can simulate directional flow in gas or liquid phases from the continuum to free-molecular regimes during a fluid vent into space (microgravity vacuum environment). Model should also be able to determine deposition concentration at various distances from exit of vent.

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.

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 spaceflight and launch environments (vibration, shock, thermal vacuum, electromagnetic interference and emissions, etc.).

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.

While venting of hypergolic propellant has been done for decades by the Russians on the fluid-servicing interface on the International Space Station (ISS), liquid-free venting of a PMD-style tank has only been performed a few times: once during the Orbital Express mission, and with some fluid experiments during approximately three space shuttle missions. To achieve the liquid-free venting of the tank in those cases, either the tank had to be highly customized (requiring years of development) or an acceleration (thruster firing) had to be performed. Enabling liquid-free venting without custom tank designs or imparting accelerations must be realized to perform on-orbit servicing in the future with tanks that are not of a diaphragm or metal bellows variety, i.e., the vast majority of propellant tanks currently flying or being planned to fly, including large cryogenic tanks for the Artemis program. If a device such as the one proposed is developed, this would enable the lowest risk solution for in-space (microgravity) liquid transfer, which is via a pumped flow loop with the liquid ports of a supply-and-receiving tank connected in addition to the ullage gas ports. This would allow for liquid transfer without thermal impacts and loss of ullage gas commodities to space (which would be required to lower a tank pressure prior to servicing of the receiving vehicle if a flow loop is not utilized).

In addition, a vent device that ejects gas or liquid away from a spacecraft without imparted forces and with lowest possible risk is currently a gap technology. It is known that the fluid flow rate, pressure, and temperature can significantly impact the trajectory of the fluid as it is leaving the spacecraft plumbing. Development of analytical tools and hardware that could optimize a technical solution would significantly lower a risk of contamination of the fluid ejected onto spacecraft external surfaces as well as lowering the risk of forces imparted onto the spacecraft.

Relevance / Science Traceability:

Microgravity venting is relevant to missions such as On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1), OSAM-2, 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.

References:

1. NASA's Exploration & In-Space Services (NExIS). Propellant Transfer Technologies. https://nexis.gsfc.nasa.gov/propellant_transfer_technologies.html
2. 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: Clean Robotics for Highly Sensitive Systems

Scope Description:

NASA requests conceptual designs for significant improvements in cleanliness of robotic systems that will enable in-space servicing and assembly of highly sensitive spacecraft and platforms, such as the Habitable Worlds Observatory and other future telescopes. With increasing inclusion of in-space servicing, assembly, and manufacturing in future architectures, there is a need to reduce contamination for operations around highly sensitive platforms. The current state of the art for robot systems poses risks for servicing of platforms with ultraviolet (UV) systems that may be susceptible to contamination which could dramatically reduce instrument performance.

Moving parts, lubrication, thermal management systems, harnesses, sensors, and other arm subsystems are likely to result in outgassing, particulate ejection, and other forms of contamination. Specific missions set contamination budgets and deploy verification and validation approaches for mission assurance. This scope seeks best practices or models to estimate contamination ranges to be expected from robotic arms as a function of specific designs, material choices, and other parameters during the acquisition phase.

Approaches for validating these models or best practices through test data on existing space robotic arms or their subsystems are also encouraged. Approaches for improving the overall cleanliness of robotic arms beyond the current state of the art are also highly encouraged. The goal here is to understand the cleanliness characterization of current robotic arm offerings and new means, incremental or otherwise, to improve the same. Engineering estimates of the impact of improving the overall cleanliness on design complexity, schedule, cost, and risk are encouraged.

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

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.6 Robotics Integration

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis

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.
- Concept for environmental characterization of improved performance.

Phase II deliverables include:

- Validation of current contamination budget/estimates.
- Validation of methods to improve contamination performance at system or subsystem level.

State of the Art and Critical Gaps:

The current state of the art includes robot arms systems such as Canadarm2; Japanese Module Remote Manipulator System; On-Orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1); and Robotic Servicing of Geosynchronous Satellites (RSGS) robot arms, which have primarily been used in low Earth orbit (LEO). Future servicing and assembly applications require expanded capabilities in multiple orbital domains, including LEO, geostationary orbit (GEO), Lagrange points, and beyond.

This scope provides a potentially enabling capability for planetary science mission concepts that implement robotics for instrument upgrades and/or assembly, and improved robotics for minimizing contamination risk for sample return.

Relevance / Science Traceability:

NASA is evaluating architectures that involve upgrade and modernization of instruments or subsystems on multiple platforms. An improved-cleanliness robotic system provides additional options for science instrument modernization at optimized costs.

References:

1. On-Orbit Satellite Servicing Study Project Report. October 2010. https://sspd.gsfc.nasa.gov/images/NASA_Satellite%20Servicing_Project_Report_0511.pdf

Z8.09 Small Spacecraft Transfer Stage Development (SBIR)

Related Subtopic Pointers: T1.15
Lead Center: MSFC
Participating Center(s): GRC, JSC

Subtopic Introduction:

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 distant, nontraditional 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.

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 PNT services. Advancement and extension of these capabilities will be needed for future planetary exploration.

NASA seeks proposals for the development, improvement, or maturation of small spacecraft stage designs to increase performance, reliability, and/or safety. While the end goal of this topic is a stage-level design, an initial targeted focus on propulsion system component or subsystem-level development is acceptable as long as there is detailed discussion and planning for its integration into a stage-level design. 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 translunar 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 $-0.6\ \text{km}^2/\text{s}^2$.
- (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 design concept for flight operations, regardless of whether exploring the full-stage concept or component/subsystem development, 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. If the Phase I effort focuses on subsystem or component development, a stage-level concept as well as a plan for subsystem/component integration into that stage-level concept during the Phase II effort should be provided as part of the Phase I deliverable. 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. If the Phase I effort focused on component or subsystem development, the Phase II effort should make significant progress toward integration into the stage-level concept design, as defined by the plan submitted as part of the Phase I deliverable. 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 tested, 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 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.

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10. Example SST: Bradford Green Prop Systems. Bradford ECAPS - High Performance Green Propulsion Thrusters
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14. Deep Space Network (DSN) handbook. https://deepspace.jpl.nasa.gov/dsndocs/810-005/
15. Space Frequency Coordination Group (SFCG) handbook. https://www.sfcgonline.org/Resources/default.aspx
16. NASA Delay/Disruption Tolerant Networking (DTN). http://www.nasa.gov/content/dtn

TX02: Flight Computing and Avionics

This area covers unique electronics and computing hardware when applied to flight systems, whether in space or atmospheric.

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

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

Subtopic Introduction:

Neuromorphic computing (that is, mapping of lessons from neuroscience to silicon) and deep neural net processors have already achieved substantial advances for artificial intelligence 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 an 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 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 or **T**rillions of **O**perations **P**er **S**econd), low power (1 watt or less per TeraOPS), and robustness across wide temperature variation, RFI, launch vibration, and especially the radiation encountered in space and the lunar/martian surface.

One prominent aspect of the brain is its extraordinary, estimated throughput at extremely low power. 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.

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 STT-RAM, and phase-transition devices are especially interesting. Traditional radiation-tolerant layout techniques can include buried guard rings that act like 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 latchup, such as the 22-nm FDSOI technology node that is being used for automotive chip fabrication and shows promise for space processors. At the hardware architecture level and higher, 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 of computation errors such as radiation-induced bit flips than traditional computing. Innovation for radiation tolerance that maximizes the throughput-power-robustness combined metrics is desirable.

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.

Subtopic scopes:

1. AIML 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 achieve autonomous space capabilities such as cognitive communications, extraterrestrial robotic surface navigation and guidance at higher speeds, spacecraft health management from anomaly detection through fault detection and mitigation, and science data processing starting with noisy sensor data through sensor fusion and finally producing science information such as surface topography from orbital observations.

Scope Title: Radiation-Tolerant AIML Learning Hardware

Scope Description:

This hardware scope is for embedded radiation-tolerant AIML processors and accelerators that provide hardware support for efficient adaptation and learning in the space environment. This includes neuromorphic processors capable of programmable fine-grained synaptic update rules, neural net accelerators with adaptation capabilities based on back-propagation, and highly efficient vector and signal processors that incorporate compute-in-memory capabilities. 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. A distinguishing feature would be that most of the data flow between processing steps is localized within the processor for energy and throughput efficiency rather than between the processor and main memory. Through this localization, the Von Neumann bottleneck is overcome. In contrast to the second scope for radiation-hard, inference-only processors, the AIML learning processors should be capable of billions or more of write cycles corresponding to synaptic updates during learning; this excludes some types of devices that are write-cycle limited.

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 (a custom 16-bit floating point format) 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 higher than 50 krad and no destructive latchup. Note that unhardened commercial off-the-shelf (COTS) devices are typically rated at less than 10 krad. Single-event latchup 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 the Loihi processor 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 by 10 cm. The preference is for a prototype processor fabricated in a technology node suitable for the space environment, such as the 22-nm FDSOI, which has become increasingly affordable.

The Phase II deliverables should include a maturation plan for a ruggedized production processor fabricated at a competitive technology node with high performance metrics, which 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 state of the art (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:

In the field of radiation-tolerant AI/ML learning hardware, certain key components take center stage. First and foremost, radiation-tolerant neuromorphic machine learning processors and radiation-tolerant high-performance memory modules are indispensable. These components are specifically engineered to endure the challenges posed by space radiation, ensuring the reliability of AI and optimization algorithms essential for autonomous systems in space exploration. Complementing these, the integration of autonomous self-sensing technology becomes crucial. This capability empowers machines to adapt and respond intelligently to their surroundings, a vital feature for autonomous systems navigating unpredictable space environments. Alongside this, the careful development of robotic actuators, sensors, and interfaces enhances the adaptability of autonomous systems, enabling effective interactions with the diverse space environment. Additionally, the incorporation of Integrated system fault/anomaly detection, diagnosis, and prognostics is pivotal. This feature ensures the safety and reliability of these systems by promptly identifying and addressing issues, even in radiation-rich space conditions. The convergence of these elements strengthens the resilience of AI/ML hardware, aligning seamlessly with NASA's objectives to enhance robotic and autonomous systems for space exploration, fostering the development of advanced and enduring technologies in the realm of space exploration.

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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 AIML Learning Hardware."

First, the processor for this scope 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 total ionizing dose (TID) immunity of 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× 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-min, for the worst 5-min 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 latchup, even under the extreme environment of Jupiter and Saturn. Single-event latchup 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 a layout of 10 by 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 the 22-nm FDSOI, which has become increasingly affordable.

The Phase II deliverables 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 state of the art (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 to the 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:

In the field of extreme radiation-hard neuromorphic hardware, specific components are critical in the pursuit of resilience during space exploration. Radiation-tolerant general-purpose processors, neuromorphic machine learning processors, and high-performance memory, meticulously crafted, must endure the rigors of extreme radiation, thus ensuring the stability of indispensable AI and optimization algorithms crucial for space missions. This shift toward extreme radiation-hardened hardware is a vital bridge between the scientific aspirations of NASA and our desired engineering innovations. Particularly in the demanding environments outside of low-Earth orbit (LEO), where radiation levels are intense, these hardened components help guarantee the longevity and precision of scientific experiments. Their ability to withstand this harsh environment is essential, as it secures accurate data, fundamental for meticulous analysis. The incorporation of components for autonomous self-sensing and robotic actuators while maintaining low size, weight, and power (SWaP) is paramount. These integrated elements, equipped with advanced sensors and autonomous capabilities, facilitate intelligent navigation and responsive actions within radiation-rich environments. These advancements in extreme radiation-hard neuromorphic hardware and integrated components exemplify NASA's commitment to advancing space exploration by enhancing our operational capabilities.

References:

1. 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
2. Bengio, Y., Lecun, Y., and Hinton, G. Deep Learning for AI. 2018 Turing Award. Communications of the ACM, 64(7) 58-65. (2021)
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6. Cognitive Communications for Aerospace Applications (CCAA) Workshop Papers. Available at: https://strs.grc.nasa.gov/ccaa23/
7. Alena, R. Mission Radiation Environment Modeling and Analysis Avionics Trade Study for Rad-Neuro. NASA Technical Memorandum 20220011775. (August 2022)
8. Schumann, J. Radiation Tolerance and Mitigation for Neuromorphic Processors. NASA Technical Memorandum 20220013182. (November 2022)
9. NASA short course: Radiation Hardness Assurance: Evolving for NewSpace. Available at: https://nepp.nasa.gov/
10. 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
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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 (SOCs) 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 lower 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 target radiation tolerant neuromorphic processors potentially developed under Scopes 1 or 2 or from another source only after Phase II. 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™ (Google Inc), PyTorch™ (Linux Foundation), Nengo™ (Applied Brain Research), Lava™ (Intel Corporation), 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 Field-Programmable Gate Arrays (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™, Brainchip's Akida™, and Google Inc's Tensor Processing Unit (TPU™) 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 are 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:

In the field of neuromorphic software for cognition and learning crucial to space missions, advancements should be made in several key areas. Autonomous self-sensing, consolidated advanced sensors, and low SWaP proximity range sensors enhance the perceptual abilities of autonomous systems. These innovations are complemented by collision avoidance maneuver design, robotic actuators, sensors, and interfaces, enabling these systems to navigate complex environments. Additionally, autonomous capabilities, such as on-board "thinking" autonomy, integrated system fault detection, diagnosis, and prognostics, as well as the creation, scheduling, and execution of activities by autonomous systems, ensure adaptive responses and fault resilience. These advancements can enable NASA's continued dedication to advancing space exploration technology and assists the agency's commitment to fostering intelligent, adaptable, and fault-tolerant systems, crucial for the success of future space missions.

References:

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2. 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)

3. Bengio, Y., Lecun, Y., and Hinton, G. Deep Learning for AI. 2018 Turing Award. Communications of the ACM, 64(7) 58-65. (2021)
4. Davies, M. et al. Loihi: A neuromorphic manycore processor with on-chip learning. IEEE Micro 38(1) 82-99. (2018)
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9. Barszcz, E. Neural Network Pipelines for Autonomous Rovers in Space Applications. NASA Technical Memorandum 20220013240. (November 2022)
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11. 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
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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: 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 Reduced Instruction Set Computer-V (RISC-V) 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 design intellectual property (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 coprocessor/accelerator devices and design IP are continuously being developed to support heterogeneous computing systems for use in self-driving cars, data centers, and modern smartphones. State-of-the-art heterogeneous computing systems use FPGAs, graphics processing units (GPUs), tensor processing units (TPUs), and neuromorphic processors as accelerators to offload specialized tasks like machine learning or image processing. Accelerator programming models include a variety of different programming models, such as OpenCL, CUDA, and TensorFlow. These programming models make it easier to develop and deploy applications for accelerators in heterogeneous computing systems. Critical technology gaps include:

- Performance - Existing space-grade coprocessor/accelerator devices are not yet powerful enough to meet the performance requirements of NASA's next-generation systems for future missions. Next-generation autonomous systems need to be able to process a large amount of sensor data in real time to make safe decisions.
- Energy Efficiency - Existing accelerator devices are not yet efficient enough to meet NASA's power and thermal constraints. Next-generation systems need to be able to operate under solar-array-with-a-battery power constraints (no radioisotope thermoelectric generators (RTGs)).

- Scalability/Versatility - Existing accelerator devices are often designed for specific workloads, such as machine learning or image processing. Next-generation autonomous systems need to be used for a variety of different workloads, such as perception, planning, and control. These needs will be mission specific.
- Resilience - NASA systems need to self-heal due to harsh environmental conditions. Commercial accelerator devices can be leveraged, but a redundant system design with health monitoring is needed.

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:

1. nVDLA: http://nvdla.org. Open-source deep learning accelerator successfully implemented in FPGAs (Xilinx). See also https://github.com/nvdla/hw
2. nVDLA on RISC/V - SiFive sponsored work. Details in this codebase: https://github.com/CSL-KU/firesim-nvdla
3. Miaow: https://github.com/VerticalResearchGroup/miaow. Open-source GPU.
4. FlexGrip: https://github.com/Jerc007/Open-GPGPU-FlexGrip-. Open-source GPU from the University of Turin and U MASS. See also http://www.ecs.umass.edu/ece/tessier/andryc-fpt13.pdf
5. VeriGPU: https://github.com/hughperkins/VeriGPU. Open source - Amateur project with plans to use SYCL.

Alternately, license a GPU, TPU (tensor processing unit), or DSP core from a vendor and prototype it in the FPGA:

1. https://www.design-reuse.com/sip/?q=GPU
2. https://www.xilinx.com/products/technology/dsp.html
3. https://www.microsemi.com/product-directory/technology/1742-dsp
4. Experience of Qualcomm enabling code generation for their Hexagon DSP with LLVM: https://www.llvm.org/devmtg/2011-11/Simpson_PortingLLVMToADSP.pdf

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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 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. NASA needs more providers of solid-state memory drives (SSDs) because future missions will be generating more science data and system logs. SSDs will be needed for both real-time and long-term data storage with possible security considerations.

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.

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1. RISC-V: https://riscv.org/news/2019/09/risc-v-gains-momentum-as-industry-demands-custom-processors-for-new-innovative-workloads/
2. Next Generation Space Interconnect Standard (NGSIS) SpaceVPX Tutorial: https://www.vita.com/resources/Learn/SpaceVPX%20Tutorial%20%202023_08_04.pptx
3. He, J., et al. Provably Correct Systems. Formal Techniques in Real-Time and Fault-Tolerant Systems, pp. 288-335. ProCoS.1994.
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6. 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.
7. Yanguas-Gil, A., et al. Neuromorphic Architectures for Edge Computing Under Extreme Environments, pp. 39-45. IEEE Space Computing Conference Proceedings. 2021.
8. Sabogal, S., et al. A Methodology for Evaluating and Analyzing FPGA-Accelerated, Deep-Learning Applications for Onboard Space Processing, pp. 143-154. IEEE Space Computing Conference Proceedings. 2021.

Scope Title: Reduced Instruction Set Computer-V (RISC-V) Software Tools

Scope Description:

NASA is seeking software enhancements that would enable leading application programming interfaces (APIs) and operating systems to maximize the capabilities of emerging multicore RISC-V architectures. Specific areas of interest are:

- Graphics (e.g., VulkanSC).
- Graphics processing unit (GPU) computation (e.g., OpenCL, OpenCV on Nvidia).
- Robotic operating systems (e.g., ROS/ROS2).
- Machine learning (e.g., Dlib).

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

Primary Technology Taxonomy:

- Level 1: TX 11 Software, Modeling, Simulation, and Information Processing
- Level 2: TX 11.1 Software Development, Engineering, and Integrity

Desired Deliverables of Phase I and Phase II:

- Software

Desired Deliverables Description:

Phase I Deliverables:

- Market research.
- Conceptual design.
- Use case analysis.
- Detailed plan for porting to RISC-V.
- Business case, including any plans for providing and supporting open-source.

Phase II Deliverables:

- Prototype software operating on representative RISC-V platform.

State of the Art and Critical Gaps:

The current state of the art (SOA) in RISC-V software tools for the specified domains (Graphics, GPU Computation, Robotic Operating Systems, Machine Learning) involves predominantly using proprietary architectures like x86 and ARM. These architectures have well-established ecosystems and support from major vendors and software developers.

- Graphics (e.g., VulkanSC): At the SOA, graphics APIs like Vulkan have limited support for RISC-V architectures. Most graphics-intensive applications and games are optimized for x86 and ARM platforms, and RISC-V support is in its early stages.
- GPU Computation (e.g., OpenCL, OpenCV on Nvidia): GPU computation libraries like OpenCL and OpenCV are primarily designed for x86 and Nvidia GPUs. RISC-V support for such libraries is underdeveloped, resulting in limited access to GPU acceleration on RISC-V platforms.
- Robotic Operating Systems (e.g., ROS/ROS2): ROS and ROS2 are widely used in robotics, but their support for RISC-V is limited. The majority of robotic hardware and software components are designed for x86 and ARM architectures, creating a gap for RISC-V adoption.
- Machine Learning (e.g., Dlib): Machine learning frameworks like Dlib are well-established on x86 and ARM, with hardware acceleration support from major GPU manufacturers. RISC-V lacks comprehensive support in this domain, hindering the development of machine learning applications on RISC-V platforms.

Critical Gaps:

1. Lack of Optimization: The critical gap lies in the absence of optimized software and libraries for RISC-V architectures in these domains. Existing software is primarily tailored for x86 and ARM, resulting in suboptimal performance on RISC-V platforms.
2. Limited Ecosystem: RISC-V lacks a mature software ecosystem compared to x86 and ARM. This includes development tools, libraries, and a robust community of developers, which is crucial for rapid software development and adoption.
3. GPU Support: The absence of comprehensive GPU support for RISC-V hinders the acceleration of graphics and computation-intensive workloads, making RISC-V less attractive for applications that rely on GPU power.
4. Compatibility: Many existing applications and systems are not compatible with RISC-V, making it challenging for organizations to transition to RISC-V platforms without significant software redevelopment efforts.

5. Community Engagement: Building a vibrant open-source community around RISC-V software is essential but currently lacking. This gap affects collaborative development and support for RISC-V software projects.

Addressing these critical gaps is essential to unlock the full potential of RISC-V architectures in the specified domains, enabling their widespread adoption in various applications, including those relevant to NASA's needs. The proposed RISC-V software tool enhancements aim to bridge these gaps and make RISC-V a competitive choice for developers and organizations.

Relevance / Science Traceability:

The Science Mission Directorate's (SMD's) missions involve collecting and analyzing vast amounts of scientific data from space, Earth, and beyond. Efficient data processing and computation are essential for achieving scientific objectives. Enhancing RISC-V software tools can be directly relevant to SMD by improving the computational capabilities of spacecraft and instruments, leading to more effective data analysis and scientific discoveries.

List of Missions, Programs, or Projects:

1. Astrophysics: Future astrophysics missions concepts require starlight nulling to allow imaging of exoplanets. These RISC-V software tools can enable the high-bandwidth processing needed for adaptive wavefront sensing and control approaches for starlight nulling.
2. Endurance: NASA's lunar rovers are equipped with advanced scientific instruments for exploring the Moon. Improved software tools can enhance the autonomy of these rovers, enabling more sophisticated data analysis and decision making during missions.
3. Mass Change: Many Earth science instruments, including multispectral/hyperspectral imagers and synthetic aperture radars, gather high volumes of data. These RISC-V software tools can improve data processing efficiency, allowing onboard data classification and intelligent data compression to maximize science return and provide time-critical alerts to users.

Benefits for Identified Mission/Program/Project:

- Data Processing Efficiency: RISC-V software optimizations can significantly reduce the time required for data processing, allowing scientists to receive and analyze mission data more quickly.
- Enhanced Autonomy: Improved software can enhance the autonomy of spacecraft and rovers, enabling them to make real-time decisions based on scientific objectives and mission priorities.
- Reduced Computational Resource Demands: Efficient RISC-V software can reduce the computational resource demands on spacecraft, leading to reduced power consumption and increased mission longevity.

Potential Advocates to Contact:

When seeking advocates within NASA's Science Mission Directorate for this technology, consider reaching out to the following individuals or groups:

1. SMD Chief Scientist: The Chief Scientist of SMD can be a key advocate, as they have a deep understanding of the scientific priorities and data processing needs of SMD missions.
2. Mission Project Scientists/Principal Investigators: The scientists leading specific missions or projects can advocate for technology enhancements that directly impact their scientific objectives.
3. Mission Managers: Mission managers responsible for overseeing SMD missions can be supportive advocates for technology improvements that enhance mission efficiency and data quality.

4. SMD Technology and Data Systems Division: This division within SMD is responsible for managing technology investments. They can provide guidance on technology adoption and potential advocacy.
5. SMD Data Centers: SMD operates data centers that support various missions. Contacting the heads of these centers can lead to advocacy within the data management community.

Engaging with these advocates can help align RISC-V software enhancements with SMD's mission goals and priorities, ultimately benefiting NASA's scientific endeavors in space and Earth sciences.

References:

1. High-Performance Spaceflight Computing (HPSC) Processor: https://www.nasa.gov/press-release/nasa-awards-next-generation-spaceflight-computing-processor-contract
2. VulkanSC: https://www.vulkan.org/
3. GPU Computation: https://opencv.org/
4. Robotic Operating Systems: https://www.ros.org/
5. Machine Learning: http://dlib.net/

Z2.03 Human Interfaces for Space Systems (SBIR)

Lead Center: JSC
Participating Center(s):

Subtopic Introduction:

NASA's vision for human spaceflight requires the crew to execute increasingly complex tasks in more demanding and dangerous environments. As a result, advances in display technologies, human spacecraft, and spacesuits are sought that can be infused into current and future human spaceflight programs, including orbiting spacecraft, surface habitats, surface mobility vehicles, microgravity suits, and surface suits. Subtopic goals are to advance technologies that increase the reliability of display systems in the radiation environment beyond low Earth orbit (LEO), while also increasing the crew’s capabilities and effectiveness in performing mission tasks. Standards-based interfaces are of particular interest to promote interoperability and equipment reuse across spacecraft.

Scope Title: Human Spacecraft Display Systems

Scope Description:

Successful proposal concepts should significantly advance the state of the art. Furthermore, proposals should indicate an understanding of fault tolerance and fault mitigation strategies as well as reliable design practices for a given environment. Note that environmental requirements such as lighting levels, heat, and pressure vary significantly between space systems and missions, with some spacecraft and surface vehicles supporting human operations for days and others supporting periodic crewed missions for 15 or more years.

Specific technologies sought by this subtopic include display systems capable of supporting long-duration human spaceflight beyond LEO. Multifunctional visual displays provide the highest bandwidth and most versatile means for the crew to receive complex information, but unique component technologies with limited radiation performance data prevent high-reliability displays from being developed. The following design parameters and data are sought for the display panel and pixel technologies:

- A scalable architecture that permits different levels of performance.
- Radiation test data, analysis of failure modes, radiation-tolerant designs, and prototype hardware/software solutions.
- A display panel diagonal measurement of at least 14 in. with the capability to render complex graphics, including high-definition video, at a frame rate of at least 20 frames per second.

Design and performance parameters are driven by use cases requiring crewmembers to directly control the spacecraft using live-streaming video, such as in-space docking, controlled landing, robotic operations, and surface mobility.

Expected TRL or TRL Range at completion of the Project: 3 to 7

Primary Technology Taxonomy:

- Level 1: TX 02 Flight Computing and Avionics
- Level 2: TX 02.2 Avionics Systems and Subsystems

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software
- Analysis

Desired Deliverables Description:

The desired Phase I deliverables include designs, simulations, and analyses to demonstrate the viability of proposed designs and components.

The desired Phase II deliverables for display systems include a prototype demonstration of a custom or modified display panel technology that mitigates radiation failure modes of electronic components. The proof-of-concept design should consider scalability and integration with other display components.

State of the Art and Critical Gaps:

Commercial display technologies have been used in LEO on the International Space Station for decades, but radiation test data for complex electronics beyond LEO are very limited, and existing test data indicate displays may be more susceptible to radiation than other electronic components. As a result, spacecraft designers are forced to take an unquantified risk of equipment failure due to radiation effects and to include backup crew interface systems that take up valuable mass, volume, and power on the spacecraft. While ongoing Government and industry investments seek to improve processor and graphics processing unit (GPU) performance, quantifying and improving the radiation tolerance of display panel components remains unaddressed.

Relevance / Science Traceability:

This subtopic is relevant to human spaceflight programs in the development and planning phases, including Gateway, HLS (Human Landing System), Orion, xEVAS (Exploration Extravehicular Activity System), and Pressurized Rover, as well as to lunar and Martian surface habitation systems. Technology solutions developed under this subtopic have the potential for a direct infusion path as these spacecraft are designed and developed.

Electronic visual displays are required for human spaceflight (NPR 8705.2C, NASA Human-Rating Requirements for Space Systems) and will be at the center of any spacecraft's crew interface architecture. By quantifying and improving the reliability of radiation-tolerant displays, spacecraft designers will be able to simplify this architecture by reducing the need for redundancy, sparing, and operational constraints while also reducing mass, volume, and power needs.

References:

1. Computer Human Interface Challenges in Space Exploration: https://ntrs.nasa.gov/citations/20230009205
2. Towards A Radiation-Tolerant Display System: https://ntrs.nasa.gov/citations/20230008652
3. Update on Radiation Testing of Electronic Display Technologies: https://ntrs.nasa.gov/citations/20230008119
4. NASA Electronic Parts and Packaging Program: https://nepp.nasa.gov
5. Radiation Effects and Analysis Homepage: https://radhome.gsfc.nasa.gov/top.htm
6. NASA Cross-Program Design Specification for Natural Environments (DSNE): http://ntrs.nasa.gov/citations/20200000867
7. The Past, Present, and Future of Display Technology in Space: https://arc.aiaa.org/doi/10.2514/6.2010-8915
8. NASA Active Matrix Organic Light Emitting Diode (AMOLED) Environmental Test Report: https://ntrs.nasa.gov/citations/20140003471
9. OLED Technology Evaluation for Space Applications: https://ntrs.nasa.gov/citations/20150016975

Scope Title: Spacesuit Augmented-Reality (AR) Display and Optics Systems

Scope Description:

Future suited crew operations will be expected to be more self-reliant, as communication time delays constrain the ability for crew to interact with mission control support from Earth in a real-time capacity. A spacesuit-compatible AR display system is a potential crew-autonomy-enabling technology to help cope with future mission work demands during extravehicular activity (EVA). In the short term, this AR system offers a new modality of communication between crew and Mission Control by adding dynamic visual cueing. In the long term, this AR system is necessary to enable interplanetary human exploration by supplementing and in some cases replacing Earth-based mission support, ultimately enabling the crew to make informed decisions.

Essential to any spacesuit AR system is the ability to comfortably display information to the suited crew member via a minimally intrusive see-through display. Due to many operational and system integration issues, head-worn (near-to-eye) display configurations are not considered at this time. Therefore, this subtopic is driven to display configurations that are physically decoupled from the user's head, similar to Heads-Up-Display (HUD) systems; however, the suit volume prohibits conventional HUD designs (see

References). In addition, suit operations with a variety of user anthropometries will require an eye-box much larger (>50 mm^2) and eye relief much longer (approx. 75 mm) than typically seen for head-worn systems, while delivering minimal apparent field of view (>30 deg).

Specific technologies sought by this subtopic include optical technologies that enable the unique and challenging combination of performance requirements that a head-decoupled AR system presents, including the physiological aspects of using an AR system periodically for up to 8 hr during a single EVA. Technology areas of interest include the following:

- Low-profile optical image transfer and image formation technologies that can deliver key optical performance parameters with minimal intrusion into the helmet bubble space (e.g., Waveguides, Freeform Optics, Meta Surfaces, Coatings, etc.) (Joint AR Request for Information; see References).
- Technology that reduces or eliminates vergence-accommodation conflict (VAC) for bi-ocular/binocular AR systems.
- Small, high-efficiency, high-brightness display sources for AR systems that can be utilized in the demanding conditions of suited EVA operations.

Successful proposal concepts should significantly advance the state of the art and demonstrate an appreciation for the unique and challenging aspects of a head-decoupled optical system, including the harsh operating environment.

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

Primary Technology Taxonomy:

- Level 1: TX 02 Flight Computing and Avionics
- Level 2: TX 02.2 Avionics Systems and Subsystems

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software
- Analysis

Desired Deliverables Description:

Phase I deliverables should include analysis and simulation results of system-level designs and component-level optical designs. If any hardware prototyping and/or initial manufacturing attempts are undertaken as part of Phase I, they should concentrate on the most technologically challenging aspects of the proposed design.

Phase II deliverables should include a working prototype that demonstrates success in all the key performance areas required for a head-decoupled spacesuit AR display system. Prototype systems should be capable of being tested with existing NASA suit mock-ups in EVA-like landscape and lighting conditions. The Phase II prototype should also be capable of being driven by industry-standard video source formats such as High-Definition Multimedia Interface (HDMI), DisplayPort, Digital Visual Interface (DVI), Low-Voltage Differential Signaling (LVDS), and others.

State of the Art and Critical Gaps:

HUDs (typically seen in cockpits or the automotive industry) have a large distance between the eye and the image substrate (or long eye relief). Helmet-mounted displays (HMDs) (F-35 helmet, HoloLens, etc.) require the eye to be closely coupled with the display (short eye relief distance). The spacesuit has a medium eye relief distance along with other constraints related to anthropometry and its 100% oxygen environment. Market research indicates that no commercial, industrial, or (based on publicly available information) military entities are currently pursuing these constraints for AR displays. Two market studies were completed: yet2-NASA - JARVIS AR Optics - Pivot-Summary Report - 1 April 2022.pptx and NASA Heads-In Display - Pivot Summary Report, both available here: https://nen.nasa.gov/web/tech-search-reports

The Joint AR project has contributed to the definition and refinement of the Heads Up Display (HUD) Optics for Exploration EVA; however, the next important step toward closing this gap will be enabling an industry partnership to develop a spacesuit-compatible AR solution.

Relevance / Science Traceability:

This subtopic is relevant to human spaceflight programs in the development and planning phases, including Exploration Extravehicular Activity Services (xEVAS) for International Space Station and Artemis Lunar missions, Commercial Crew Program, and Orion, as well as to Martian surface habitation systems and spacesuits. Technology solutions developed under this subtopic have the potential for a direct infusion path as these spacecraft are designed and developed.

Electronic visual displays are required for human spaceflight (NPR 8705.2C, NASA Human-Rating Requirements for Space Systems) and will be at the center of any spacecraft's crew interface architecture. By quantifying and improving the medium in which suited crew members interact with digital content, hands-free context-relevant augmented reality, increasingly complex EVA operations can be enabled for further human exploration of the lunar and Martian surface.

References:

1. Joint AR Request for Information: https://sam.gov/opp/57630e33eeae4762a9118b0e98171fce/view
2. Realizing a Spacesuit Compatible Augmented Reality System to Meet the Work Needs of Future Human Spaceflight Exploration: https://arc.aiaa.org/doi/abs/10.2514/6.2022-4235
3. Trades, Architecture, and Design of the Joint Augmented Reality Visual Informatics System (Joint AR) Product: https://ttu-ir.tdl.org/handle/2346/94711
4. NASA Cross-Program Design Specification for Natural Environments (DSNE): http://ntrs.nasa.gov/citations/20200000867

TX03: Aerospace Power and Energy Storage

This area covers the different components of a power system—power generation, energy storage, and power management and distribution—that require technological improvements to enable or enhance NASA missions.

S13.06 : Dynamic Power Conversion (SBIR)

Related Subtopic Pointers: T3.04, T7.05
Lead Center: GRC
Participating Center(s):

Subtopic Introduction:

NASA is considering high-efficiency power conversion technologies, including dynamic and thermoelectric convertors, for use in Radioisotope Power Systems (RPSs) to power science missions to the Moon and other solar system bodies of interest. High-efficiency power conversion technologies directly align with the SMD strategic technology investment plan for space power and energy storage. In general, RPSs are needed for very long missions to dark, dusty, or distant destinations where solar power is not practical. Current work is focused on maturing high-efficiency conversion technologies that would be integrated with a radioisotope heat source to provide thermal-to-electric power conversion. Heat source options include plutonium-238 and other isotopes currently being developed to support future commercial lunar applications. Desired technologies would have high efficiency, low mass, long life, and high reliability for planetary spacecraft, landers, and rovers.

Scope Title: High-Efficiency Power Conversion Technologies

Scope Description:

High-efficiency RPSs are desired across a range of power levels. A lower power RPS could convert single-digit thermal watts available from one or more 1-Wth light-weight radioisotope heater units (LWRHUs) to a few electric watts for powering battery chargers on distributed networks or small science stations. A higher power RPS could convert hundreds to thousands of thermal watts available from one or more 250-Wth general purpose heat sources (GPHSs) to hundreds of electric watts for powering small spacecraft, such as rovers in permanently shadowed regions of the Moon. Waste heat could be removed from the cold end of the power convertor using conductive coupling or a pumped loop to a radiator. Proposals are sought that address the following technical challenges:

1. Dynamic power convertor designs that are robust and highly reliable, have long life, and have high thermal-to-electric conversion efficiency.
2. Electronic controllers able to control one or more Stirling convertors. There is a special interest in controller architectures able to manage multiple convertor pairs with fault tolerance.
3. Robust subassemblies, such as linear alternators, able to survive extended exposure to at least 200 °C in high gamma and neutron fields; heat pipe directly coupled to the Stirling heater head; robust multilayer insulation (MLI) able to survive internal temperatures of 900 °C; and recuperators and radiators that improve system performance and reliability.
4. Advanced solid-state thermal-to-electric power-conversion components and RPS-integration components, including advanced thermoelectric 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 they 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, high-temperature- and radiation-tolerant systems 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 networks, small spacecraft, and other systems that take advantage of lower power electronics for the exploration of surface phenomena on icy moons and other bodies of interest. There is a desire to develop reliable and robust systems and subsystems for power convertors as well as generators. These would include efficient and robust efficient alternators able to survive 200 °C, thermoelectric couple configurations, robust high-efficiency recuperators, heat pipes for heat addition or rejection, radiators, and controllers.

Relevance / Science Traceability:

This technology directly aligns with the SMD 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:

1. NASA: "About RPS," https://rps.nasa.gov/about-rps/overview/
2. Oriti, Salvatore: "Dynamic Power Convertor Development for Radioisotope Power Systems at NASA Glenn Research Center," AIAA Propulsion and Energy 2018, AIAA 2018-4498.
3. 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.
4. Wong, Wayne: "Advanced Stirling Convertor (ASC) Technology Maturation," AIAA Propulsion and Energy 2015, AIAA 2015-3806.

5. 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)

Related Subtopic Pointers: T3.04, T7.05
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 Power Components for Lunar and Mars Missions

Scope Description:

NASA's directives for space exploration and habitation require high-performance, high-voltage transistors and diodes capable of operating without damage in the natural space radiation environment. Recently, significant progress has been made in the research community in understanding the mechanisms of heavy-ion-radiation-induced damage and catastrophic failure of wide bandgap (WBG) power transistors and diodes. This scope seeks to facilitate movement of this understanding into the successful development of radiation-hardened, high-voltage transistors and rectifiers to meet NASA mission power needs reliably in the space environment. These needs include:

- High-voltage, high-power solutions: NASA Technology Taxonomy TX 03.3.2, Power Management and Distribution: Distribution and Transmission calls out the need for development of radiation-hardened, high-voltage, extreme-temperature components for power distribution systems. NASA has a core need for diodes and transistors that meet the following specifications:
    - Diodes: minimum 1200 V, 40 A, with fast recovery <50 ns.
    - Transistors: minimum 600 V, 40 A, with <24 mohm on-state drain-source resistance.
- High-voltage, low-power solutions: In support of TX 08.1, Remote Sensing Instruments and Sensors, radiation-hardened, high-voltage transistors are needed for low-mass, low-leakage, high-efficiency applications such as light detecting and ranging (LIDAR) Q-switch drivers, mass spectrometers, and electrostatic analyzers. High-voltage, fast-recovery diodes are needed to enhance performance of a variety of heliophysics and planetary science instruments.
    - Transistors: minimum 1000 V, <40 ns rise and fall times.
    - Diodes: 2 kV to 5 kV, <50 ns recovery time.
- High-voltage, low- to medium-power solutions: In support of peak-power solar tracking systems for planetary spacecraft and small satellites, transistors and diodes are needed to increase buck converter efficiencies through faster switching speeds.
    - Transistors: minimum 600 V, <50 ns rise and fall times, current ranging from low to >20 A.

Successful proposal concepts should result in the fabrication of transistors and/or diodes that meet or exceed the above performance specifications without susceptibility to damage due to the heavy-ion space radiation environment (single-event effects resulting in permanent degradation or catastrophic failure). These diodes and/or transistors will form the basis of innovative, high-efficiency, low-mass and low-volume systems and therefore must significantly improve upon the electrical performance available from existing heavy-ion-radiation-tolerant devices. Proposals must state the initial state of the art for the proposed technology and justify the expected final performance metrics. Well-developed plans for validating the tolerance to heavy-ion radiation must be included, and the expected total ionizing dose tolerance should be indicated and justified. Target radiation performance levels will depend upon the device structure due to the interaction of the high electric field with the ionizing particle:

- For vertical-field power devices: No heavy-ion-induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface-incident linear energy transfer (LET) of 40 MeV-cm^2/mg and sufficient energy to maintain a rising LET level throughout the epitaxial layer(s).
- For all other devices: No heavy-ion-induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface-incident LET of 75 MeV-cm^2/mg and sufficient energy to fully penetrate the active volume prior to the ions reaching their maximum LET value (Bragg peak).

Other innovative heavy-ion-radiation-tolerant, high-power, high-voltage discrete device technologies will be considered that offer significant electrical performance improvement over state-of-the-art heavy-ion-radiation-tolerant power devices. Lateral (with the exception of GaN-based high-electron-mobility transistors (HEMTs)) and charged balanced devices are still largely unexplored technologies. These, along with other cutting-edge WBG technologies, are excellent candidates for lunar surface technologies.

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

Primary Technology Taxonomy

- Level 1: TX 03 Aerospace Power and Energy Storage
- Level 2: TX 03.3 Power Management and Distribution

Desired Deliverables of Phase I and Phase II:

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

State of the Art and Critical Gaps:

A prior version of this scope, "High-Power, High-Voltage Electronics," was active in 2016-2017 and paused to give funded proposals and a similar Early Stage Innovation topic, designed to understand the radiation-induced failure mechanisms in WBG semiconductors, time to mature. This pause has allowed these studies to mature, and it is now time to reopen this scope to provide a means for applying the knowledge gained toward fabrication of radiation-hardened power devices that are tailored to meet performance criteria of a number of NASA technology needs. High-voltage silicon power devices are limited in current ratings and have limited power efficiency and higher losses than do commercial WBG power devices. Efforts to space-qualify WBG power devices to take advantage of their tremendous performance advantages revealed they are very susceptible to damage from the heavy-ion space radiation environment (galactic cosmic rays) that cannot be shielded against. Higher voltage devices are more susceptible to these effects; as a result, to date, there are space-qualified GaN (gallium nitride) transistors now available, but these are limited to 300 V. Recent radiation testing of 600-V and higher GaN transistors has shown failure susceptibility at about 50% of the rated voltage, or less. Silicon carbide power devices have undergone several generation advances commercially, improving their overall reliability, but catastrophically fail at less than 50% of their rated voltage. NASA has funded modeling and experimental efforts to understand silicon carbide's susceptibility to heavy-ion radiation. Reopening of this topic will provide a path for development and fabrication of hardened designs based upon this research and will encourage progress in other WBG technologies, such as higher voltage GaN, gallium oxide, and possibly diamond.

Specific needs in STMD and SMD areas have been identified for spacecraft power management and distribution (PMAD) and science instrument power applications, and device performance requirements to meet these needs are included in this subtopic nomination. In all cases, there is no alternative solution that can provide the mass and power savings sought to enable game-changing capability. Current power processing units (PPUs) and instrument power systems rely on older silicon technology with many stacked devices and efficiency penalties. In NASA's move to do more with less (smaller satellites), the technology of this subtopic nomination is truly enabling.

Relevance / Science Traceability:

Power transistors and diodes form the building blocks of numerous power circuits for spacecraft and science instrument applications. This subtopic therefore feeds a broad array of space technology hardware development activities by providing single-event effect (heavy-ion) radiation-hardened state-of-the-art device technologies that achieve higher voltages with lower power consumption and greater efficiency than is presently available.

TX 03.3.2 Power Management and Distribution: Distribution and Transmission calls out the need for development of radiation-hardened, high-voltage, extreme-temperature components for power distribution systems. The solicited developments in this scope will feed systems development for Kilopower due to the savings in size/mass combined with radiation hardness. In addition, power distribution for lunar and Martian habitats will benefit from power circuits adopting this subtopic through significantly improved power efficiencies and radiation hardness. Per TX 08.1, Remote Sensing Instruments and Sensors, radiation-hardened, high-voltage transistors are needed for low-mass, low-leakage, high-efficiency applications such as LIDAR Q-switch drivers, mass spectrometers, and electrostatic analyzers. These applications are aligned with science objectives including Earth Science LIDAR needs, Jovian moon exploration, and Saturn missions. Finally, mass spectrometers critical to planetary and asteroid research and in the search for life on other planets such as Mars require high-voltage power systems and will thus benefit from mass and power savings from this subtopic's innovations.

References:

The following is only a partial listing of relevant references:

1. S. Kuboyama et al., "Thermal Runaway in SiC Schottky Barrier Diodes Caused by Heavy Ions," IEEE Transactions on Nuclear Science, vol. 66, pp. 1688-1693, 2019.
2. D. R. Ball et al., “Ion-Induced Energy Pulse Mechanism for Single-Event Burnout in High-Voltage SiC Power MOSFETs and Junction Barrier Schottky Diodes,” IEEE Nuclear and Space Radiation Effects Conference, San Antonio, TX, July 2019.
3. J. McPherson et al., "Mechanisms of Heavy Ion Induced Single Event Burnout in 4H-SiC Power MOSFETs," International Conference on Silicon Carbide and Related Materials (ICSCRM), Kyoto, Japan, September, 2019. https://ntrs.nasa.gov/citations/20190033217
4. C. Abbate et al., "Gate Damages Induced in SiC Power MOSFETs During Heavy-Ion Irradiation--Part I," IEEE Transactions on Electron Devices, 2019. [see also Part II]
5. J.-M. Lauenstein, “Getting SiC Power Devices Off the Ground: Design, Testing, and Overcoming Radiation Threats,” Microelectronics Reliability and Qualification Working (MRQW) Meeting, El Segundo, CA, February 2018. https://ntrs.nasa.gov/search.jsp?R=20180006113
6. E. Mizuta et al., "Single-Event Damage Observed in GaN-on-Si HEMTs for Power Control Applications," IEEE Transactions on Nuclear Science, vol. 65, pp. 1956-1963, 2018.
7. M. Zerarka et al., "TCAD Simulation of the Single Event Effects in Normally-OFF GaN Transistors After Heavy Ion Radiation," IEEE Transactions on Nuclear Science, vol. 64, pp. 2242-2249, 2017.
8. J. Kim et al., "Radiation Damage Effects in Ga2O3 Materials and Devices," Journal of Materials Chemistry C, vol. 7, pp. 10-24, 2019.
9. S. J. Pearton et al., "Perspective: Ga2O3 for Ultra-high Power Rectifiers and MOSFETS," Journal of Applied Physics, vol. 124, p. 220901, 2018.

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

Scope Description:

NASA seeks innovative solutions and technologies that would enable the use of low-mass, highly conductive power transmission cables for lunar and Mars Missions.

- Low-mass, highly conductive wires and terminations that can operate over the full range of lunar south polar environments (-230 °C to -100 °C) and 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 to enable up to 1,500-Vdc cables and/or up to 3,000-Vac 3-phase cables with low inductance at 1,000 Hz; and low-loss/low-mass electromagnetic interference (EMI) shielding.
- Electrical connectors that can survive the harsh lunar environments, such as extreme temperature ranges at the south polar locations (-230 ºC to -100 ºC); can be exposed to the lunar dust; and can be connected by robots or by 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:

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

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Scope Title: Wireless Power Beaming for Lunar and Mars Missions

Scope Description:

NASA seeks innovative solutions and technologies that would enable the use of high end-to-end efficiency (>40%) and long-distance (>1 km) power beaming for lunar and/or Mars missions in the range of 100 to 500 W. The focus on proposals in this subtopic should be on the high-efficiency transmitters/receivers/converters that are the main components of interest to the electrical power discipline. Proposals are not sought on pointing or tracking technologies of those transmitters or receivers; however, the fusion of communications and/or navigation with power beaming is sought.

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, 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:

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

Z1.09 : Energy Storage for the Lunar/Mars Surface (SBIR)

Related Subtopic Pointers: T3.04, T7.05
Lead Center: GRC
Participating Center(s): JSC

Subtopic Introduction:

NASA is seeking innovative energy storage solutions for lunar surface missions. The objective is to develop lightweight, long-lived energy storage systems for landers, equipment, crew rovers, and science platforms that can deliver power and survive the variable conditions on the lunar surface. Power requirements for mobile assets are expected to range up to 10 kW. Power requirements for stationary assets used in combination with surface solar arrays are expected to range up to 40 kW. Applicable technologies such as batteries and regenerative fuel cells should be lightweight, low cost, and have system-level service lives >10 years to survive multiple crew campaigns. Of particular interest are technologies that can be used across multiple platforms. Strong consideration should be given to environmental robustness for surface environments that include day-night thermal cycling, natural radiation, partial gravity, vacuum or very low ambient pressure, reduced solar insolation, dust, and solar wind.

Scope Title: Advanced Secondary Batteries

Scope Description:

Advanced secondary/rechargeable batteries that go beyond state-of-the-art lithium-ion batteries and can safely provide >300 Wh/kg (at 20 °C) at the cell level are of interest. For lunar surface applications, these secondary batteries are expected to operate safely and continuously over a lunar day-night cycle at mid-latitude locations where the temperature will range between -230 and 120 °C while retaining operational capability without serious degradation. Advanced secondary batteries would have a stretch goal of >150 Wh/kg (net module including all packaging and thermal management) over 500 cycles over the wide temperature range. Novel battery pack/thermal management designs and technologies that enhance battery reliability and safety while reducing system weight are also of interest. Combinations of cell-level improvements and/or battery-pack-level improvements for enhanced temperature capability will be considered, but a path must be shown toward a full battery pack meeting the performance requirements. Solutions focused solely on individual cell component (e.g., anode, cathode, etc.) development and demonstration will not be considered.

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

Primary Technology Taxonomy:

- Level 1: TX 03 Aerospace Power and Energy Storage
- Level 2: TX 03.2 Energy Storage

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype

Desired Deliverables Description:

Research should be conducted to demonstrate technical feasibility in a final report for Phase I and show a path toward Phase II, and when possible, deliver a demonstration unit for NASA testing at the completion of the Phase II contract. Phase I deliverables should include at least a high-fidelity thermal model proving feasibility of the design over the intended operational ranges. Phase II emphasis should be placed on developing and demonstrating the technology under as many relevant test conditions as feasible within Phase II resources. Additionally, a path should be outlined that shows how the technology could be commercialized or further developed into science-worthy systems.

- Phase I: Model and test reports and technology development plan
- Phase II: Prototype hardware with test reports and an updated technology development plan

State of the Art and Critical Gaps:

State-of-the-art rechargeable cells are limited in both capacity and temperature range. Typical rechargeable Li-ion cells operate within a narrow temperature range of -20 to 40 °C and suffer from extreme 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 during charge. Extended operation at one temperature extreme does not typically favor operation at the other extreme. This solicitation is aimed at the development of batteries that can maintain performance across the lunar temperature extremes, and/or advanced thermal management and packaging techniques to allow functionality and survivability of the battery system at these temperature extremes.

Relevance / Science Traceability:

These batteries are applicable over a broad range of exploration and science missions. Low-temperature batteries are needed to enable science and exploration missions aligned with Artemis, including supporting science missions such as Commercial Lunar Payload Services and Lunar Quest. These batteries may also serve for potential NASA decadal missions to ocean worlds (Europa, Enceladus, Titan) and the icy giants (Neptune, Uranus). Low-temperature batteries developed under this subtopic would enhance these missions and could be enabling, particularly for missions that are highly mass- or volume-limited.

References:

1. NASA STMD Taxonomy: NASA TechPort - Strategic Framework
2. NASA Science: https://science.nasa.gov/
3. Lunar Surface Innovation Consortium: https://lsic.jhuapl.edu/
4. Moon-to-Mars Architecture (Introduction): https://www.nasa.gov/MoonToMarsArchitecture

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Scope Title: Regenerative Fuel Cell Systems

Scope Description:

Specific energy (kJ/kg or Wh/kg) is the primary characteristic to differentiate lunar energy storage technologies. A regenerative fuel cell (RFC) combines water electrolysis and fuel cell power generation processes into an energy storage system by closing all process fluid loops. An RFC system must have a packaged, system-level specific energy of at least 320 Wh/kg to be considered viable for NASA's identified space missions. Research to date has identified the hydrogen/oxygen/water triad as the most likely chemical combination to achieve this minimum specific energy.
Lunar energy storage technologies face a minimum maintenance interval ≥3 years. Operating for at least 3 years on the lunar surface without maintenance requires exceedingly reliable components beyond what the market offers. NASA has particular interest in technologies that extend the operational life of system components. The primary failure mechanism results from extended contact (years) with ultra-high-purity deionized water, resulting in shunt currents/corrosion. Pumps, both high-lift and recirculating pumps, require unacceptably high power and fail quickly when pumping the ultra-high-purity deionized water required by this application. RFC process water ranges from 4 °C to 90 °C with system pressures ranging from 35 psia (0.24 MPa) to 2,500 psia (17.2 MPa) and must remain above >14 MΩ·cm as measured at 25 °C.

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

Primary Technology Taxonomy:

- Level 1: TX 03 Aerospace Power and Energy Storage
- Level 2: TX 03.2 Energy Storage

Desired Deliverables of Phase I and Phase II:

- Research
- Prototype

Desired Deliverables Description:

Research should be conducted to demonstrate technical feasibility in a final report for Phase I and show a path toward Phase II, and when possible, deliver a demonstration unit for NASA testing at the completion of the Phase II contract. Phase I emphasis should be on component and/or material compatibility analysis and testing with the operational environment. Phase II emphasis should be placed on developing and demonstrating multiple units under specified process fluid conditions. Additionally, a path should be outlined that shows how the technology could be commercialized or further developed into space-worthy systems.

- Phase I: Test reports and technology development plan
- Phase II: Prototype hardware with test reports and an updated technology development plan

State of the Art and Critical Gaps:

This solicitation targets the primary component limiting RFC durability: deionized water pumps. The need to use the $H_2/O_2/H_2O$ reactant couple results in a requirement to recirculate and pressurize ultra-high-purity water (>14 MΩ·cm at 25 °C) for very long periods of time. This ultra-high-purity water may not contain any additives (lubricants, surfactants, etc.) that might react within the water electrolysis hardware. Depending on the specific architecture, RFC systems contain pumps with one of two basic functions: high-pressure (~2,500 psia, 17.2 MPa) recirculation and high lift (2,500 psid, 17.2 MPa). All pumps have a minimum maintenance interval requirement of 25,000 hr (eventually 50,000 hr) when matured. This solicitation focuses on innovations (materials, coatings, bearings, dynamics seals, etc.) that enable devices to move the deionized water without introducing contaminants for the mission duration. Preference will be given to solutions resulting in pumps with the longest mean time between failures (MTBF), lowest power, and lowest mass.

Relevance / Science Traceability:

Regenerative fuel cells are an alternative energy storage solution for missions with high energy requirements and restricted mass allocations that are unfavorable to existing battery solutions. RFC systems have been identified as a potential solution for both stationary and mobile crewed lunar surface assets to survive the lunar night.

References:

1. "Lunar Equator Regenerative Fuel Cell System Efficiency Analysis," P. Smith et al., NASA TM 20210014627, https://ntrs.nasa.gov/citations/20210014627
2. "Aerospace Regenerative Fuel Cell Fluidic Component Design Challenges," P. Smith et al., NASA TM 20210024659, https://ntrs.nasa.gov/citations/20210024659
3. "Regenerative Fuel Cell Power Systems for Lunar and Martian Surface Exploration," M. Guzik et al., NASA TM 20170009088, https://ntrs.nasa.gov/citations/20170009088
4. "Mars Surface Solar Arrays With Storage (SAWS) Seedling Study," F. Eliott et al., NASA TM 20200004325, https://ntrs.nasa.gov/citations/20200004325
5. "Energy Storage for Lunar Surface Exploration," M. Guzik et al., NASA TM 20190000472, https://ntrs.nasa.gov/citations/20190000472
6. "Advanced Oxygen Generation Assembly for Exploration Missions," K. Takada, NASA TM 20190030425, https://ntrs.nasa.gov/citations/20190030425
7. "Status of ISS Water Management and Recovery," L. Carter et al., NASA TM 20180006341, https://ntrs.nasa.gov/citations/20180006341
8. "Investigation of the Makeup, Source, and Removal Strategies for Total Organic Carbon in the Oxygen Generation System Recirculation Loop," E. Brown et al., NASA TM 20150016495, https://ntrs.nasa.gov/citations/20150016495

TX04: Robotic Systems

This area covers technologies for robotic systems that will be leveraged as science explorers, precursor explorers preceding crewed missions, as crew helpers, as EVA mobility aids, and as caretakers of unattended assets.

H10.02 Autonomous Operations Technologies for Launch Systems and Surface Infrastructure (SBIR)

Lead Center: KSC
Participating Center(s): ARC, LaRC, SSC

Subtopic Introduction:

Space exploration planning relies, in part, on launch and surface systems placed wherever we intend to have a sustained presence. These launch and surface systems are considered to be the planetary or lunar surface-based infrastructure and processes used to support critical spaceport functionality such as the assembly, validation, support, and maintenance of launch vehicles and payloads (including non-spacecraft payloads), support of lunar in-situ resource utilization (ISRU) activities such as propellent processing plants and the planning, preparation, and maintenance of surface systems infrastructure.
In contrast to other subtopics that deal with systems that interface directly with crew, this subtopic focuses on autonomous systems to develop and maintain surface infrastructure. In order to sustain a crewed presence on the lunar surface, critical infrastructure will be required on the surface to enable launch, landing, fuel production, ISRU activities, resource collection, and more. The operations taking place on the lunar surface in support of this infrastructure and in support of other critical activities are referred to as "surface operations." A wide range of surface operations will be necessary to support a lunar presence. Many of these operations will require completion before crew presence is established, and others will be required in large volumes and frequency even after crewed landings. Additionally, the risk posed by many of these operations to astronauts must be mitigated. For these reasons, it is vital that as many of these as possible critical surface operations be conducted robotically and autonomously. In support of these surface operations are core technologies that enable autonomy on a dynamic and

evolving lunar surface. These include localization techniques, end effectors, sensors for robotic perception, driving and path planning techniques, vison-based navigation techniques, and other technologies that perform in a dynamic surface environment with evolving topography, relocating hazards, and other changes as surface preparation, excavation, and construction activities take place. These critical pieces of technology consisting of both hardware and software are referred to as "Autonomy Enabling Technologies (AET)." These core technologies are the critical stepping stones to developing the systems, rovers, and tools that will establish an uncrewed lunar surface presence initially, and will carry us forward to a crewed presence.

Additionally, managing all of these operations will require a high level of integration and coordination of surface systems and operations. Efficient operation of surface systems will be critical to operations on the surface where time, energy, and resources are precious. High-level coordination and planning of robotic systems are also necessary. This could include, but not be limited to, autonomous resource management and forecasting, swarming robotic techniques, collaborative and coordinated robotics, health monitoring, distributed control, task prioritization, automated scheduling, management of robotic caretakers, or other concepts.

Scope Title: Autonomous Operations Technologies for Launch Systems and Surface Infrastructure

Scope Description:

NASA seeks Autonomy Enabling Technologies (AETs) in software, mechanical, or combined forms. The proposed technology can be component level, system level, or even architectural level as long as it clearly advances autonomous surface operations as described above. Preference is given to interoperable solutions that enable additional flexibility or provide new capabilities to adjacent hardware. AETs of interest can be integrated into the processing and launch of vehicles and payloads. To provide an example of a specific task, AETs are expected to enable autonomous propellant management, which will require unattended storage, transfer, monitoring, and sampling of cryogenic propellants. Completing these steps will require the uncrewed manipulation, connection, stowing, and operation of fluids and propellant systems. AETs will also be integrated into surface operations and the maintenance and repair of surface and launch infrastructure. This includes robotic end effectors and tools to interact with surface infrastructure like cables, interfaces, umbilicals, etc. It also includes the algorithms for intelligent robotic interaction with these environments, such as gripping, turning, manipulation, and sensing. Intelligent systems and robotic caretakers that can aid in the monitoring, sensing, and health determination of ground and launch infrastructure such as propellant fluid systems are also necessary. AETs are expected to enable uncrewed surface Operations and Maintenance (O&M), which requires a high degree of autonomy and reliability for unattended operations during extended periods of time. A deep AET toolset will complement in-situ resource utilization (ISRU) operations by enabling the uncrewed collection and delivery of surface resources such as regolith to ISRU processing plants. AETs will enable additional uncrewed surface operations such as excavation, construction, and outfitting (ECO) by providing manipulation, collection, and placement of surface rocks and regolith. AETs may include systems capable of measuring, analyzing, and mapping topography and surface hazards, and optimization of paths and placement of surface equipment.

Additionally, higher level AETs could focus on the management, planning, and development of surface operations and infrastructure by providing asset management, surface infrastructure planning, and logistical optimizations. Coordination, path planning, infrastructure routing, layout, and maintenance optimization techniques for uncrewed surface operations should be considered. Simulation environments that enable the development and testing of AETs for surface and launch operations and simulations of surface architecture and planning are also in scope.

Specifically, this subtopic seeks the following:

- Development and testing of perception, navigation, and mapping techniques for use in dynamic and changing lunar conditions to support surface infrastructure and ISRU activities. Technologies that enable core functionality of uncrewed surface operations in a changing lunar topography, such as:
    - Vision-based algorithms that are designed and optimized for lunar lighting, features, surface texture, topography, hazards, etc.
    - Development of computer vision-based navigation and mapping techniques or simultaneous localization and mapping (SLAM) algorithms that are optimized to enable higher autonomous driving speeds on the limited computational capabilities of flight like rover avionics.
    - Development of vision processing, exposure control, feature detection, and feature descriptor techniques that are robust to extreme sensor noise, motion blur, or other emergent limitations of digital imagery in harsh lunar lighting (extreme contrast, permanently shadowed regions, direct lighting, low Sun angles, dust occlusions, etc.).
    - Development of terrain or landmark-based navigation techniques for use in Global Positioning System (GPS)-denied environments such as lunar surface in support of surface and launch operations. Techniques that make use of topographical features, rocks, craters, etc.
    - Development of technologies that enable precision mapping and surveying of lunar surface topography for use in surface operations and ECO planning.
    - Development of surface hazard recognition, classification, and measurement systems. AET that can autonomously detect rocks and craters in real time and provide measurements or other quantifying data.

- Development of simulation environments in support of surface and launch systems operations:
    - Development of high-fidelity 3D simulation environments for use in development of vision-based navigation and mapping techniques. Simulation environments should provide configurable and realistic lighting conditions, terrain, surface properties, optics, etc.
    - Simulation environments that enable planning, testing, and training of robotic surface operations, including ECO tasks such as site preparation.
    - Simulation environments with deformable terrain, integrated discrete element modeling, granular mechanics, and soil interaction simulations that can run in real time or faster than real time.

Technologies that are not suitable for infrastructure development and maintenance in a lunar surface environment (dust, harsh lighting, temperatures, etc.) are considered nonresponsive to this topic.

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: Bench or lab-level demonstrations of hardware or software are desirable. Software demonstrations in simulation environments are acceptable. Deliverables shall include a report documenting findings.

Phase II deliverables: 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 TRL 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 simulation environments for lunar surface operations, including regolith granular mechanics and lunar lighting.
2. Localization techniques that are robust to lunar surface conditions, extreme lighting, dust, surface texture, etc.
3. High-level supervisory autonomy for prioritization, coordination, and control of surface systems and rovers.
4. Autonomous inspection, maintenance, and repair (IM&R) technologies for maintenance of surface systems and assets.
5. Autonomous technologies for excavation, outfitting, and construction.
6. Architecture for integrated autonomous operations.

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:

1. Moon to Mars Architecture Moon to Mars Architecture - NASA
2. Lunar Surface Innovation Consortium, Autonomy Workshop 2023 Recording Lunar Surface Innovation Consortium (jhuapl.edu)
3. EXPLORE: Autonomous Systems & Robotics (ASR) https://techport.nasa.gov/file/144879

4. LIVE: Surface Systems Envisioned Future https://techport.nasa.gov/file/267183
5. LIVE: Excavation, Construction, and Outfitting (ECO) https://techport.nasa.gov/file/143281
6. LIVE: In Situ Resource Utilization (ISRU) https://techport.nasa.gov/file/143280
7. Aerospace Research Central, Uncrewed Lunar Surface Operations and Support Activities, 15-October-2022, Uncrewed Lunar Surface Operations and Support Activities | ASCEND (aiaa.org)
8. Lunar Surface Innovation Consortium, 2023 Fall meeting day 1 recording, 2023 LSIC Fall Meeting Day 1 - YouTube

H15.01 : Autonomous Capabilities for Lunar Surface Mobility Systems (SBIR)

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

Subtopic Introduction:

The NASA Extravehicular Activity (EVA) and Human Surface Mobility (HSM) Program (EHP) seeks to advance the technologies associated with human mobility in support of NASA's Artemis missions. The EHP vision is to provide safe, reliable, and effective EVA and HSM capabilities that allow astronauts to survive and work outside the confines of a spacecraft on and around the Moon. Artemis missions will return humans to the surface of the Moon using innovative technologies to explore more of the lunar surface than ever before. NASA will collaborate with commercial and international partners and establish the first long-term presence on the Moon. Then, we will use what we learn on and around the Moon to take the next giant leap: sending the first astronauts to Mars.

EHP Flight Projects include Exploration EVA suits (xEVA suits) and tools, Lunar Terrain Vehicle (LTV), and Pressurized Rover (PR), with this subtopic focused on LTV and PR enabling technologies. For early Artemis missions, crewmembers are planned to be on the lunar surface for only about one month out of the year. While crewmembers are away (approximately 11 months out of the year), NASA surface assets and vehicles will continue operations, performing post-crew-departure activities, scientific and exploration objectives, vehicle relocation to future landing sites, and crew arrival preparations.

Technologies are specifically sought that will enable these autonomous or semiautonomous mobility systems to operate effectively while crew is away. NASA is interested in advancements that will increase the operational cadence of surface mobility systems, improve the robustness of autonomous surface mobility, and reduce reliance on ground operator intervention. These technologies must be operable and effective in the harsh environmental conditions of the lunar south pole (e.g., temperature extremes, radiation, harsh lighting).

New capabilities in this domain will inform more detailed Artemis mission concepts of operation, reduce risk and improve mission outcomes, and provide industry with the ability to offer more capable lunar surface services and subsystem technologies to NASA, international partner space agencies, or commercial providers of lunar surface systems.

Terrestrial autonomous mobility is a rapidly growing domain, with significant commercial interest. The unique challenges of the lunar surface environment make it difficult to effectively leverage any of this prior development, however, and this lack of infusion adds further risk to mission success. This subtopic seeks to advance autonomous mobility through novel development that translates current terrestrial capabilities to the lunar surface environment and lunar surface applications, while also addressing current deficiencies in existing state-of-the-art performance.

Scope Title: Efficient On-board Autonomy for Robust High-Progress-Rate Driving Under Lunar Surface Environmental Conditions

Scope Description:

Autonomous mobility is essential for enabling Artemis mission success during uncrewed periods, yet current state-of-the-art uncrewed lunar surface mobility does not provide the required speed-made-good or long-duration robustness to meet required mission performance. Current reliance on ground operators will also dramatically limit the operational impact surface rovers will have in between crew visits.

Limited situational awareness and communication challenges (time delay, latency, bandwidth limitations, etc.), coupled with challenging mobility requirements that exceed the level of performance demonstrated by prior lunar surface systems, necessitate advances in autonomous navigation in order to achieve NASA's Moon-to-Mars objectives.

The lunar environment presents unique challenges beyond those encountered by terrestrial autonomous vehicles, including: the lack of precise localization infrastructure (e.g., Global Positioning System or GPS), harsh and low-angle sunlight, and a monochromatic environment. Additionally, autonomy solutions must be suitable for use on resource-constrained, space-rated computing or establish a path to flight by leveraging new flightworthy processor architectures.

To achieve high-progress-rate driving on the lunar surface while being robust to the many hazards present, technology areas of interest include, but are not limited to:

- Autonomous navigation, path planning, localization, mapping, or simultaneous localization and mapping (SLAM) algorithms suitable for the lunar surface environment and optimized for deployment on lunar-worthy computing platforms (existing and/or new high performance spaceflight processors in development).
- Navigation techniques suitable to the GPS-denied lunar surface environment.
- Hazard detection and avoidance, feature segmentation, and other perception-based algorithms and behaviors robust to the unique features of the lunar south pole region (lunar lighting; terrain texture, color, and lack of defining landmarks; etc.).
- Intelligent terrain assessment and classification (slopes, regolith density, etc.) to determine safe driving paths.
- Machine learning approaches to autonomous driving development compatible with limited datasets and training opportunities available for lunar surface mobility.
- Novel approaches to increase efficiency, decrease required power, or eliminate reliance on off-board computing for autonomous mobility algorithms.

A significant body of research and prior/current commercialization efforts exist in related technology areas as applied to terrestrial applications, and innovative ways to translate this work to lunar-worthy solutions is encouraged. New capabilities are also sought to address unique lunar surface challenges and expand autonomous rover capability. All proposed technologies, however, must be explicitly targeted to lunar surface application with a viable path to operation on board surface mobility systems leveraging flight-rated processors. To establish this, infusion path proposals are encouraged, but not required, to:

- Target near-term integration and testing on flight-proven computing platforms and/or new, in-development, high-performance spaceflight processors likely to provide extended life in the lunar south pole environment (Note: New processor development is not in scope within this subtopic, but integrated testing is seen as beneficial).

- Use industry-standard software interfaces, architectures, and frameworks that align with relevant NASA and commercial space robotic efforts to reduce future integration effort and facilitate multiplatform adoption of offered technology.
- Provide analog testing and demonstration to establish performance in lunar surface conditions.

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

Primary Technology Taxonomy:

- Level 1: TX 10 Autonomous Systems
- Level 2: TX 10.1 Situational and Self Awareness

Desired Deliverables of Phase I and Phase II:

- Software
- Prototype
- Research
- Analysis

Desired Deliverables Description:

Desired deliverables for this scope include software algorithms and/or example programs that demonstrate one or more technology areas of interest. Greater maturity and complexity will differentiate Phase II deliverables from Phase I.

Phase I deliverables may 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 may include:

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

State of the Art and Critical Gaps:

Terrestrial autonomous driving capabilities are still in the fledgling stages of widespread implementation and adoption. These state-of-the-art technologies still require oversight by a driver. For consumer applications on public roads, that driver is in the vehicle. For controlled environments, such as military or mining operations, a driver could be remotely overseeing the vehicle's operations. These current technologies rely on many resources that are not yet available on the Moon, such as GPS, rich datasets for training machine learning algorithms, high-performance embedded processors, high-speed wireless communications, and machine vision algorithms created to exploit terrestrial features (e.g., stop signs, road markings, etc.). Adaptations or extensions of these approaches must be developed to translate existing levels of terrestrial performance to the lunar surface, and further innovative technologies are needed to expand mobile surface system capabilities to meet future operational requirements and enable mission success.

Relevance / Science Traceability:

The main NASA target for infusion of this subtopic's successful proposals is EHP. Several areas of EHP responsibility could use efficient on-board autonomy, including the Lunar Terrain Vehicle and Pressurized Rover. High-progress-rate driving on the lunar surface will enable productivity during uncrewed periods between Artemis missions.

References:

1. NASA Cross-Program Design Specification for Natural Environments (DSNE), current version Revision I as released on the NASA Technical Reports Server (NTRS). SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE) REVISION I.pdf (nasa.gov)
2. Artemis information: https://www.nasa.gov/artemisprogram
3. EHP information: https://www.nasa.gov/suitup

Scope Title: Sensing and Perception Systems Suitable for Extended Use on the Lunar Surface

Scope Description:

Accurate sensing and perception are critical for enabling autonomous mobility on the lunar surface. Current state-of-the-art approaches to autonomous mobility on Earth typically rely on a variety of sensors that do not have corresponding lunar surface analogs, however. For example, lunar-worthy lidar (laser imaging, detection, and ranging) for rover navigation on the Moon is not currently available, and the performance and survivability of sensors used terrestrially have not been established in the lunar environment. This introduces considerable risk to surface mobility system design and/or a significant limit to operational effectiveness if advances are not made.

This scope targets new sensor hardware that will survive long-duration lunar surface operation and provide performance levels at or beyond existing terrestrial state-of-the-art to enable robust lunar surface autonomous mobility. Technology areas of interest include:

- Availability of lidar hardware (systems and components) suitable for long-duration use in the lunar environment (e.g., lighting conditions, radiation, temperature, dust).
- Novel approaches to efficient data processing/point cloud generation.
- Other sensing modalities with application to lunar navigation.

Innovative approaches to adapting terrestrial autonomous vehicle sensors to lunar conditions are welcomed, as is new sensor hardware design. Unique sensing modalities not typically used for mobility are appropriate if associated driving performance can be clearly established as exceeding current capabilities. Adapting sensors with prior spaceflight heritage, or established flight-like design, to the lunar surface mobility use-case is acceptable as well, if the proposed innovation leads to greater autonomous capability for surface rovers.

A clear understanding of existing relevant state-of-the-art sensors and how the proposed technology compares in performance must be demonstrated. And in all cases, new sensors must have a viable path to lunar surface operation, be designed for integration into human-scale lunar surface rovers and be compatible with autonomous driving algorithms or approaches. To facilitate infusion, proposals are encouraged but not required, to:

- Use industry-standard hardware and software interfaces and architectures to reduce future integration effort and ease adoption.
- Limit dependence on third-party proprietary technologies that might complicate NASA or commercial adoption of the technology.
- Target near-term demonstration of sensor technology in a relevant mobility context.

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

Primary Technology Taxonomy:

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

Desired Deliverables of Phase I and Phase II:

- Hardware
- Software
- Prototype
- Research
- Analysis

Desired Deliverables Description:

Desired deliverables for Phase I 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 (may be particularly relevant for novel adaptations to existing designs).

Desired deliverables for Phase II ideally include:

- Initial sensor prototype and corresponding design details.
- Test/performance data in an analog environment with associated analysis.
- Integrated demonstration in a surface mobility context.

State of the Art and Critical Gaps:

Existing state of the art consists of sensors used for terrestrial autonomous mobility. Commercial lidar technology is unproven in lunar surface conditions, however. Flight development to date has largely focused on in-space applications, not surface applications. Therefore, direct focus on lunar surface survivability and performance requirements associated with surface mobility is needed.

Devices with lower power and less constrained thermal requirements are needed, as are sensors suitable for long-duration operation in the radiation, dust, and thermal environment of the lunar south pole.

Surviving the lunar night is a critical gap, and the ability to operate throughout the lunar night would greatly expand surface system capabilities.

Mobility based on visual cameras is significantly hindered by lighting conditions at the lunar south pole and robust sensors that overcome this challenge are needed.

Relevance / Science Traceability:

EHP missions provide immediate infusion potential for the subject sensor technologies, with highly relevant projects like the Lunar Terrain Vehicle, Pressurized Rover, and other future mobility systems all requiring robust lunar-worthy perception sensing. The current EHP Autonomous Mobility and Operations Roadmap identifies lunar-worthy perception sensing (and lunar-worthy lidar in particular) as a significant near-term priority.

Comparable SMD activities on the lunar surface, epitomized by the high-priority Endurance-A mission called out in the latest Planetary Science Decadal, are also enabled by long-life sensors for autonomous navigation.

References:

1. NASA Cross-Program Design Specification for Natural Environments (DSNE), current version Revision I, as released on the NASA Technical Reports Server (NTRS). SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE) REVISION I.pdf (nasa.gov)
2. Artemis information: https://www.nasa.gov/artemisprogram
3. EHP information: https://www.nasa.gov/suitup

Scope Title: Supervised Autonomy and Shared Control Paradigms for Remote Surface Operations

Scope Description:

As NASA begins Artemis missions, the communications environment will be different from decades of human spaceflight operations in low-Earth orbit (LEO). Whereas communications latency to the International Space Station is on the order of hundreds of milliseconds, the time it takes for signals to reach the Moon is expected to be approximately 3 seconds, and it can take as much as 24 minutes each way to Mars. Additionally, less bandwidth is expected to be available, along with extended periods of communication blackout and/or intermittent communication connections, especially when crew is not present. This communications scenario drives a need for increased autonomy in surface mobility systems. Existing approaches to remote command and control in LEO or on Mars are not suited for the unique lunar surface time delay and other operational constraints. And unlike current operations on the martian surface, lunar surface operations (along with future Mars exploration activities) will occur at a faster, human-scale, operational cadence (both with and without crew), necessitating both a greater real-time response to remote commands and autonomous onboard decision making. These two components must also work in tandem, and cohesive integration is critical to realizing effective human-robot coordination during surface operations.

Enabling the wide range of robotic surface operations outlined in NASA's Moon-to-Mars objectives, including important near-term surface mobility tasks, requires the development and implementation of new supervised autonomy and shared control paradigms.
Technology areas of interest include but are not limited to:

- Novel supervisory control techniques to accommodate intermediate time delays, data latencies, and unreliable/intermittent communication.
- Integrated command and control interfaces for remote operators to oversee lunar surface activity (extensible to multiple and/or varied surface mobility systems).
- Autonomous recognition of objects/areas of interest for science investigation.
- Intelligent path planning and waypoint generation over long distances.
- Contextual data prioritization for communicating relevant system health information over limited bandwidth.
- Task primitives or task parameterization related to surface mobility.
- Improved autonomy for planning, scheduling, and execution.

All technologies must provide a demonstrable advance over current state-of-the-art solutions and offer a viable path to adoption in lunar surface operations. Dual-use technologies with broad applicability to robotic operations in other space environments or mission scenarios are encouraged, as is relevance to terrestrial needs for improved supervisory control and remote autonomous operations, but impact to near-term lunar surface mobility objectives is a high priority.

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-robot supervisory control solutions.

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

Primary Technology Taxonomy:

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

Desired Deliverables of Phase I and Phase II:

- Software
- Prototype
- Research
- Analysis

Desired Deliverables Description:

Phase I deliverables include:

- Background research and feasibility studies.
- Conceptual design, trade studies, and description of proposed solutions.
- Initial software algorithms and/or example programs demonstrating desired technical advances.

Desired deliverables for this scope include software algorithms and/or example programs that demonstrate one or more of the items listed in the technology areas of interest. Greater maturity and complexity will differentiate Phase II deliverables from Phase I.

Deliverables for Phase II will be of greater maturity and complexity than Phase I deliverables and may include:

- Software source code and/or block diagrams, user manual/instructions, documentation.
- Test and/or performance data with associated analysis.
- Demonstration of software prototype on representative robot(s), rover(s), or flight computing hardware.

State of the Art and Critical Gaps:

The current state of the art consists of the following areas (followed by specific shortcomings/gaps that still need to be addressed to meet lunar surface operational needs):

- Mars science rover operations: Large communication delays prevent real-time operations, but this also allows for significant off-line human/operator analysis and planning before robot execution. Human decision making and robot/rover autonomy must be better integrated in the lunar surface setting.
- ISS robotic operations: Lower time delays and direct human-in-the-loop command and control allow for less autonomy than is needed during remote lunar surface operations.
- Low TRL robotic manipulation: A large body of low TRL research exists developing supervised autonomy and remote human-robot interaction, typically in structured environments or zero-time-delay situations. Extending these approaches to robotic mobility and developing technology products robust to the unstructured environment of the lunar surface is needed.
- Terrestrial remote robotic applications (e.g., military, undersea, etc.): Even in these scenarios, remote operator situational awareness is better than can currently be achieved on the lunar surface. Remote command and control of terrestrial assets can leverage Earth-based infrastructure not available to lunar surface mobility systems.

Relevance / Science Traceability:

NASA's Moon-to-Mars objectives highlight the need for "local, regional, and global surface mobility in support of a continuous lunar presence" (LI-6) and the need to "operate robotic systems that are used to support crew on the lunar or martian surface, autonomously or remotely from the Earth or from orbiting platforms" (OP-10). These specific objectives and others like them speak to the immediate relevance of supervised autonomy and remote shared control paradigms and products to NASA's near-term lunar surface activities and the broader desire to expand and sustain lunar surface operations. Focusing this technology development on surface mobility specifically serves to enable initial uncrewed activities, enhance early crew missions, and provide a path to rapid spaceflight operational infusion for commercial offerors.

Successful proposals to this subtopic will directly address EHP program needs, and mature needed technology outlined in the current EHP Autonomous Mobility and Operations roadmap. As the number of surface assets grows over the course of Artemis missions, the need for more robust supervised autonomy extending across a broader set of surface systems becomes even more important to ensure effective interoperation.

References:

1. NASA Cross-Program Design Specification for Natural Environments (DSNE), current version Revision I, as released on the NASA Technical Reports Server (NTRS). SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE) REVISION I.pdf (nasa.gov)
2. Artemis information: https://www.nasa.gov/artemisprogram
3. EHP information: https://www.nasa.gov/suitup

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

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

Subtopic Introduction:

The NASA Decadal Survey for the 2023 to 2032 decade identifies missions to solar system bodies—including comets, asteroids, Ceres, Enceladus, Titan, Venus, Mars, and Earth's moon—that 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.

Scope Title: Robotic Mobility, Manipulation, and Sampling

Scope Description:

The NASA Planetary Science Decadal Survey for the 2023 to 2032 decade identifies missions to solar system bodies—including comets, asteroids, Ceres, Enceladus, Titan, Venus, Mars, and Earth's Moon—that 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. For example, an Endurance-A rover mission to Earth’s Moon needs wheel, long-life actuator, sampling, manipulator, and autonomy technologies to enable fast and long-distance traverse, sample acquisition, and sample storage.

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. Technologies to enable fast and long-distance robotic lunar surface mobility are of interest.

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. Longer distance rovers with sampling systems are such a need for a mission to Earth's Moon.

Relevance / Science Traceability:

This subtopic supports multiple programs within the 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 returning to Earth's Moon, the mobility and sampling technologies could support a future long-distance traverse and sampling rover mission to the Moon. The NASA Decadal Survey for the 2023 to 2032 decade identifies various future missions that require these technologies, including missions to Ceres, comets, asteroids, Enceladus, Venus, Mars, and Earth's Moon.

References:

1. "Mars Exploration: Missions," National Aeronautics and Space Administration: https://mars.nasa.gov/programmissions/
2. "Solar System Exploration," National Aeronautics and Space Administration: https://solarsystem.nasa.gov/
3. "Ocean Worlds," National Aeronautics and Space Administration: https://www.nasa.gov/specials/ocean-worlds/
4. "New Frontiers," National Aeronautics and Space Administration: https://science.nasa.gov/planetary-science/programs/new-frontiers/
5. "Planetary Science and Astrobiology Decadal Survey 2023-2032," National Aeronautics and Space Administration: https://www.nationalacademies.org/our-work/planetary-science-and-astrobiology-decadal-survey-2023-2032
6. "OSIRIS-REx," National Aeronautics and Space Administration: https://science.nasa.gov/mission/osiris-rex/

S16.04 High-Altitude Platform Systems (HAPS) Capability Demonstration (SBIR)

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

Subtopic Introduction:

High-altitude platform systems (HAPS) are a new and exciting capability for providing persistent communications and Earth observations from the stratosphere. The high altitude regime is also of interest to the Space Biology community given the high-radiation environment that over several days is analogous to International Space Station (ISS) or Mars exposure levels. In order to enable HAPS access to the airspace, the NASA Aeronautics Research Mission Directorate (ARMD) is developing a HAPS Traffic Management System for upper Class E airspace.

This subtopic is on focused on flight testing with a NASA-relevant payload (HAPS) to mature this class of aircraft to support current and future NASA Earth, space, and aeronautics programs seeking this vantage point. The other focus of this subtopic is to mature low-SWaP (size, weight, and power) optical communications and associated computing to provide data telemetry from onboard payloads as well as to provide airborne network terminals.

For Scope #1: This solicitation seeks respondents that have developed, or have access to through a partnership, existing HAPS that have conducted initial flight testing and are capable of flying a payload of 10+ lb at FL550 and above for 30+ days.

Phase I proposals are sought for a formulation study to describe the platform capability, propose a science use case, downselect a science payload, and develop a concept of operations. A detailed approach on addressing Federal Aviation Administration (FAA) airspace regulations and restrictions shall be included as part of the concept of operations. The outcome of Phase II will be a flight of 14+ days with a NASA-relevant payload in the National Airspace System.

For Scope #2: This solicitation seeks respondents to modify or develop an optical communications terminal for a flight from a high-altitude balloon.

Phase I proposals are sought for a comprehensive design utilizing commercial or custom-built hardware. The developer will need to balance size, weight, power, and cost to develop a system that this low-cost and power-limited platform can utilize for both balloon-to-space and balloon-to-ground networks. The result of Phase II will be a flight test provided by the NASA Balloon Program Office from their launchsite in New Mexico.

Scope Title: High-Altitude Platform Systems (HAPS) Capability Demonstration

Scope Description:

NASA is interested in increased utilization of innovative, cost-effective HAPS, including both heavier and lighter than air, to perform NASA missions in the stratosphere in order to supplement current piloted and satellite platforms. HAPS are a new and exciting capability for providing persistent communications and Earth observations from the stratosphere. The high altitude regime is also of interest to the Space Biology community, given the high-radiation environment that over several days is analogous to ISS or Mars exposure levels.

HAPS missions will enable new discoveries in Earth and space science by enabling sustained access and control in the stratosphere. High-spatial- and high-temporal-resolution observations from high-altitude, long-endurance (HALE) platforms can improve measurements of Earth system processes or phenomena requiring sustained observations, including: air quality monitoring, coastal zone and ocean imaging and monitoring, mapping of geologically active regions, forest and agricultural monitoring, and imaging of polar regions. The NASA Surface Biology and Geology mission, for example, is anticipating the need for measurements of leaf canopy chemistry during the growing season, and significant changes can happen between overpasses of polar orbiting satellites. Similarly, the Surface Topography and Vegetation Incubation team recently released a report citing the need for more frequent observations of areas prone to landslides and other ephemeral or episodic events where time-series observations can improve Earth-system models.

Phase I proposals are sought for a formulation study to describe the existing flight-tested platform capability, the use case, TRL 3 or higher payload or candidates, and a concept of operations to meet science or applications goals. It is expected that the flight duration will be 2 weeks or more. An existing flight proven platform at TRL 5 must be used for the proposed effort. The payload should be a TRL 3 or higher and the Phase I plan should include a thermal management plan.

Phase II will consist of a flight mission of 14+ days relevant to NASA Science or Aeronautics. Examples might include high-resolution terrain or vegetation mapping, fire or other thermal anomaly mapping, and atmospheric or weather measurements.

Partnerships between industry and academia are encouraged as are cost sharing and cost matching.

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

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.2 Mobility

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Deliverables from Phase I will include:

1. Detailed flight system configuration description, including platform, science payload, onboard computing, and telemetry.
2. Use case or science description and notional flight plan.
3. Concept of operations to include launch/recover site(s) and associated agreements and partnerships. Detailed approach for addressing FAA airspace regulations and restrictions shall be included.
4. Detailed risk assessment and matrix detailing mitigations required in Phase II.

The Phase II effort will implement the flight demonstration plan outlined in the Phase I study. Phase II deliverables will include:

1. NASA airworthiness and flight safety briefing and actions.
2. NASA Flight Readiness Review Board briefing and actions, including a flight test plan and a safety and mishap plan.
3. FAA application for a Certificate of Authorization (COA) and Beyond Visual Line of Sight (BVLOS) waiver.
4. Flight test report.
5. Archived data with metadata.

State of the Art and Critical Gaps:

For stratospheric observations NASA primarily relies on the ER-2, WB-57, and scientific balloons. The Global Hawk was used for several years, but the operations proved too costly, and the flight duration was limited to 32 hr. Current HAPS provide capability for loitering over an area for days or weeks with persistent observation and communications or for providing air-mass following to study physical and chemical processes in the atmosphere. Measurements like this with high spatial and temporal resolution cannot currently be collected from satellites or conventional aircraft. HAPS can provide a geostationary-like capability to provide nearly continuous observations of quickly changing phenomena—such as landslides, volcanoes, and floods—that are difficult to image or otherwise observe from space without a very dense constellation.

Recently, the United States Forest Service (USFS) has funded Swift Engineering to fly a NASA SBIR-funded HAPS to fly an infrared (IR) payload for real-time fire imaging. NASA Ames Research Center has also partnered with the USFS to fly the Aerostar station-seeking Thunderhead balloon to provide persistent communications to remote fire responders. For these use cases, HAPS enables persistence that can't currently be provided from ground or orbit.

Current fixed-wing HAPS can carry from 5 to 100 lb and stay aloft from several days to a month or more. There is currently need for government investment to mature the vehicles and the procedures for gaining access to the airspace.

Relevance / Science Traceability:

NASA ARMD has two current projects related to this technology area. In order to enable HAPS access to the airspace along with other users of Upper E airspace, NASA ARMD is working with the FAA to develop a HAPS UTM system for upper Class E airspace. Use of HAPS for wildland fire response monitoring and communications is of interest to the NASA ARMD Advanced Capabilities for Emergency Response Operations (ACERO) project, a project currently in formulation.

The NASA SMD Earth Science Division (ESD) FireSense Project is also planning to include HAPS platforms in a mission in the FY 2027 to 2028 timeframe for fire and atmospheric observations. The NASA SMD ESD Surface Topography and Vegetation Incubation Study Team that was formed in response to the National Academies' Decadal Survey for Earth Science highlighted, in their initial report, the need for HAPS to provide high-frequency measurements to complement orbital observations.

NASA, other Government Agencies, and private companies have also shown increased interest in utilizing uncrewed aircraft system (UAS) platforms—both heavier and lighter than air—for Earth Science data collection, supplementing satellite and piloted Earth Science aircraft. This is largely because of the ability of UAS to perform dull, dirty, difficult, and dangerous missions more easily than other platforms.

There is interest from the highest levels of Government to invest in the domestic UAS manufacturing base to reduce reliance on foreign manufacturers as well as security concerns with foreign UAS platforms and technologies.

References:

1. "Airborne Platforms to Advance NASA Earth System Science Priorities: Assessing the Future Need for a Large Aircraft," Committee on Future Use of NASA Airborne Platforms to Advance Earth Science Priorities, 2021: https://www.nap.edu/catalog/26079/airborne-platforms-to-advance-nasa-earth-system-science-priorities-assessing (see page 142).
2. "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space: A Framework for The Decade," National Academies of Sciences, Engineering, and

Medicine, 2018: https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth
3. "Observing Earth's Changing Surface Topography and Vegetation Structure," NASA's Surface Topography and Vegetation Incubation Study Team Report, 2021: https://smd-cms.nasa.gov/wp-content/uploads/2023/06/STV_Study_Report_20210622.pdf (see page 122).

Scope Title: Free-Space Optical Communications for a Stratospheric Balloon Platform

Scope Description:

Scientific balloon payloads are capable of gathering between 10 and 1,000 GB/day, but current satellite communications links used during long-duration balloon flights are limited to short bursts at 1 Mbps (most often limited to 300 kbps because of older satellite technology). Further, coverage dropouts over the Pacific Ocean persist, causing periods of low transmission rates. Recent research and development in optical communications systems show promise for improving the telemetry capabilities for balloon missions. The specific requirements for successful implementation from a balloon platform in the 90,000- to 150,000-ft altitude range are specific to stratospheric balloon flight and exclude aircraft-borne and spacecraft-borne instruments. Although modifications to those instruments may provide an acceptable solution, such a solution is not optimized for balloon mass, operational cost, and power limitations, nor does it consider the unique pointing challenges or atmosphere.

Expected TRL or TRL Range at completion of the Project: 2 to 7

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:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables to include:

- Design and analysis of an optical terminal.
- Documentation of trades between functionality, power, and cost.
- Identification of all required hardware with a full bill of materials.

Phase II deliverables to include:

- A prototype system tested in a laboratory setting.
    - Thermal and vacuum qualification at a subsystem level at a minimum.

State of the Art and Critical Gaps:

The work performed to date by government, commercial, and university organizations has been focused on ground, aircraft, or space-based terminals. They utilize either Consultative Committee for Space Data Systems (CCSDS) or Space Development Agency (SDA) communications standards and are rarely compatible. A low-cost solution would likely rely on SDA protocols, but commercial terminals are not designed for flight at 100,000 ft or for low-cost, low-power use cases. Balloon-to-ground communication would require further tradeoff between functionality, power consumption, and cost, and no solution exists that is within the requirements of a HAPS system.

Relevance / Science Traceability:

The NASA Balloon Program Office launches 12 to 20 large missions per year worldwide. These missions perform groundbreaking science and require massive telemetry links to retrieve data. Recovery of the payload is not always guaranteed, and current missions are generating from 10 to 1,000 GB/day. The Program Office would like to provide this platform enhancement to encourage development of higher resolution instruments.

References:

1. "Optical Communications," National Aeronautics and Space Administration, 2023: https://www.nasa.gov/directorates/space-operations/space-communications-and-navigation-scan-program/
2. "Scientific Balloons," National Aeronautics and Space Administration, 2023: https://www.nasa.gov/scientificballoons

Z5.09 Robotic Hardware for In-Space Manipulation (SBIR)

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

Subtopic Introduction:

The growth of commercial operations, whether in Earth orbit, in cislunar space, or on the lunar surface, is contingent upon affordable, readily available robotic assets capable of projecting robust manipulation capability into these challenging environments. The objectives of maximizing science return and establishing a sustainable exploration infrastructure, highlighted in NASA's Moon-to-Mars objectives, are directly impacted by the availability of robust, capable robotic manipulation. In-space servicing and assembly, the outfitting of lunar surface infrastructure, and science sample collection in extreme environmental conditions are just a few of the many example applications enabled by robotic manipulators. The commercial availability, cost-effectiveness, environmental survivability, and performance capability of existing flight-worthy robotic manipulation hardware is limited, however, and novel advancements in these areas will significantly impact the degree to which robotics can be leveraged by NASA and commercial entities in future space operations.

To foster the expansion of U.S. industry and innovation beyond Earth orbit and establish long-term sustainability of deep space and lunar operations, as outlined in the foundational recurring tenets of the Agency's Moon-to-Mars Objectives, novel advancements in manipulator dexterity, strength-to-weight performance, power efficiency, robustness, and sensing are needed. Additionally, cost must be driven down, and innovation is needed to translate current successes in the terrestrial marketplace to the challenging constraints of spaceflight application.

This subtopic seeks to encourage new approaches and novel design adaptations to in-space robotic manipulation to enable the broad set of tasks required in remote deep space and lunar surface settings.

Scope Title: End Effectors for Complex In-Space Manipulation Tasks

Scope Description:

Establishing a sustainable exploration infrastructure (on the lunar surface, in lunar orbit, in cislunar space, and on to Mars) requires extensive robotic operations. Much of this work will be performed during uncrewed periods, highlighting the need for broader manipulation capabilities to perform a wider range of autonomous tasks, many of which would typically be reserved for human hands or handheld tools terrestrially. Initial deployment, assembly, and outfitting of lunar surface infrastructure will need to be done robotically, as will maintenance, logistics management, and sustained utilization of equipment, instruments, and experiments (both internal and external to vehicles and habitats). The ability to interact with tools, interfaces, and components not expressly designed for robotic manipulation is highly desirable, as this expands the range of design solutions that mission planners, architects, and the science community can adopt for their space systems.

Novel end-effector designs with improved dexterity, versatility, and overall task performance in the space environment are specifically sought for a range of intravehicular, lunar surface, and in-space servicing tasks, including:

- Assembly, maintenance, and outfitting (e.g., mating/demating power, data, and fluid connections; opening/closing panels; installation, stowage, and handling of cables and fluid lines; manipulation of soft goods).
- 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).
- Satellite capture (particularly the grasping of interfaces not purpose-built for robotic manipulators and/or interaction with uncontrolled, i.e., noncooperative, targets).
- Logistics management (e.g., payload handling; packing/unpacking bags; kitting items).
- Sample collection (particularly cold samples in cryogenic conditions).

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

- Robust fine dexterity for human-hand-like tasks and tool/interface manipulation.
- Multipurpose and adaptable grasping.
- Modularity.
- Lightweight, low-volume, and/or low-power actuation solutions.
- Novel strength-to-weight or force/torque density improvements.
- End effectors suitable for environmental extremes (e.g., long-duration use in permanently shadowed lunar regions, cryo-sample interaction).

- Compact integrated sensing approaches (improving, for example, tactile sensitivity or controllability) .

All technologies must provide a demonstrable advance over current state-of-the-art solutions and present a viable path toward use in intravehicular or extravehicular space applications. Dual-use technologies with broad applicability to both space and terrestrial applications are encouraged, as are both system-level 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:

- 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).
- Limit dependence on third-party proprietary technologies that might complicate NASA adoption of the technology.
- Target near-term integration and testing on relevant NASA robots and/or flight manipulators, with existing spaceflight interfaces, or in coordination with ongoing spaceflight development efforts (Government or commercial).
- Demonstrate technology advances in the context of relevant manipulation or utilization task performance.

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

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.3 Manipulation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

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 robotic end effectors are found in terrestrial-industry-targeted applications (e.g., factory floor manipulation), early-TRL dexterous robots, and new advanced prosthetic devices. Each suffers shortcomings that, to date, have limited infusion into spaceflight applications. Industrial manipulators typically rely on end effectors that have limited dexterity and less integrated sensing, or grippers that are purpose-built for specific structured tasks. More complex dexterous robotic hands have, in theory, greater versatility but are also less robust and more sensitive to environmental extremes. Achieving high force/torque capability and adequate sensing in a compact volume for these high-degree-of-freedom systems is also difficult. A new generation of prosthetic robotic hands offers promise, but force range and sensing is still limited, as is the suitability of these designs to the challenging space environment and more rigorous use cases.

Existing flight systems are limited in dexterity and significantly larger than fine manipulation tasks require. Transitioning terrestrial advances to challenging spaceflight applications is needed. 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, and low size and mass solutions are needed that can nevertheless withstand human-scale forces and offer long operational life.

Relevance / Science Traceability:

This scope represents an enabling technology for remote robotic manipulation on the lunar surface in support of infrastructure outfitting and asset utilization and maintenance. Intravehicular robot (IVR) operations on Gateway and other future vehicles/habitats require improved manipulation for science utilization, logistics management, payload handling, etc., and in-space servicing and assembly activities across NASA and commercial mission portfolios are significantly expanded by more capable flight-worthy robotic end effectors.

Manipulation leveraging the novel hardware technologies targeted directly supports 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:

1. Robot Operating System (ROS): https://www.ros.org/
2. Astrobee: https://www.nasa.gov/astrobee
3. Space Robot Operating System: https://space.ros.org/ and https://techport.nasa.gov/view/116403
4. Practical End-Effector Development Through Task Interface Taxonomy Analysis: https://doi.org/10.1115/DETC2022-89299
5. Robotic Systems Technology: https://www.nasa.gov/er/er4
6. NASA Outlines Lunar Surface Sustainability Concept: https://www.nasa.gov/feature/nasa-outlines-lunar-surface-sustainability-concept
7. NASA's Plans for Commercial LEO Development: https://ieeexplore.ieee.org/document/9172512

Scope Title: Cost-Effective Flight Robotic Manipulators and Related Actuation Components

Scope Description:

Currently, flight robotic arms and their drive electronics are bespoke systems carefully designed for custom applications with significant emphasis on mass efficiency and life. The robotic arms also undergo detailed sensitivity analyses, characterization, calibration, and testing over a large range of joint positions and load conditions at both the system and individual actuator level. The overall cost of these systems reflects the uniqueness of each arm. Similarly, motor controllers and other drive electronics needed for the robot arm are typically customized and tuned for specific robot characteristics. The need for high reliability over years of performance life in the challenging environmental conditions of space drive this level of rigor (and its associated cost), but the availability and selection of space-qualified robotic manipulators is highly limited as a result.

Conversely, mass-produced, standard components with specific, short-duration applications typically have a lower cost than bespoke systems. Recent progress in terrestrial robotic actuators, for example, has led to cost-effective, high-performance integrated robotic actuator modules used across academia and industry (e.g., the Massachusetts Institute of Technology (MIT) Cheetah robot actuators and similar drives in other commercially available quadrupeds). Fully integrated collaborative robot manipulators are ubiquitous in academic labs and commercial robotic applications. Availability of comparable spaceflight manipulators, by comparison, is significantly limited, with few vendors (and even fewer domestic suppliers), few flight-proven solutions, and much higher costs.

The goal of this scope is to characterize and subsequently validate opportunities for cost saving and standardization; to present novel design approaches to robotic manipulators suitable for in-space use; and, in so doing, to broaden the availability and reduce the cost of capable flight robotic manipulators. Cost, manufacturability, and overall availability in the marketplace should not come at the cost of performance in spaceflight use cases, however. In fact, achieving new levels of manipulator performance is a driving need for sustainable lunar surface infrastructure outfitting, utilization, and maintenance; the manipulation of in-space assets during deep space servicing and assembly; and accomplishing challenging science objectives on the Moon, Mars, and distant destinations throughout the solar system. This performance, though, must be achieved hand-in-hand with attainable cost and multi-mission versatility to effectively expand commercial activities beyond Earth orbit and deploy robotic capabilities at greater scale across NASA's entire mission portfolio.

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

- Novel adaptation or translation of terrestrial robot manipulators, actuation modules, or other subsystem components for robust use in relevant space environments (e.g,. lunar surface, cislunar space, Earth orbit).
- Unique design improvements to drive down the cost of previous flight-proven or flight-targeted manipulators.
- Unique design improvements to increase flight manipulator performance without increased cost.
- Expanding the use-case environments of existing manipulators (e.g., novel adaptation of Earth-orbit manipulators for use in lunar surface permanently shadowed regions).
- Novel robot arm design that achieves cost-effective multi-mission versatility.
- Cost-effective approaches to robustness, reliability, and fault tolerance.

Specific applications of interest include:

- Lunar surface manipulation.
- Cold-temperature sample collection and curation.

- In-space servicing and assembly.

Parameters typically used in robotic arm acquisition, such as precision, accuracy, configuration, overall mass allocation, margins, etc., are expected to be treated as free variables in the interest of bringing down overall cost or introducing novel capabilities. Production lot sizes should be assumed small (e.g., 1, 10, or 25 units) in any cost analysis to reasonably project infusion potential. And while target arm length and degrees of freedom are not specified, dexterous manipulation at the 1- to 2.5-m scale is expected to have the most immediate impact on operational scenarios.

Dual-use technologies with broad applicability to both space and terrestrial applications are encouraged, but all technologies must provide a viable path to flight use and demonstrate advances that will lead to likely mission infusion and adoption by NASA and/or the broader commercial space community.

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

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.3 Manipulation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

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.
- Concept for low-cost flight demonstration.

Phase II deliverables include:

- Validation of concept and cost range.
- Prototyping with viable path toward production.

State of the Art and Critical Gaps:

A general heuristic used for early-stage cost modeling is that a 1-degree-of-freedom actuator subsystem costs on the order of a million dollars for a class-B type mission. There is very little data, and very few models, to characterize cost of robotic arms designed for use cases described in this topic. Agile space missions for emerging new space use cases are likely to require low-cost robotic arms that fit within the budget ranges of Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA)-based or SmallSat-based missions. The current costs associated with space robotic arms are unfavorable for easy adoption of robotics in such mission classes. Industrial applications, however, are seeing increased adoption of robotic manipulation and widespread growth in cost-effective collaborative robots for human-scale tasks. The translation of similar capabilities to flight-use cases is needed.

Further, current practice does not typically include standardization of components or even joints across specific arms or manipulator product lines, and very few standard products are available for use in space robotic manipulation. Low-cost, high-reliability robotic manipulators with performance capabilities suitable for the challenging use cases of sustained lunar presence and reuse across cislunar operations are needed.

Relevance / Science Traceability:
Infusion of robotic in-space servicing, assembly, and manufacturing (ISAM) missions or demonstrations for science, commerce, exploration, and national interest are challenging due to the high cost of overall systems and related logistics. Ability to fly low-cost, short-duration missions and demonstrations would lower the threshold for access to space and encourage infusion of ISAM.

Current programmatic and architectural decisions are often driven by cost constraints, putting the integration of needed robotic capability at risk and potentially sacrificing long-term success toward Moon-to-Mars objectives.

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Scope Title: Sensors for In-Space Robotic Manipulation

Scope Description:

Autonomous robotic manipulation in space is contingent on a robot's ability to safely sense and interact with equipment, interfaces, and natural features in the environment. Supervisory control, and remote operations more generally, are enabled by rich sensor feedback that relays situational awareness to remote operators. Robust sensing is a challenge in robotics, and even more so in the harsh space environment. This scope aims to improve sensor hardware and the integration of sensors into robotic manipulators for the difficult tasks required on the lunar surface, in cislunar space, and in the rapidly expanding marketplace of Earth orbit.

Specific sensors of interest include, but are not limited to:

- Low-mass, low-volume, high-dynamic-range force/torque sensors.
- Integrated tactile sensors for manipulation.

- Novel sensors for system health and/or task completion monitoring.
- Integrated perception sensors addressing challenges unique to manipulation. (Note: Sensing and perception systems targeted for lunar surface mobility and/or other use cases and environments should be addressed to other subtopics.)

All new sensor technology should address robustness to radiation, temperature extremes, and other environmental factors unique to use in space applications. Improvements in both performance and environmental robustness beyond the existing state of the art are desired.

Dual-use technologies with broad applicability to both space and terrestrial applications are encouraged, but new sensor development should have a clear path to flight readiness and targeted spaceflight use cases. To facilitate infusion, proposals are encouraged, but not required, to:

- Use industry-standard interfaces (hardware and software) to reduce future integration effort.
- Limit dependence on third-party proprietary technologies that might complicate NASA adoption of the technology.
- Demonstrate sensor performance in the context of relevant spaceflight manipulation or utilization task performance as described throughout this subtopic.

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

Primary Technology Taxonomy:

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

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 sensor 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.

State of the Art and Critical Gaps:

Many sensors currently used in terrestrial robotic manipulation cannot survive or effectively perform in the space environment. State of the art varies across sensor type, but a lack of robustness to radiation and thermal extremes is common. Compact, low-mass sensing integrated into robot arms and/or end effectors is needed to reduce robot size and eliminate the need for external support equipment during manipulation tasks, as current solutions do not offer the high dynamic range required for more dexterous tasks.

Relevance / Science Traceability:

Autonomous manipulation and utilization enabled by novel sensors for robotic manipulation directly supports 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."
Manipulation for in-space servicing and assembly, sustained lunar surface operations, and science exploration and utilization requires robust sensing.

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Z5.10 Extensible Planning, Perception, and Control for Autonomous Robotic Systems (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 and in cislunar space. The following scopes highlight key challenges toward:

- Advancing remote robotic manipulation technologies to enable autonomous robots to interact with their environment and perform utilization, maintenance, logistics management, infrastructure outfitting, and in-space assembly tasks.
- Novel autonomy solutions needed for lunar surface systems, habitats, transit vehicles, and other persistent space platforms operating for extended periods of time without direct intervention from Earth, pursuing enabling robot/autonomy/human integration and function allocation for sustaining and extending exploration infrastructure and operations deeper into space.
- Software interoperability for sustained collaborative operations, mission extensibility, the efficient reuse of assets, and the accelerated integration and advancement of autonomy across these assets, so that multiple lunar surface and deep space robotic systems can more easily leverage rapidly evolving and maturing autonomous capabilities while commercial involvement and growth of a sustainable lunar surface and cislunar ecosystem is facilitated.

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 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 autonomy on board 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 or extravehicular space environment and relevant mission operation constraints.

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

- Semantic simultaneous localization and mapping (SLAM).
- Affordance recognition.
- Object/obstacle detection and segmentation.
- Object classification and/or registration.
- Pose estimation.
- 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 are specifically sought. Novel approaches to leveraging machine learning for manipulation in the space environment (i.e., without reliance on significant cloud computing resources or large prior datasets) is also of potential interest.

Technologies must be applicable to intravehicular robotics, lunar surface, or other in-space manipulation use cases, 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 soft goods).
- 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).
- Intravehicular robot (IVR) spacecraft inspection, monitoring, and anomaly detection.

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 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 04.1 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 internal habitat or in-space environments, significant cloud computing resources, or large external datasets and training time. 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 of onboard 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 remote robotic manipulation, more generally, 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.”

Greater robotic autonomy for infrastructure-related manipulation tasks on the lunar surface and in cislunar space is needed: (1) to prevent an undue burden on crew time to perform many of these tasks, and (2) to address the communication limitations (time delay, latency, loss of communications, etc.) that prevent direct ground control from Earth in many of the target use cases.

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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. Codesign 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 codesigned 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 DST 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-machine interfaces (HMIs).
- Scalable ground operations for persistent missions in space exploration and science.

This is within the context of a design reference mission (DRM), such as:

- Large, complex campaigns underway, including Artemis and Mars Sample Return. These campaigns consist of multiple spacecraft and/or robotic platforms with complex interoperations and span almost two decades. An example for Artemis is remote 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.
- Large observatories such as the Large UV/Optical/IR Surveyor (LUVOIR), Origins Space Telescope (OST), Habitable Exoplanet Observatory (HabEx), Lynx, and the Nancy Grace Roman Space Telescope.

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
- Software
- Hardware

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 concept of operations (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.

It also 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.); and 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."

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Scope Title: Modular, Interoperable, and Extensible Flight Software Frameworks

Scope Description:

With multiple lunar surface assets from various vendors representing a core component of NASA's strategy to build a sustainable lunar surface ecosystem, software interoperability is critical for sustained collaborative operations, mission extensibility, the efficient reuse of assets, and the rapid evolution and integration of autonomy between these assets. Infusion of commercial robotic capabilities is slowed, however, by the lack of a flight software framework compatible with the widespread terrestrial commercial standards (e.g., Robot Operating System (ROS)). Robust robot control software and infrastructure developed to the rigors of spaceflight verification and validation standards is needed. This includes, but is not limited to:

- Spaceflight versions of ROS, core packages, middleware, and oft-used components (e.g., Space ROS).
- Innovative approaches to continuous integration along with easily reusable and reproducible tools and processes targeted to satisfying spaceflight software standards.
- Methods to apply code quality standards automatically to ground-focused software to enable use in spaceflight.
- Standardized interfaces and software bridges between robot software frameworks such as ROS and existing spaceflight software architectures (e.g., cFS (core Flight System), F Prime).
- New build/compiler improvements to enable use of existing software tools in resource-constrained applications.
- Novel run-time monitoring, deployment, and management approaches for non-spaceflight software that enables its use in lieu of certification of the frameworks themselves.
- Adapting, modifying, extending, and/or certifying existing open-source robotic software tools for spaceflight computer architectures (e.g., RISC-V (Reduced Instruction Set Computer-V)).

It is desirable to see relevant robotic task capabilities tested and demonstrated using these new software architectures and robotic autonomy/control frameworks. Contributing improvements and processes to upstream open-source projects, maintaining or supporting continuous integration tools/processes, and/or providing support to foster communities around spaceflight-focused robotics software is encouraged to accelerate development of needed advances beyond individual offeror contributions.

A clear infusion path to NASA mission use cases must be demonstrated, but an open-source business model that enables reuse and interoperability of software components (e.g., open-core) to provide benefit to many potential hardware and software providers and applications is encouraged. Such a model would maximize utility across flight applications while enabling a revenue stream for the offeror, serving to bolster both flight software development efforts and the growth of commercial space and autonomy small businesses.

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

Primary Technology Taxonomy:

- Level 1: TX 04 Robotics Systems
- Level 2: TX 04.6 Robotics Integration

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, description of proposed solutions, references to contributions made to upstream projects.
- 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, contributions to upstream projects.
- Test and/or performance data.
- Demonstration of software prototype on robot hardware.

State of the Art and Critical Gaps:

State of the art consists of terrestrial standards like ROS that are not fully matured for robust spaceflight use, and existing spaceflight software frameworks like cFS that do not address the specific challenges of robotic control and robot task development and performance.

Innovative approaches to code quality verification and validation, new software architecture designs, and novel software interfaces are needed to accelerate infusion of autonomous robotic capabilities into flight applications. The lack of such solutions has led to a dramatic underutilization of terrestrial robotic and autonomy technologies in space. Recent work toward developing SpaceROS and ROS-cFS bridge software has exposed multiple gaps in existing technology that must be addressed to successfully field such software frameworks and realize the desired benefits of interoperability and extensibility called for within NASA's Moon-to-Mars recurring tenets.

Relevance / Science Traceability:

This scope represents an enabling capability for rapid software infusion for advanced robotic capabilities across a broad range of potential missions. The needs for interoperability, common interfaces, and extensibility are explicitly highlighted in NASA's Moon-to-Mars objectives, and the pursuit of such software tools and frameworks would serve to broaden industry collaboration and commercial access to lunar surface and deep space applications (again, in support of Agency recurring tenets).

Producing software frameworks and standard interfaces specifically geared toward autonomous and robotic capabilities is highlighted as a need in the current Extravehicular Activity (EVA) and Human Surface Mobility (HSM) Program (EHP) Autonomous Mobility and Operations Roadmap, and technologies within this scope would enable rapid integration of terrestrial technology in support of lunar surface infrastructure and cislunar in-space servicing, assembly, and manufacturing (ISAM) needs.

References:

1. Space Robot Operating System: https://space.ros.org/ and https://techport.nasa.gov/view/116403
2. FreeRTOS: https://www.freertos.org/RTOS.html
3. SAFERTOS: https://www.highintegritysystems.com/safertos/
4. ROS-Industrial: https://rosindustrial.org/

TX05: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

This area covers technologies for transferring commands, spacecraft telemetry, mission data, and voice for human exploration missions, while maintaining accurate timing and providing navigation support. Orbital debris can be tracked and characterized by some of the same systems used for spacecraft communications and navigation, as well as by other specialized systems.

A2.01 Flight Test and Measurement Technologies (SBIR)

Related Subtopic Pointers: T8.06
Lead Center: AFRC
Participating Center(s): ARC, GRC, LaRC

Subtopic Introduction:

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.

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 flight measurement sensors, wired or wireless, high-acquisition-rate data interrogators, as well as ruggedized sensors and health monitoring systems for flight applications.

- Measurement technologies for in-flight steady and unsteady aerodynamics, juncture flow measurements, propulsion airframe integration, structural dynamics, stability, and control related to turbulence, and propulsion system performance in order to validate and improve flight modeling for next-generation conventional, short, and vertical takeoff and landing (CTOL, STOL, and VTOL) vehicles.
- Prognostic and intelligent vehicle health monitoring for hybrid and/or all-electric propulsion systems.

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), Revolutionary Vertical Lift Technology (RVLT), and Hypersonic Technology Project (HTP), 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.

For single longitudinal mode continuously tunable laser systems, the current state of the art can either utilize an external cavity setup that involves a mechanically swept-tuned laser that is susceptible to vibration or an electronically tunable laser that will mode-hop at low bandwidth range (for a couple of nanometers of tuning range). A desirable laser is an electrically tuned laser that can sustain 10 nm of tuning range while maintaining single mode throughout the sweeping range.

For high-gain signal conditioning systems, the current state of the art for these systems has the bandwidth and data storage capability but is somewhat limited in anti-alias filtering capabilities. For example, some of the off-the-shelf options for high-bandwidth systems may be limited in gain up to only 1,000x or have no options to adjust gains. Freestream measurements in quiescent flow may require up to 32,000x gain.

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. Also, the technologies could support IASP and EPFD projects, as well as CST and RVLT projects and the AETC Portfolio Office. Potential hardware from this solicitation will provide improved measurement capabilities that can be implemented in flight experiments.

References:

1. 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
2. NASA Armstrong Fact Sheet: Fiber Optic Sensing System:https://www.nasa.gov/centers-and-facilities/armstrong/fiber-optic-sensing-technology-providing-data-every-quarter-inch-of-the-way/
3. Schlieren Images Reveal Supersonic Shock Waves: https://www.nasa.gov/image-article/schlieren-images-reveal-supersonic-shock-waves-4/
4. NASA’s Commercial Supersonic Technology (CST) Project: https://www.nasa.gov/aeroresearch/programs/aavp/cst
5. NASA’s Revolutionary Vertical Lift Technology (RVLT) Project: https://www.nasa.gov/aeroresearch/programs/aavp/rvlt
6. NASA’s Aerosciences Evaluation and Test Capabilities (AETC) Portfolio Office: https://www.nasa.gov/aetc

Scope Title: Time, Space, and Position Information and Radar Technologies

Scope Description:

Background
The Dryden Aeronautical Test Range (DATR) employs two RIR-716 instrumentation radar systems to provide high-accuracy position information by utilizing C-Band beacon and skin tracking. This “Time, Space and Position Information” or TSPI is used in various ways for flight test projects. Notably, the high-accuracy tracking provides space-based vehicle navigation information to navigators at Johnson Space Center during orbital support. For aeronautical missions, C-band beacon tracking provides real-time and recorded data for post-analysis by Armstrong engineers. Skin tracking allows for a completely independent source of TSPI data, which can satisfy a Range Safety requirement when unpiloted vehicles operate in our controlled airspace, provided the radar cross-section is adequate for skin tracking. The RIR-716 radar systems can be described in two parts: the control console and data processing portion, and the RF or transmit and receive portion. The RF components and the physical pedestals and reflectors are in excellent condition. Periodic overhaul has been accomplished per the manufacturer's recommendation.

Problem State

The control console and data processing portions systems were last upgraded in the 1990s. They are now aging, obsolete, and failing. The system utilizes a very old Virtual Machine Environment (VME) architecture, wire-wrapped circuit boards, and many other analog components that are no longer available to purchase or to find in surplus. There are several single-point-of-failure components that, if failed, would render the entire radar system unusable.

The manufacturer (BAE) has a standing upgrade program to address the aging parts of our systems. That upgrade is expensive (>$3M per radar). This upgrade program has not gained a lot of traction among users because of the perception that it is a minimally acceptable upgrade. Other companies have RIR-716 upgrade programs, some in C-Band, others in X-Band.

At the core of the DATR's radar dilemma is the lack of solid programmatic requirements to justify an investment of any large amount. Utilization has steadily decreased over the last decade and fewer customers are reaching out for availability. The use of various GPS-based products has supplanted the use of a high-accuracy tracker.

The DATR is looking for new sources of TSPI data that can support aeronautical projects and potentially astronautical projects as well. The equipment that provides this data should be cost-effective, robust, and based on current or future technologies that are not hindered by supply chain issues (e.g., using parts that are no longer in production).

The highest priority will be given to systems/proposals that address the following:

- Independent source of TSPI from the tracked object in real time (>/= 10 samples/sec) and archived for post-processing. TSPI systems for conducting range safety of Class 3 UAS and greater sized air vehicles in any attitude, heading, altitude and speed within the DATR are sought.
- Performance equal to or greater than current RIR-716 systems and Range Commanders Council (RCC) Standard 167-95, also low maintenance and upgradeable.

Any innovative approach should be able to track and provide TSPI data for current and future air vehicles for the independent source range safety function.

Additionally, these new sources of TSPI data should consider additional challenges, such as ease of deployment, low maintenance, and an open software architecture to easily allow for future capabilities. Other considerations would include maintenance cycles. Is this a system that is upgradeable; does this system depend on mechanical parts that will wear over time?

Expected TRL or TRL Range at completion of the Project: 4 to 7

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:

- Research
- Analysis

- Prototype
- Hardware
- Software

Desired Deliverables Description:

For the Phase I effort, the small business is expected to provide a mid-term report outlining the analysis and technology investigation thus far. A summary report is expected at the end of Phase I describing the results of the analysis and feasibility of applying innovative solutions.

For the Phase II effort, the small business is expected to present a demonstrable technology or technologies that meets or exceeds the specifications outlined, as baseline standards. In addition, an implementation plan for hardware and software that can be tested by NASA is desired.

State of the Art and Critical Gaps:

Current TSPI solutions across flight test ranges generally come from two types of sources: GPS-based and radar tracking. When critical range safety concerns arise, sources independent of the flight-test vehicle are required. Tracking radars have been the standard for independent, high-accuracy TSPI data for decades. GPS-based systems have been implemented in various ways, but almost always rely on the test vehicle's data system to provide the needed TSPI data. Non-independent sources of data pose additional risk to range safety.
Fidelity of the data used for post-processing and engineering analysis creates another set of challenges when developing alternative sources of TSPI data. RADAR data provides high-fidelity, and dGPS sources do as well.

There are critical gaps between the two general groups of data, and a single, lower-cost solution, independent of flight test vehicle could fill those gaps. While GPS-based solutions exist in abundance, truly independent sources are less available. Commercial off-the-shelf (COTS) solutions that provide performance for vehicles traveling beyond Mach 1.0 are also less available.

Relevance / Science Traceability:

The technologies produced for this subtopic directly address the current and ongoing need for high-accuracy TSPI data sources for the Armstrong and greater NASA Aeronautics flight test programs. Innovation in this area would greatly simplify operations, and drastically reduce operational and maintenance costs for ranges currently dependent on radar tracking systems.

References:

1. 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
2. Dryden Aeronautical Test Range Overview: https://www.nasa.gov/aeroresearch/programs/iasp/fdc/datr

H9.03 Flight Dynamics and Navigation Technologies (SBIR)

Related Subtopic Pointers: T8.06
Lead Center: GSFC

Participating Center(s): JPL, JSC, MSFC

Subtopic Introduction:

NASA is planning and proposing increasingly ambitious missions such as crewed and uncrewed 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. 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 explore trade spaces more fully and more quickly respond to changes in the mission.

Future NASA missions require precision landing, rendezvous and proximity operations, noncooperative object capture, formation flying, constellation design, 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 assets in the near-Earth and cislunar environment. The NASA Conjunction Assessment Risk Analysis (CARA) program determines the risk posed by close approach events (conjunctions) between NASA satellites and other space objects as predicted by operators at the Vandenberg Space Force Base, and recommends risk mitigation strategies, including collision avoidance maneuvers, to spacecraft owners/operators to use to protect space assets and prevent the proliferation of space debris. The ability to perform close approach risk assessment and mitigation 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.
- Anytime abort (return to Earth) for crewed spaceflight missions (e.g., from the lunar surface or a near rectilinear halo orbit).
- Low-thrust spiral trajectories that account for eclipsing and perturbing forces.
- Distributed coordinated multi-spacecraft constellation design.

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.
- Exploration of optimal solutions within large trade spaces that trade common mission design parameters (i.e., launch date, launch mass, time of flight, etc.).

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., multi-moon/multibody tours and low thrust), and/or provide initial guesses that can be used to improve convergence of complex trajectories in an 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 Toolkit Environment (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 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. Copernicus, https://software.nasa.gov/software/MSC-26673-1, https://www.nasa.gov/centers/johnson/copernicus/index.html
5. Mission Analysis Low-Thrust Optimization (MALTO), https://software.nasa.gov/software/NPO-43625-1
6. Mission Analysis, Operations, and Navigation Toolkit Environment (MONTE), https://montepy.jpl.nasa.gov/

Scope Title: Autonomous Onboard Spacecraft Navigation and Guidance

Scope Description:

Future human and robotic lunar, Mars, and small-body 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) as well as Distributed Systems Missions (DSMs) require rendezvous, precision formation flying, proximity operations, noncooperative object capture, and coordinated spacecraft navigation and guidance 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 (HLSs), 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 efficient algorithms and software that can be run onboard a spacecraft 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 at unmapped bodies without a long survey/mapping phase and can operate 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) and guidance algorithms and software, which support cooperative and collaborative multi-spacecraft operations.
- Autonomous onboard mission design and trajectory planning for crewed and uncrewed missions. For crewed missions a loss-of-communication scenario in cislunar space could require potentially complex multiburn transfer trajectory solutions to return to Earth without inputs from ground controllers. This includes onboard trajectory optimization and analytical or semi-analytical methods to seed optimization or guidance algorithms. Uncrewed missions may require the autonomous computation of maneuvers to maintain or reconfigure a formation of spacecraft.

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, GIANT, 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 and guidance 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).
- Starshade (planned to fly in coordination with the Roman Space Telescope).

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://nexis.gsfc.nasa.gov/osam-1.html, https://www.nasa.gov/mission_pages/tdm/osam-2.html
3. LunaNet, https://esc.gsfc.nasa.gov/news/_LunaNetConcept
4. GIANT, https://github.com/nasa/giant

5. 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 27,000 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 program is responsible for protecting NASA assets from collision with other objects by submitting owner/operator trajectory information for the protected spacecraft, including predicted maneuvers, to operators 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). Unlike Earth-orbiting objects, deep space spacecraft are not tracked by the Space Surveillance Network, and all trajectory data for them must be provided by their respective navigation teams that compute orbits based on tracking data obtained from a suitable deep space antenna and provide the orbit determination solution to MADCAP for screening of close approaches against other objects orbiting the same point.

Because neither CARA nor MADCAP produces ephemeris data for the NASA-protected assets or the cataloged objects, the orbit determination aspect of the problem is not of interest in this subtopic. Additionally, CARA does not control the screening process and therefore is not looking for solutions in that area. Only the conjunction assessment (CA) risk analysis 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. Several concerns with the use of the Pc; however, have been identified, including “diluted” probability (see Reference 2), “false confidence” (see Reference 3), and “statistically biased” (see Reference 15). 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 to emerge with a range or Probability Density Function (PDF) of possible collision probabilities, or some other parameter that takes account of these uncertainties. Parameter uncertainties to consider include space weather, atmospheric density, solar radiation pressure,

object effective area, empirical covariance scale factors, etc. 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 19th Space Defense Squadron (19 SDS) process (see Space-Track.org). 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, it is sometimes necessary to analyze 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 accessible via a website platform and would have the ability to be packaged and sent out as an email summarizing 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 6

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 missions in the near-Earth, cislunar, lunar, and other solar system 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.

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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, https://www.nasa.gov/sites/default/files/atoms/files/an_updated_process_for_automated_deepspace_conjunction_assessment.pdf
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H9.08 Lunar 3GPP Technologies (SBIR)

Related Subtopic Pointers: T8.06
Lead Center: GRC
Participating Center(s): JSC

Subtopic Introduction:

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) subtopic focuses on any aspect of network development that may enhance capabilities for operating 3GPP networks in service of the Artemis program. This may include 3GPP compatible hardware that can operate in space and on the lunar surface, channel modeling, and emulation pertinent to operation of 3GPP networks on the lunar surface, advances in 3GPP waveforms beneficial to deployment of lunar networks, and/or demonstration of Non-Terrestrial Networking (NTN) capabilities applicable to use from lunar orbit to the lunar surface.

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 for 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 multiprotocol (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 with 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 Level [TRL] 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 of prototype hardware/software is encouraged.

Phase II will emphasize hardware/software/waveform/model development with delivery of a 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 (Commercial Lunar Payload Services (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 and 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:

1. 2020 NASA Technology Taxonomy: https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy.pdf
2. LunaNet Interoperability Specification: https://www.nasa.gov/sites/default/files/atoms/files/lunanet_interoperability_specification_version_4.pdf
3. International Communications System Interoperability Standards (ICSIS): https://nasasitebuilder.nasawestprime.com/idss2/wp-content/uploads/sites/45/2020/10/communication_reva_final_9-2020.pdf
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TX06: Human Health, Life Support, and Habitation Systems

This area covers technologies that are specific to the human element and those that directly affect crew needs for survival and wellbeing, including the environment and interfaces that crew encounter.

H12.08 High-Throughput Platform for Identification of Senescence Altering Therapeutics Post Space Radiation Exposure (SBIR)

Lead Center: JSC
Participating Center(s):

Subtopic Introduction:

Space radiation is a significant obstacle when sending humans on long-duration missions beyond low-Earth orbit (BLEO). Although various forms of radiation exist in space, BLEO astronauts will be constantly exposed to galactic cosmic radiation, which consists of high-energy particles ranging from protons to extremely heavy ions. The resulting astronaut health risks from space radiation exposure include carcinogenesis, late and early central nervous system (CNS) effects, and degenerative risks, which include cardiovascular diseases (CVD) and maladies related to premature aging. Cellular senescence is the process by which cells undergo reproductive mortality but remain metabolically active within tissues. Recent discoveries, including that of the Senescence Associated Secretory Pathway (SASP), suggest a role for senescent cells in the processes of carcinogenesis and in age-related pathologies such as cognitive degeneration and cardiac decline. As such, using countermeasures (CMs) to target senescence is a promising approach to prevent radiation-induced health risks.

Scope Title: High-Throughput Platform for Identification of Senescence-Altering Therapeutics Post Space Radiation Exposure

Scope Description:

This scope solicits proposals to identify a high-throughput CM screening platform that quantifies the effectiveness of CMs in reducing the consequences of and/or number of senescent cells in ionized irradiated cells, tissues, or surrogate models relevant to space exploration. A successful application would identify a screening platform capable of high-throughput capacity (96-well plate or superior/alternative throughput) using imaging-based cytometry or comparable techniques. Also desired is a proof of principle demonstration that CMs targeting senescent pathways (senolytic drugs, gene editing, gene therapy, biomolecule-based alternative methodologies, etc.) are effective against ionizing radiation (IR).
In Phase I of the project, the efficacy and sensitivity of the platform in measuring radiation-induced senescence as well as a known senescence-modifying therapy in conjunction with IR should be demonstrated. Required deliverables for the Phase I will be: 1) data generated from the platform demonstrating sensitivity to changes in IR-induced cellular senescence in a high-throughput capacity, and 2) data demonstrating that a known senescence-modulating intervention can be screened. This testing can be done with cell models at the location of choice using y rays, x rays, and/or proton irradiation and do not require irradiation using high-energy and charged ions. After contract award, due to the nature of this research, the contractor should immediately coordinate with their technical monitor for any special considerations for testing and guidance on relevant radiation doses. In Phase II of the project, we would expect testing to be expanded to include combinations of different particles and energies that better simulate the space radiation environment.

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

Primary Technology Taxonomy:

- Level 1: TX 06 Human Health, Life Support, and Habitation Systems
- Level 2: TX 06.5 Radiation

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

Required deliverables for Phase I will be: 1) data generated from the platform to demonstrate sensitivity to changes in IR-induced cellular senescence in a high-throughput capacity, and 2) data demonstrating that a known senescence-modulating intervention can be screened. Phase I will demonstrate a platform for assessing, in a high-throughput capacity, the ability to screen therapeutics for the potential use of reducing the long-term health impacts of IR-induced senescence. Phase II will identify CM approaches using the platform established in Phase I to reduce the consequences of cellular senescence arising from space radiation exposures. A test plan for in vivo evaluation that describes the expected effect from the therapeutic should be included. Access and funding to support testing in space radiation simulated facilities will be provided for Phase II in addition to the standard award.

State of the Art and Critical Gaps:

Exposure of crewmembers to space radiation during lunar and Mars missions can potentially impact the success of the missions and cause long-term decrements. Space radiation risks include cancer, late and early central nervous system (CNS) effects, cardiovascular diseases (CVD), and accelerated aging. This subtopic addresses the development of a screening technique to identity CMs that can reduce senescent cell population or SASPs and thus the potential to mitigate one or several of the identified space radiation risks. Countermeasures for adverse health effects from radiation exposure are of interest to the Department of Defense (DoD), the Department of Homeland Security (DHS), and the radiation therapy community as well.

Relevance / Science Traceability:

This subtopic seeks technology development that benefits the Space Radiation Element of the NASA Human Research Program (HRP). Senescent cell populations are rapidly becoming a subject of concern regarding not only degenerative disease but also diseases as diverse as cancer and diabetes. Potential benefits and interventional, therapeutic approaches can help to identify new modalities to improve long-term health outcomes arising from space radiation exposure.

References:

The following references discuss the different health effects NASA has identified in regard to space radiation exposure:

1. Evidence report on central nervous systems effects: https://humanresearchroadmap.nasa.gov/evidence/reports/CNS.pdf
2. Evidence report on degenerative tissue effects: https://humanresearchroadmap.nasa.gov/evidence/reports/Degen.pdf
3. Evidence report on carcinogenesis: https://humanresearchroadmap.nasa.gov/evidence/reports/Cancer.pdf

H3.11 Spacecraft Water Recycling Systems for Short Duration Human Exploration Missions (SBIR)

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

Subtopic Introduction:

The development of a new class of lightweight, low-power and low-volume water recovery systems that will allow for high-efficiency recycling of spacecraft wastewater into potable water is needed. These systems would be intended for short-duration human exploration missions using landers and pressurized rovers with limited capacity to support conventional large-scale regenerative life support technologies. In addition, these new lightweight, high-efficiency systems may be useful for contingencies and/or as backup systems for longer duration missions employing more conventional spacecraft water recovery systems.

Baselined mission elements for early lunar and Mars missions, such as landers, habitats and rovers, are not likely to have water recovery capability. Analysis indicates that the incorporation of water recovery and reuse has a significant benefit in mission resupply costs and logistics, even for short-duration missions of up to 30 days. The current state-of-the-art (SOA) spacecraft water recovery system in use on the International Space Station (ISS) is a heavy, large, power-intensive system that's not well-suited for short-duration missions, for vehicles with minimal space and/or support infrastructure, or for the reliability needed to transition into and out of long periods of dormancy.

The development of a new class of spacecraft water recovery systems designed for short-duration missions is expected to fill a significant gap in NASA's Moon-to-Mars System Architecture by enhancing and/or enabling lunar and Mars exploration through significant reductions in the mass of resupply water needed to support these missions. These technologies also align with several NASA Center strategies to develop and test integrated water recovery systems for micro- and partial-gravity spacecraft.

Scope Title: Spacecraft Water Recycling Systems for Short-Duration Human Exploration Missions

Scope Description:

NASA is soliciting proposals for water recycling systems for short-duration missions ranging from days to up to several months. Of primary interest are systems to recover potable water from humidity condensate generated within the spacecraft cabin atmosphere. However, the recovery of other spacecraft waste streams, including urine, are also of interest. As such, proposed design solutions can focus on the recovery of water from humidity condensate alone, humidity condensate and urine as separate waste streams, and/or humidity condensate and urine as a mixed waste stream. Systems should be targeted for early phases of NASA’s Moon-to-Mars campaign and be designed for water recovery applications in vehicles associated with the Artemis missions, Gateway, lunar and Mars habitats, landers, and pressurized rovers. The interfaces and infrastructure to support water recovery on these early-phase vehicle platforms should be considered minimal. Designs should have an eye toward systems that can operate standalone, with concepts of operations that include system interfaces, fluid transfer, storage, processing, and waste disposal. Systems capable of being easily integrated late into a mission architecture and/or a vehicle design cycle would be highly desirable. The ideal system would be lightweight and low volume, have a long storage life, be generally “passive” (consuming little to no power), and requiring minimal crew time to operate. Systems should be able to treat up to a four-person crew load for up to at least one month (see requirements below). Systems should have considerations for how to transition into and out of dormancy that include return to full service and generating potable water with minimal effort after being left idle for periods of up to one year. Consumables should be minimized. Simplicity of design is highly desired and disposable systems are acceptable, provided system mass, including any consumables, can be shown to have a highly favorable trade relative to the mass of water recovered.
Some performance metrics and goals to include or to consider:

1. Simplicity of design, low maintenance requirements, minimal need for crew interaction, and high system reliability.
2. Lightweight systems. Equipment mass, including consumables, must be no more than a small fraction of the amount of water recycled.
3. Ability to process humidity condensate to potable water. (See Ref. 5 for estimates of the major constituents in humidity condensate.) (See Ref. 3 for spacecraft potable water quality standards.)
4. Ability to process human urine wastewater to potable water, (See Ref. 4 for estimates of the major constituents in urine.)
5. Capable of processing up to 2.5 kg/crewmember-day for humidity condensate and/or approximately 2.0 kg/crewmember-day of urine, with typical crew sizes of from two to four persons.
6. Minimal requirements for vehicle integration (i.e., would allow for easy implementation within a vehicle platform with little to no vehicle or system modification).

7. Use of low-toxicity processes and/or chemicals (e.g., pH > 2 and avoiding use of strong oxidizers, carcinogens, etc.
8. System data should be provided on expected recovery of processed water and the purity of the water to be produced. Preferred solutions should meet NASA potable water specifications. This includes meeting microbial limits: Bacterial Counts < 50 CFU/mL, Coliform Counts (CFU/100 ml) - non-detect, and removal of protozoa, as well as chemical limits for organic and inorganic contaminants, (See Refs. 3 and 4, Appendix 1.)
9. Proposed system should consider a concept of operation, including other vehicle system interfaces and, if needed, requirements for monitoring and control for both nominal systems use and for strategies for transition into and out of dormancy.
10. Proposals should provide estimates of mass, crew time, consumables and resupply, power, mass, volume, and cooling requirements.
11. System analysis should include how the system scales with respect to number of crew and or amount of water processed.
12. Proposed systems should provide a potential list of planned components, including materials of construction, especially wetted materials.
13. System hazards should be considered and identified and, where appropriate, concepts for proposed mitigation strategies provided.

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

Primary Technology Taxonomy:

- Level 1: TX 06 Human Health, Life Support, and Habitation Systems
- Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I Deliverables—Reports demonstrating proof of concept, test data from proof-of-concept studies and concepts and designs for Phase II. Phase I tasks should address critical questions focused on reducing development risk prior to entering Phase II. The final report should include a plan or strategy that explains in detail the approach for providing a solution for short-duration, lightweight, water recovery systems for exploration.

Phase II Deliverables—Delivery of technologically mature components/subsystems that demonstrate performance over the range of expected spacecraft conditions. Prototypes must be full scale. Robustness must be demonstrated with long-term operation and with periods of intermittent dormancy. Systems and chemical agents should incorporate safety and design features to provide safe operation upon delivery to a NASA facility. Deliverables shall include complete documentation, including an operating manual, technical data sheets with detailed description and composition of the material or product, testing methods and test data, design sketches or drawings, and full information on material and/or chemical sourcing. The

Phase II deliverables shall also include a final report documenting all work accomplished for the Phase II effort and shall not duplicate the Phase II proposal.

State of the Art and Critical Gaps:

State of the Art (SOA) water recovery systems for human spacecraft were specifically designed for water recovery from waste streams typical of the operations on the International Space Station (ISS) (Ref. 7). They are large, heavy, and power intensive. The SOA systems were designed for continuous operations, have not been proven for use after long periods of dormancy, and were not designed for repairability except by replacement of large orbital replacement units (ORUs). Future missions are expected to have a broad range of wastewater, have crewed mission increments that are relatively short in duration, have long periods of dormancy, and have mission elements that lack the infrastructure to support the SOA water recovery systems. A new class of low-power, mass and volume water recovery systems are envisioned for short-duration water recovery to fit the gap associated with these specific near-term mission profiles. In addition, these technologies could serve for contingencies or backup to primary systems for use on longer duration missions with full recycling.

This technology need addresses several potential gaps under the Systems Capability Leadership Team (SCLT) Environmental Control and Life Support (ECLSS) Roadmap for Water and Wastewater Processing. including: STPRT #1011 “Water Recovery System for Surface Missions (lunar and Mars)”, STPRT #984 “Robust Advanced Water Recovery System” and #867 “Water Recovery Mitigation for Dormant Periods.” Fulfillment of these gaps would be considered enhancing or enabling for lunar exploration where limited resupply may be tolerated and depending on mass constraints for a specific vehicle element. For lunar missions, however, any mass savings will benefit other mission objectives, including science. For Mars exploration, where resupply will be highly restrictive, these systems could be potentially enabling. If these gaps are not closed, mission requirements for water resupply will be considerable and possibly even mission limiting.

Relevance / Science Traceability:

Water recovery technologies for short-duration missions will be useful for all phases of NASA’s Moon-to-Mars campaign. Initial missions to the lunar surface are expected to be approximately 30 days in duration and occur on a yearly basis. These short-duration water recovery systems could be deployed in the lander, pressurized rover, and habitats. These systems are also relevant to Gateway, which also will initially be inhabited on a short-term basis. These short-duration water recovery technologies will also be applicable to surface assets on Mars, given our initial human missions may have short stays and be supported only by rovers for the early missions. However, these systems could also be used for contingencies and backup systems for long-duration habitats, orbital stations, and transit vehicles. NASA's Exploration Systems Development Mission Directorate (ESDMD) manages the human exploration system development for lunar orbital, lunar surface, and Mars exploration. Programs in the mission directorate include Orion, Space Launch System, Exploration Ground Systems, Gateway, Human Landing System, exploration Extravehicular Activity (xEVA), and Human Surface Mobility. Many of the future near-term mission campaigns call for short-duration crew stays with long periods of dormancy, especially as related to Gateway, lunar, and Mars surface missions. Early missions will involve EVAs and high crew mobility by way of rovers. Water consumption rates to provide cooling and potable water for these systems are very high. At the same time, many of these early mission assets will lack the interface and/or infrastructure requirements to support the SOA water systems. A new class of short-duration, low-mass, low-power, and low-volume water recovery systems are warranted to help conserve water supplies, ease the cost and logistics, and to tolerate the long periods of dormancy associated with these early mission classes.

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H3.12 Quiet and efficient fans for spacecraft cabin ventilation (SBIR)

Lead Center: JSC
Participating Center(s): GRC

Subtopic Introduction:

It is important to control acoustical noise aboard crewed space vehicles and space habitats to provide a satisfactory environment for voice communications, alarm audibility, and restful sleep, and to minimize the risk for hearing loss and annoyance. As with most noise control efforts, it is best to control the noise at the source; for spaceflight vehicles, these are typically the fans associated with the Environmental Control and Life Support (ECLS) system. These include ventilation fans, such as the main air conditioning fan (the cabin fan), intermodule ventilation (IMV) fans, air revitalization fans (for removal of carbon dioxide and trace contaminates), and thermal cooling fans.

Throughout the history of crewed spaceflight, there have been issues with noise from ECLS ventilation fans. In the Apollo Command Module (CM), the crew would turn off the CM cabin fan once in orbit and use the backup suit-loop fan for ventilation because noise from the cabin fan interfered with communications and was an annoyance. On the Space Shuttle, the ventilation system underwent significant redesign, including the addition of ventilation system mufflers, with resulting noise levels that were still too high for long-duration missions. In the early years of International Space Station (ISS) operations, acoustical noise in the Russian Segment was one of the top two habitability issues, resulting in significant noise controls being implemented on-orbit (along with significant cost and crew-time impacts) on many fans. Significant noise reductions were only realized after replacing noisy fans with fans of a quieter design, funded by the ISS Program. Noise levels in the ISS U.S. Segment were well controlled, mostly meeting requirements, although significant mass and volume were allocated for noise controls, including mufflers/silencers and acoustically treated duct-lining.

With the spaceflight vehicles and habitats currently being developed, there are again concerns with noise levels from ventilation fans. In the Orion vehicle, additional duct mufflers needed to be added to address the cabin fan noise. The Gateway's Habitation and Logistics Outpost (HALO) module and low-Earth orbit (LEO) Freeflyer habitats are currently working to solve this problem. This will also be an issue for lunar and Mars spaceflight vehicles, space suits, and surface habitats.

In an effort to address this problem, NASA is working to leverage the technology developed in its Aeronautics Research Mission Directorate (ARMD), specifically at the Glenn Research Center (GRC), to design highly efficient and quiet fans for reducing community noise levels from civilian aircraft. This technology was created over decades of research and development and was proven to be effective at reducing aircraft noise levels. The current collaboration across NASA Centers, including Headquarters, GRC, and Johnson Space Center (JSC) in this area is the first effort at repurposing these tools (i.e., design codes and techniques, developed for high Reynolds number fans, to spaceflight vehicle and habitat, small, lightweight, low Reynolds number, fans). This effort has resulted in the NASA Spacecraft Cabin Ventilation Fan, which is to be used as the baseline for this SBIR project effort, requesting small businesses to improve upon this technology and demonstrate these improvements. Additionally, these improvements can benefit the public given that quiet, efficient fans are also needed for ventilation systems in aircraft, watercraft, land vehicles, and buildings.

Scope Title: Quiet and Efficient Fans for Spacecraft Ventilation Systems

Scope Description:

Using NASA's Spacecraft Cabin Ventilation Fan as a baseline, improvements to maximize fan efficiency and operational life while minimizing noise, weight, and size are sought. NASA's Spacecraft Cabin Ventilation Fan is described in a set of reports publicly available on the NASA Technical Report Server and is to be used as the baseline to show improvements in measured performance (same or better efficiency) and noise emissions (at least a 5 dB improvement from the 66 dB Overall Sound Pressure Level, measured at 2-ft distance from inlet of the fan, as described in Ref. [8]), at the same design point, by comparison. This fan was intended for use with air at a pressure of 14.7 psi at 70 °F. At design point conditions, the design goal flow rate was 150.3 cfm and the design goal total pressure rise was 3.64 inches of water. At the design point, this fan had an efficiency of 75% and produced an overall sound pressure level (OASPL) of 66 dB, measured 2 ft from the inlet. Other design goals for the fan are summarized in Table 1 of NASA Conference Report 20230003262, "A Study of Preliminary Design Method for Low Noise Fans," https://ntrs.nasa.gov/citations/20230003262. The geometry and solid model files for this fan, to be used for development of a baseline fan for this solicitation, are provided as supplementary materials for this NASA Technical Memorandum: "Highlights of Aeroacoustic Tests of a Metal Spacecraft Cabin Ventilation Fan Prototype," NASA TM 20220012622, 2022, https://ntrs.nasa.gov/citations/20220012622. See References for further information. Although the design point of this fan is 14.7 psia, testing at 8.2 psia should also be performed to characterize and understand extensibility to vehicles and habitats of the cislunar and Mars transit architecture. If successful, infusion has high probability, regardless of NASA exploration architecture, and into commercial space.

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

Primary Technology Taxonomy:

- Level 1: TX 06 Human Health, Life Support, and Habitation Systems
- Level 2: TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

Desired Deliverables of Phase I and Phase II:

- Prototype
- Analysis

Desired Deliverables Description:

Phase I deliverables would consist of a fan design (for the same design point as the baseline fan) with relevant aerodynamic and acoustic predictions and mechanical, electrical, and thermal analyses.
Phase II deliverables would consist of a working prototype fan and measurements with comparisons to predicted aerodynamic and acoustic performance from Phase 1, and also comparisons of measurements and predictions to the published aerodynamic and acoustic performance of NASA's Spacecraft Cabin Ventilation Fan (the baseline for this SBIR project); see References. Measurement comparisons to the baseline (with air at a pressure of 14.7 psi and temperature of 70 °F) should show improvements in measured performance (same or better efficiency) and noise emissions (at least 5 dB improvement from the 66 dB Overall Sound Pressure Level, measured at 2-ft distance from inlet of the fan, described in the Sutliff paper, Ref. [8]), at the same design point. This fan is intended for use with air at a pressure of 14.7 psi; however, aerodynamic and acoustic testing at 8.2 psia is also to be performed and reported to characterize and understand extensibility to vehicles and habitats of the cis-lunar and Mars transit architecture.

State of the Art and Critical Gaps:

Current cabin ventilation fans, with duct-borne sound power levels of 80 dB, are too loud and require a significant amount of noise controls to meet crew-cabin acoustic requirements. Development of prime mover ventilation fans that produce duct-borne sound power levels <70 dB without acoustic treatment, is desired in order to meet crew-cabin acoustic requirements.

For this SBIR project, the figure of merit will be that the measurement comparisons to baseline should show improvements in measured performance (same or better efficiency) and noise emissions (at least 5 dB improvement from the 66 dB Overall Sound Pressure Level, measured at 2-ft distance from inlet of the fan, as described in Ref. [8]), at the same design point.

Relevance / Science Traceability:

All NASA and commercial space flight vehicle programs would benefit from this technology. These include ISS, Orion, Gateway, Human Landing System (HLS), and Commercial LEO Destination Program (CLDP), including Commercial Destination Free-flyer (CDFF) and Commercial Destination ISS (CDISS) programs. This technology can also be used for lunar and Mars surface habitats, as well as the Mars Transfer Vehicle, and Lunar/Mars Pressurized Rovers. Successful operations from 14.7 psia to 8.2 psia, in exploration atmospheres, would provide extensibility to vehicles and habitats of the cislunar and Mars transit architecture. If successful, infusion has high probability, regardless of NASA exploration architecture and into commercial space.

References:

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[8] Sutliff, D., "Quiet Spacecraft Cabin Ventilation Fan: Acoustic Measurements Results," 2023, https://ntrs.nasa.gov/citations/20230006061

H4.09 Long-Duration Exploration Portable Life Support System (PLSS) Capabilities (SBIR)

Lead Center: JSC
Participating Center(s):

Subtopic Introduction:

A spacesuit needs to function properly and for extended periods of time during long-duration exploration missions to allow an astronaut to work efficiently on the surface of the Moon or on Mars. The focus for long-duration PLSS capabilities centers on non-venting CO_2/H_2O removal from the ventilation loop and non-venting heat rejection from the suit thermal control loop. The technology innovations are needed in the following focus areas:

1. Non-Venting CO_2/H_2O Sequestration.
2. Condensing Heat Exchanger (CHX) With Gravitational Field (g-Field) Independent Slurper.
3. Non-Venting Heat Rejection for Mars Atmosphere.
4. Continuous CO_2 Removal Capable of Operating in Mars Atmosphere and Vacuum.

Scope Title: Long-Duration Exploration Portable Life Support System (PLSS) Capabilities

Scope Description:

Innovative designs for PLSS are sought to enable future long-duration missions to the Moon and Mars.

1. Non-Venting CO_2/H_2O Sequestration.
For long-duration Exploration PLSSs supporting both long-term lunar and Mars operations, the need to save the water released from the human operator during an extravehicular activity (EVA) increases with the EVA count and mission duration as water is not readily available from the environment. Non-venting carbon dioxide (CO_2)/water (H_2O) sequestration would seek to mount within the PLSS, sequester

CO_2/H_2O from the ventilation loop of the suit, which is closed and circulated by a fan keeping the outlet CO_2/H_2O levels low for subsequent return of the gas to the suit volume. Upon completion of the EVA, the recovered water and CO_2 could be regenerated by some mechanism to provide it to the vehicle Environmental Control and Life Support System (ECLSS) for subsequent processing.

Key parameters include:

- CO_2 uptake rates: 2.5 g/min at 1600 BTU/hr and 3.2 g/min at 2000 BTU/hr with outlet gas concentration <2.5 mmHg
- H_2O uptake rates: 2 g/min at 1600 BTU/hr to 2.4 g/min at 2000 BTU/hr (this is limited by the usage of a liquid cooling and ventilation garment in the suit volume) with outlet gas concentration below 50% RH and <45 ºF dew point
- Overall volume constraints with any valve/manifold: W (<10 in.) x H (<8 in.) x D (<5 in.)
- Overall mass constraints: <12 lbm with goal of <6 lbm
- Flow rate through system: 6 acfm (170 lpm)
- Allowable pressure drop: <2 in.-H_2O at 4.3 psia, 6 acfm, 60 ºF
- Operating pressure range: 3.5 to 23.5 psia
- Gas inlet temperature range: 50 to 90 ºF
- Working fluids: air or 100% oxygen
- g-field operations: 1g, 1/6g, 3/8g, microgravity (ug)

2. Condensing Heat Exchanger (CHX) With Gravitational Field (g-Field) Independent Slurper.
For long-duration Exploration PLSSs supporting both long-term lunar and Mars operations, the need to save the water released from the human operator during an EVA increases with the EVA count and mission duration as water is not readily available from the environment. Almost regardless of the selected CO_2 scrubbing option, sequestration, or semi-open loop, a CHX could be used upstream of the CO_2 scrubber to recover. Upon completion of the EVA, the recovered water could be removed from the capture reservoir for processing by the vehicle water reclamation system. Key objectives for this CHX approach include: no coatings* required on the internal surfaces for water handling, operation in varied g-field including microgravity, and passive operation without requirement for sweep gas or differential pressure gradients.

*NOTE: Coatings tend to spall and cause system reliability issues over time.

Key parameters include:

- H_2O uptake rates: 2 g/min at 1600 BTU/hr to 2.4 g/min at 2000 BTU/hr (this is limited by the usage of a liquid cooling and ventilation garment in the suit volume) with outlet gas concentration below 50% RH and <45 ºF dew point
- Overall volume constraints with any valve/manifold: W (<10 in.) x H (<8 in.) x D (<5 in.)
- Overall mass constraints: <2 lbm
- Flow rate through system: 6 acfm (170 lpm)
- Allowable pressure drop: <0.75 in.-H_2O at 4.3 psia, 6 acfm, 60 ºF
- Operating pressure range: 3.5 to 23.5 psia
- Gas inlet temperature range: 50 to 90 ºF
- Working fluids: air or 100% oxygen
- g-field operations: 1g, 1/6g, 3/8g, ug

3. Non-Venting Heat Rejection for Mars Atmosphere.

For long-duration Exploration PLSSs supporting both long-term lunar and Mars operations, the need to minimize or eliminate the water used for evaporative cooling of the spacesuit during an EVA increases with the EVA count and mission duration as water is not readily available from the environment. The state of the art with respect to spacesuit cooling technologies for the past 60 years has been sublimation of feedwater to vacuum with more recent developments using evaporation across a membrane of feedwater to a reduced pressure environment such as vacuum. In both cases, water usage on the order of 5-10+ lbm of feedwater is experienced per EVA to enable the elimination of waste heat from the crewmember, avionics, and environmental inleakage. In order to be more efficient with usage of a limited resource during spacesuit activities, the suit needs to be able to reject heat using means that do not result in such significant water usage.

Peak Heat Rejection: 500 W metabolic waste heat, 100 W avionics waste heat, 100 W inleakage from the environment

Interface to transport loop that removes heat from the system (crewmember and avionics):

- Working fluid: water
- Nominal flow rate: 200 +20/-30 pph
- Allowable pressure drop: <1 psid
- Outlet temperature: <50 °F (10 °C)
- EVA duration: 8 hr
- Nominal heat rejection: 460 W
- Ambient pressure: vacuum to 9 Torr (CO_2)
- Ambient sink: varied
- Volume/form factors: The rear surface of the PLSS is approximately W (23 in.) x H (30 in.) x D (7 in.)
    - The internal volume that could be available if replacing the evaporator:
- Mass limitation: <15 lbm
- Additional consideration given the implementation will relate to fall impact loads should the solution be mounted to the PLSS and subject to contact with objects during a fall during an EVA in 1/6g or 3/8g

4. Continuous CO_2 Removal Capable of Operating in Mars Atmosphere and Vacuum.

For long-duration Exploration PLSSs supporting both long-term lunar and Mars operations, the need to effectively eliminate CO_2 from the ventilation loop while operating in a partial atmosphere such as that on Mars is a challenge that needs to be addressed. This could be done by extending the application of current technologies such as amine swingbeds providing the motive force via thermal swing, mechanical pumping, or other potential options. The challenge facing all of these cases includes the extreme limitations on volume, mass, and power that a spacesuit application offers.

Key parameters include:

- Ambient pressure: < 9 Torr
    - A concept with tolerance of pressures up to 1 atm would greatly simplify the integration and lower the system mass/volume impacts
- Inputs:
    - Hold the input <1.5 Torr with 3.2 g/min CO_2 + 2.4 g/min H_2O continuous at 2000 BTU/hr test condition
    - A concept with tolerance of transient pressures up to 23.5 psia would greatly simplify the integration and lower the system mass/volume impacts

- Electrical interface: 28 VDC
- Power: <25W
- Volume: <50 in^3
- Mass: <4 lbm

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 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I

- Objective: Feasibility assessment for given technology.
- Deliverables: Interim and final reports.

Phase II

- Objective: Prototype that can be integrated into the Exploration Extravehicular Mobiliy Unit (xEMU) Design, Verication, and Test (DVT) unit enabling both component and integrated system testing.
- Deliverables: Interim and final reports along with prototype hardware.

State of the Art and Critical Gaps:

The state-of-the-art PLSS components exist in the current Extravehicular Mobility Unit (EMU) that is in operation on the International Space Station. Gaps exist for spacesuit components to operate on the lunar surface for extended duration and for operation on Mars. The gaps will be defined in the PLSS Roadmap to be released to the public at a workshop planned for FY 2024.

Relevance / Science Traceability:

This technology is planned for future lunar and Mars missions where long-duration stays are required. This work can be traced to the Exploration Systems Development Mission Directorate (ESDMD) and Space Operations Mission Directorate (SOMD). The targeted suit configuration for this subtopic takes innovation beyond the xEMU that was designed, integrated, and tested in house in the EC5/Crew and Thermal Systems Division at the Johnson Space Center.

References:

1. The PLSS Roadmap—To be published in FY 2024 to the public at a NASA-sponsored workshop https://www.nasa.gov/extravehicular-activity-and-human-surface-mobility/

2. The following link will provide access to peer-reviewed papers published at the International Conference on Environmental Systems for technologies developed for the xEMU PLSS prototype in related areas such as the Rapid Cycle Amine CO_2 Removal and the Spacesuit Water Membrane Evaporator for heat rejection: International Conference on Environmental Systems (tdl.org)

H4.10 Materials for Mars Thermal Environment (SBIR)

Lead Center: JSC
Participating Center(s):

Subtopic Introduction:

Thermal insulation is a critical gap to enable operations on the Mars surface. EVA suit thermal insulation is historically accomplished using multiple layers of aluminized Mylar(R) film (multilayer insulation or MLI). These layers reflect incident solar radiation away from the suit's inner layers and greatly reduce touch temperatures inside the suit and the thermal burden to the suit's life support system. This solution is effective for vacuum environments like low-Earth orbit and the Moon, but it is not effective on Mars due to the 0.5% CO_2 atmosphere, resulting in conduction becoming the dominant heat transfer mode. On Mars, more "classical" thermal insulation layups are required. However, the Mars environment is also extremely cold; it's as low as -243 °F at the poles but still as low as -100 °F at the more feasible equatorial candidate settlement locations.

Previous development efforts for flexible formulation aerogels by NASA were partially successful and resulted in commercialization for applications in mountaineering gear such as coats and boots. However, they exhibited inadequate thermal performance and insufficient mechanical cycling performance to support long-duration missions on the Mars surface in a spacesuit application.

NASA's goal for this subtopic is to develop at least one material that can be used by NASA to evaluate a Mars Environmental Protection Garment (EPG) in a human thermal vacuum chamber test replicating the Mars environment. Additionally, the subtopic aims to develop suitable materials for boot outsoles, glove palm/finger pads, knee pads, and adhesives for extreme cryogenic environments that can be used on Mars as well as the Moon.

Possible solutions include maturation/optimization of current material formulations, new material formulations, or new/novel thermal insulation techniques suitable for an EVA application.

Scope Title: Insulation for Mars Thermal Environment

Scope Description:

At a high level, this subtopic and scope is soliciting development of thermal insulation solutions for EVA suits on the martian surface. It seeks to address deficits with previous developments as it relates to thermal resistance, cycling performance (brittleness), and feasibility for use in a spacesuit application. For this development, there are several characteristics of concern:

- Thermal conductivity less than 5 W/mK at 8.0 torr.
- Operating range -250 °F to +250 °F.

- Maximum thickness 0.5-in. (threshold) and 0.25-in. (goal).
- Tensile strength.
- Abrasion resistance.
- Stiffness (drape).
- Cycle performance at room temperature (change to thermal resistance, particulate generation/loss of mass).
- Cycle performance at -100 °F (change to thermal resistance, particulate generation/loss of mass).
    - Cycle performance testing to be based on previous testing in Reference 4 of this solicitation (Trevino et al.) with additional consideration for low-temperature testing).

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 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Desired Phase I deliverables:

- Research and analysis to down-select possible material formulations and/or processes.
- Initial prototypes (coupon level) of candidate solutions.
- Identification of appropriate material evaluations to meet requirements (see Scope Description and Ref. 4 of this solicitation (Trevino et al.)).
- Preliminary test data of candidate solutions based on selected material evaluations.
- Delivery of samples to NASA.

Desired Phase II deliverables:

- Selection of one or two candidates from Phase I to optimize.
- Optimization for performance against standardized and novel material evaluations (see Scope Description and Ref. 7 of this solicitation (Tang et al.)).
- Final test data of optimized designs per established evaluations.
- Delivery of samples to NASA.
- Fabrication of a full or subscale prototype (or acceptable surrogate test article) and delivery to NASA for additional evaluations.

State of the Art and Critical Gaps:

Critical gaps include:

- Thermal conductivity that is too high, resulting in material thickness that is too great for the suit application (resulting in increased bulk and decreased mobility/dexterity).
- Cycling performance, showing minimal loss of thermal resistance and minimal particulate generation at -100 °F for at least 250,000 bending/torsion cycles.
- Proposers will need to demonstrate feasibility of improving over the current state-of-the-art fiber-reinforced aerogels as documented in Reference 7 of this solicitation (Tang et al).

Relevance / Science Traceability:

The subtopic has relevancy for many surface elements of a Mars campaign where thermal insulation is required. Rovers, habitats, power systems etc.

References:

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Scope Title: Materials for Extreme Cold Thermal Environments

Scope Description:

This scope is for boot outsoles, pads on the EVA glove and knee, and adhesives used on the EVA suit in extreme thermal environments such as Mars or the Moon.

Materials optimized for outsoles for the boot application require sustained contact with regolith at temperatures as low as 50 K. The outsoles experience rapid temperature changes when transitioning from a sunlit area to a shaded area, and subsequent large temperature gradients between the bottom of the boot sole and the top. The outsole must be sufficiently durable to survive ambulation on the lunar or Mars surface, including jumping and crouching, as well as inadvertent kicking of rocks and inadvertent trips and falls onto the surface. The outsole may carry axial loads from the leg due to suit pressurization and human-induced loads. Lastly, it is desirable that the boot outsole provide modest flexibility within some of the total operating range of -370 °F to 200 °F.

Materials optimized for finger and palm pads on the EVA gloves, or knee pads require sustained and repeated contact with regolith at temperatures as low as 50 K. The pads will experience rapid temperature changes when transitioning from a sunlit area to a shaded area, and subsequent large temperature gradients between the outer surface of the pads and the inner surface. Delamination of the pads from the underlying glove outer fabric is a concern. The pads must be sufficiently durable to survive repeated contact with the surface and EVA tools. Lastly, it is desirable that the pads provide modest flexibility within some of the total operating range of -370 °F to 200 °F, which aids in hand mobility and tactility. This scope also covers adhesives suitable for the cryogenic environment from -370 °F to 200 °F, which will be seen on the Moon or Mars. These adhesives are used to bond plastics, metals, and textiles, often with different surface finishes, chemical compositions, and thermal expansion coefficients. The adhesives will experience rapid temperature changes when hardware transitions from a sunlit area to a shaded area. The adhesives must carry high structural loads at all temperature due to the forces induced by jumping, crouching, trips, falls, grabbing tools, and contact with the Mars or lunar surface. It is desired that the adhesives provide modest flexibility within some of the total operating range.

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 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

Desired Phase I deliverables:

- Research and analysis to down-select possible material formulations and/or processes.
- Initial prototypes (coupon level) of candidate solutions.
- Identification of appropriate material evaluations to meet requirements
- Preliminary test data of candidate solutions based on selected material evaluations. At a minimum, material evaluations include:
    - Flexure/breaking load of sample at room and cryogenic temperature.
    - Thermal shock.
    - Peel strength and/or CTE mismatch (if appropriate, e.g., glove RTV pads).

  - Additional tests at the recommendation of the vendor in order to minimize risk in a potential Phase II award.
- Delivery of samples to NASA.

Desired Phase II deliverables:

- Selection of 1-2 candidates from Phase I to optimize.
- Optimization for performance against standardized and novel material evaluation. At minimum, to include:
  - Temperature retraction (ASTM D1329 or similar).
  - Glass transition temperature (ASTM D7426 or similar).
  - Brittleness (ASTM D2137 or similar).
  - Torsion/stiffening (ASTM D1053 or similar).
  - Flexure/breaking load of sample at room temperature (Test TBD).
  - Flexure/breaking load of sample at cryogenic temperature (Test TBD).
  - Thermal shock (Test TBD).
  - UV degradation (ASTM D4329 or similar).
  - Off-gassing at NASA White Sands Test Facility (WSTF).
  - Adhesion/peel strength and/or CTE mismatch (if appropriate) (Test TBD).
- Final test data of optimized designs per established evaluations.
- Delivery of samples to NASA.
- Fabrication of a full or subscale prototype (or acceptable surrogate test article) and delivery to NASA for additional evaluations.

State of the Art and Critical Gaps:

Classic silicones for cryogenic applications (seals, etc.) offer operating temperatures as low as -100 °C (-148 °F). PTFE is often used at lower temperatures but has drawbacks such as large thermal expansion. Modified fluoropolymers such as polymonochlorotrifluoroethylene (PCTFE) or perfluoropolyether (PFPE) offer operating ranges for sealing applications down to absolute zero, but they are often for static applications without additional requirements for room temperature ductility, UV resistance, off-gassing, etc. The unique requirements set imposed by the lunar suit application have not been specifically addressed in any previous development for NASA or private industry.

Relevance / Science Traceability:

The subtopic has relevancy for many systems within a Mars campaign. It is also relevant to the Artemis Program, including the Human Landing System (HLS), the Lunar Terrain Vehicle, (LTV), and suits (EVA). There is also relevancy for EVA tools, a future pressurized rover, and any other lunar surface assets.

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TX07: Exploration Destination Systems

This area covers the broad range of technologies associated with enabling successful activities in space, from mission operations to in-situ resource utilization.

S13.04 Contamination Control and Planetary Protection (SBIR)

Related Subtopic Pointers: T7.04
Lead Center: JPL
Participating Center(s): GSFC

Subtopic Introduction:

The Contamination Control(CC) and Planetary Protection (PP) subtopic develops new technologies or supports new applications of existing technologies to measure, manage, and mitigate the presence of undesired microbial, particulate, and molecular sources, producing clean and characterized spacecraft, instrumentation, or hardware. Novel approaches to measuring, managing, and mitigating microbial, particulate, and molecular (including water vapor) contamination sources supports NASA's ability to produce compelling scientific results (CC), ensure nominal hardware operations (CC), and comply with PP requirements to prevent forward contamination (the transfer of viable organisms from Earth to another planetary body) and backward contamination (the transfer of material from another planetary body that may pose a biological threat 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.

Scope Title: Contamination Control (CC) and Planetary Protection (PP) Implementation and Verification

Scope Description:

NASA is seeking innovative approaches to address the above-mentioned CC and PP challenges through:

- Analytical and physics-based modeling technologies and techniques to quantify and validate submicron particulate contamination.
- Low-energy surface material coatings to prevent or minimize contamination.
- Modeling and analysis of particles and molecules to ensure hardware and instrumentation meet organic contamination requirements.
- Improved technologies for the detection and verification of low levels of organic compounds on spacecraft surfaces.
- Improvements to spacecraft cleaning and sterilization that are compatible with spacecraft materials and assemblies.
- Technologies for the prevention of recontamination and cross contamination throughout the spacecraft lifecycle (build, test, launch, cruise, operations).
- 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., ultraviolet 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 of 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).
- Advanced technologies for the detection and verification of organic compounds and biologicals on spacecraft hardware prior to launch.
- Advanced technologies that demonstrate the capacity to sample and deliver sampled material from a planetary body while retaining critical volatiles.
- Advanced technologies that store, seal, and contain samples with an appropriate sensitivity to static or changing environmental conditions during transport from the planetary body where samples are collected to the return to Earth (e.g., cold storage sampling for lunar sample material collection and transport to Earth, low-leak-rate storage for biological containment—consistent with Federal containment policies—for transport from Europa, Enceladus, Mars, and Titan to Earth).

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, a proof-of-concept study for the approach to include data validation and modeling.

Phase II deliverable: As relevant to the proposed effort, detailed modeling/analysis or prototype for testing.

Areas to consider for deliverables: technologies, approaches, techniques, models, and/or prototypes, including accompanying data validation reports and modeling code demonstrating how the product will enable spacecraft compliance with PP and CC requirements.

State of the Art and Critical Gaps:

Contamination Control (CC):
CC requirements and practices are evolving rapidly as planetary mission science objectives targeting detection of organics and life and increased sensitivity or ultraviolet observational needs for critical Earth and astrophysical science future missions emerge. Ultraviolet, low-level particulate (atmospheric aerosols), low-level organic (Earth pollution monitoring of volatile organic compounds) detection needs drive stricter requirements and improved characterization of flight-system- and science hardware-induced contamination. As many future missions may not require a cruise stage or other protective housing over

the main operational flight hardware, the development of a novel technology to expand the current methods for clean launch capabilities (purge, environmental control systems) is also a critical gap. Other critical gaps for CC include:

- Instrument-induced contamination modeling, characterization, and mitigation.
- 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 general contamination mission needs as well as planetary protection forward contamination scenarios of simple and complex spacecraft geometries with electrostatic loads, vibro-acoustic/launch loads, and particle detachment and attachment capabilities in continuum, rarefied, and molecular flow environments.
- Modeling and analysis of particulate flux for assessment of general contamination and PP-specific backward contamination scenarios using dynamic approaches (e.g., direct simulation Monte Carlo (DSMC) and Bhatnagar Gross Krook (BGK) formulations).
- Launch barrier technologies and modeling of launch flux.

Planetary Protection (PP):

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, for NASA-approved vapor hydrogen peroxide approach, concentration variability, delivery mechanisms, and material compatibility concerns currently limit flight mission infusion. After microbial reduction, during spacecraft integration and assembly, the hardware then is protected in a cleanroom environment (ISO 8 or better), using protective coverings. 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). 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.

- Probabilistic modeling for biological contamination 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, and transport models.
- Assessment of DNA from low-biomass surfaces (<0.1 ng/L 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 a spectrum of viable organisms.
- Enhanced microbial reduction/sterilization modalities that are flight-materials compatible.
- Recontamination prevention/mitigation systems.

Relevance / Science Traceability:

With increased interest in investigating bodies with the potential for life detection, such as Europa, Enceladus, Mars, and other bodies of astrobiological interest, and the potential for sample return from such bodies as well as increased sensitivity of instrument detection for other planetary science, Earth science, and astrophysics missions, there is increased need for novel technologies associated with PP and CC. The development of such technologies would enable missions to (1) be responsive to PP and CC engineering and science requirements, as they would be able to assess or detect prelaunch or preoperational viable organisms and other particulate and organic contaminants; (2) 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; (3) ensure compliance with sample return PP and science requirements; and (4) support model-based assessments of PP requirements for biologically sensitive missions (e.g., outer planets and sample return).

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Contamination Control:

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Planetary Protection:

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Z12.03 Space Resource Processing for Consumables, Manufacturing, Construction, and Energy (SBIR)

Related Subtopic Pointers: T7.04
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 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."
In September 2022, NASA released the Moon to Mars Objectives, which contains multiple objectives related to the characterization and utilization of resources on both the Moon and Mars.

Scope Title: Oxygen and Metals 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 following supporting technologies that may enable or enhance the ability to extract oxygen and metals from lunar regolith:

1. Regolith Hopper and Transfer
Regolith-based ISRU systems require handling and transfer of regolith from excavator delivery units into processors and/or between subsystems in order to extract resources. The direction and distance regolith may need to be conveyed will depend on the technology selection and system design. To support ISRU payloads on top of landers, the solicitation is aimed at the ability to collect regolith in a hopper and transfer the regolith a minimum height of 10 m and at a minimum rate of 10 kg/hr. Designs should consider potential wear for operating at least 1 Earth year of regolith transfer. Designs should also consider how regolith mineral characterization instruments, such as those used in x-ray fluorescence (XRF) spectroscopy, Raman spectroscopy, and laser-induced breakdown spectroscopy (LIBS), can be mounted to perform real-time measurement of the regolith being transferred.

Phase I should demonstrate the critical aspects of the regolith hopper and transfer hardware design with an analysis that shows it can meet full design/operational requirements in Phase II. Phase II should demonstrate requirements for a minimum of 2 weeks' continuous operation.

2. Non-Polar Lunar Regolith Mineral Beneficiation and Metal Extraction and Separation
While the initial focus of lunar oxygen and metal extraction is based on highland regolith at the lunar south pole, NASA is interested in developing technologies and capabilities for the separation of minerals found in mare regolith in non-polar regions of the Moon. Specifically, there is interest in the mineral separation and processing of 1) high-titanium mare/ilmenite for titanium extraction and separation, and 2) sources of KREEP (potassium, rare Earth elements, and phosphorus) for extraction and separation of rare Earth elements. If reactants are utilized in the extraction process and multiple reaction products are generated, all steps in regenerating the reactants and separating the products need to be considered. Proposed concepts must include a method to move regolith through the reaction zone (e.g., regolith inlet/outlet valves capable of passing abrasive granular material through the valve for hundreds of cycles).

Phase I should demonstrate the critical aspects of mineral separation and/or metal extraction and separation with an analysis that shows that a demonstration system can be built and tested in Phase II.

3. ISRU Critical Data/Proof-of-Concept Hardware for Commercial Lunar Payload Services (CLPS) Demonstration
NASA's ISRU Envisioned Future Priorities strategic plan calls for developing and flying demonstrations to the Moon to reduce or eliminate the risk of deploying a pilot plant that will perform end-to-end regolith

acquisition and processing, a system designed to operate for a minimum of 1 Earth year and deliver a minimum of 1,000 kg of oxygen or oxygen/hydrogen to a customer early next decade. However, NASA has not operated on the lunar surface since the Apollo program. To reduce the risk of ISRU oxygen, metal, and water extraction systems, NASA is interested in <25-kg-payload concepts that will obtain critical data and/or proof of concept of regolith flowability, size sorting, and mineral separation techniques that may be used in subsequent demonstrations and pilot plant hardware.

Phase I should demonstrate the critical aspects of the proposed hardware with an analysis that shows a demonstration system can be built and tested in Phase II that is less than 25 kg in mass. Phase II should design, build, and test hardware to as close to flight-ready as possible within the provided budget.

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:

These technologies directly address the following existing gaps for ISRU:

- Regolith transfer hardware for long-duration ISRU operations.
- Mineral separation/beneficiation methods for long-term ISRU operations.

Relevance / Science Traceability:

These technologies support the following Moon-to-Mars Objectives:

- LI-7L: Demonstrate industrial-scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.
- LI-8L: Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in situ resources, and support systems needed for continuous human/robotic presence.
- OP-11LM: Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.

- OP-12LM: Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (and from the lunar surface, in the case of Mars) to be used during exploration.

References:

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Scope Title: Lunar Ice Mining

Scope Description:

We now know that water ice exists on the poles of the Moon, based on 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 locate water resources and then extract and separate the water and other volatiles that are found with the water. For this solicitation, NASA is specifically interested in the following:

1. Locate, Sample, and Characterize Lunar Ice Resources Down to 10 m
To date, NASA has focused on developing instruments and technologies that would allow water resources (and other volatiles found with the water) to be detected and characterized down to 1 m below the surface. Scientists have hypothesized, and LCROSS data suggest, that water resources may be deeper than 1 m and potentially concentrated in the top 10 m of regolith in PSRs. Therefore, NASA is interested in developing technologies and systems that may be able to examine, characterize, and potentially sample material down to 10 m below the surface.

2. Regolith-Tolerant Valves for Low-Temperature Operations
ISRU systems that target regolith-based resources must be equipped to handle and transfer large quantities of regolith into whatever resource extraction technology is implemented. These extraction systems may require some form of valve/sealing mechanism to isolate the raw regolith (which may be contained in a regolith hopper post-excavation) from the "reactor" or vessel where regolith is being

processed. Likewise, sealing is needed to contain the process gases/commodity, where the extraction method is likely to operate at an elevated pressure with respect to the lunar environment. Operational temperature of these valves presents a particular concern, where processes that extract water from ice are likely to take place in PSRs (where ice exists) or at least must be equipped to pass the cold regolith material (regolith must be cold to minimize sublimation loss). These valves must operate without maintenance for significant periods of time. Proposals should demonstrate a regolith throughput of 10 kg/hr with an operating temperature of 125 K in a vacuum.

3. In Situ Resource Extraction and Collection in Lunar PSRs

Volatiles, such as water, trapped in lunar PSRs are a key ISRU resource. Heating is required to liberate these volatiles, and some methods use in situ heating to avoid the need to excavate/transfer regolith. However, the challenge is to drive the liberated volatiles to the capture system; volatiles will be exposed to the lunar vacuum and can expand away quickly or may be more likely to move to colder areas (e.g., deeper/nearby regolith) if the heating/capture systems are not well designed to account for this. Proposals should result in hardware that can extract and capture 1.5 kg of water/hr from an icy regolith mixture from a depth of 20 to 100 cm below the surface of a regolith bin while operating in a vacuum.

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:

These technologies directly address the following existing gaps for ISRU:

- Detection of subsurface ice at less than 10-m scale.
- Regolith-tolerant valves for low-temperature operations.
- In situ resource extraction and collection in lunar PSRs.

Relevance / Science Traceability:

These technologies address the following Moon to Mars objectives:

- LI-7L: Demonstrate industrial-scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.

- LI-8L: Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in situ resources, and support systems needed for continuous human/robotic presence.
- OP-11LM: Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.
- OP-12LM: Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (and from the lunar surface, in the case of Mars) to be used during exploration.

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Ethridge, E. C. (2011). *Using Microwaves to Heat Lunar Soil* (No. M11-0244).

Scope Title: Lunar ISRU for Energy Generation and Storage

Scope Description:

Initial human lunar missions will rely on energy generation and storage systems and reactants to be brought from Earth. However, as lunar surface operation durations and scope increase, the ability to use in situ resources to expand solar and thermal energy generation and storage capabilities beyond those delivered from Earth will be needed. NASA is interested in developing the following supporting technologies and capabilities that can generate and store solar/thermal energy for subsequent use:

1. Electrical Generation Through Use of Thermal Gradients
The lunar polar region provides a unique environment where areas of near-continuous sunlight are located near areas of near-continuous darkness. This provides an opportunity to utilize the large temperature difference between these two areas as a means of generating electricity. However, the low conductivity of lunar regolith and the need to utilize radiative heat transfer to the lunar vacuum environment are challenges to utilizing traditional geothermal energy generation concepts. Systems proposed must produce a minimum of 1,000 W of electrical energy initially and a minimum distance of 100 m between hot/cold regions. Proposed concepts must eventually be capable of being deployed robotically and be scalable to tens to hundreds of kW and hundreds of meters between hot/cold regions.

2. Solar Thermal Storage and Reuse
The approach to thermal management on all space missions to date has been to reject heat through radiators during operation and to insulate hardware to minimize heat loss during quiescence periods or during long-term exposure to shadowed locations. The 14-day lunar day/night cycle is a particularly difficult thermal environment for exploration elements, especially habitats, where heat rejection during solar "noon" and heat retention/power generation during lunar night are each difficult in different ways. A unique method for lunar thermal management is to collect and store heat into a thermal medium during daylight hours and to recover this thermal energy during the night as a way of conserving and utilizing thermal energy versus rejecting it (see References for more information on thermal wadis). Lunar regolith is a very good insulating material and very poor in heat conduction, so proposers will need to consider methods for modifying lunar regolith to have better thermal storage characteristics and propose methods for how collected thermal energy will be transferred to the in situ thermal storage media and how that thermal energy will be transferred for use. The proposal needs to address both the modification of lunar

regolith into the appropriate thermal storage media and the hardware associated with collecting and transferring the thermal energy into/out of this media, and it must be scalable to tens to hundreds of kW of thermal storage. While hardware to excavate and emplace the thermal management system does not need to be developed in the proposal, proposers do need to describe how the concept may eventually be deployed robotically.

3. Energy System Components

As extraction of resources expands across the lunar surface, the power system feeding this activity will have to expand as well. As this power system grows in scale, it will become cost effective to manufacture the power system components themselves from elements extracted from the regolith. These components include:

- Conductors, such as aluminum refined from regolith minerals, printed directly on the surface or assembled with other components to be separated from the lunar surface. This supports closure of TX03 Gap "Long-distance power cables from lunar regolith minerals (#1391)."
- Photovoltaic cells, such as silicon refined from regolith silica, printed directly on the surface or assembled into PV arrays to be separated from the lunar surface. This supports closure of TX03 Gap "Large-scale solar power generation via photovoltaic blankets produced from lunar regolith minerals (#1392)."
- Flow batteries, with anolyte and catholytes refined from regolith minerals and assembled on the lunar surface for large-scale energy storage. This supports closure of TX03 Gap "Large-scale secondary chemical energy storage produced from lunar regolith minerals (#1393)."

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:

These technologies directly address the following existing gaps for advanced thermal and power:

- Geothermal Heat Rejection in Lunar Polar Regions and on Mars.
- Variable Heat Rejection – Human Class.
- Phase Change Materials with Increased Energy Storage.
- Undifferentiated Power Systems Technologies.
- Novel Heat Transfer Fluids.

- Green Propellant Propulsion.

Relevance / Science Traceability:

These technologies address the following Moon to Mars objectives:

- LI-7L: Demonstrate industrial-scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.
- LI-8L: Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in situ resources, and support systems needed for continuous human/robotic presence.
- OP-11LM: Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.
- OP-12LM: Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (and from the lunar surface, in the case of Mars) to be used during exploration.

References

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Z13.05 Components for Extreme Environments (SBIR)

Related Subtopic Pointers: T7.04
Lead Center: KSC
Participating Center(s): GRC, JSC, LaRC

Subtopic Introduction:

NASA seeks new technologies to enable sustainable lunar and Mars surface operations by developing components capable of operating and surviving in extreme environments. 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, Heat Exchangers, and Water Containers
- Actively Controlled Louvers

Scope Title: Mechanisms for Extreme Environments

Scope Description:

Proposals are sought for mechanisms and mechanical systems that can operate on the dusty surface of the Moon and Mars for months to years. These systems will be exposed to the harsh extreme environments and will have little to no maintenance. These mechanisms in extreme environments must function in the presence of lunar regolith and charged dust, micrometeoroids, plume ejecta, extreme temperature variations, high vacuum, cosmic rays and other high-energy ionized particles, plasma, solar ultraviolet (UV) and other electromagnetic (EM) ionizing radiation, static electricity charging, changing gravitational conditions, and other electrically induced effects.

Proposals should be focused on the following mechanisms and technologies that can function in these environments:

- Sealing materials, fabrics, and flexible covers and technologies that can seal/protect mechanisms by preventing regolith intrusion and remain compliant and functional in the extreme Moon/Mars environments.
- Dust-tolerant electrical connectors that can function with (or mitigate) light dust coating in the relevant Moon/Mars environments.
- Moving components for dust protection (iris, hatch, covers, louvers, airlocks, closures, hinges, joints, trusses, etc.).

Successful solutions will have the following performance characteristics:

- Operational for extended service of 10 to 100 months with limited or no maintenance.
- Linear and static joints will function and perform the designed actuation/motion/mate-demate cycles of 1,000 or higher.
- Mechanisms will function with minimal solid film or without lubrication.
- 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 on 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 focused on solving one of the NASA technology needs listed above. Applications with direct infusion path to current and future NASA projects/programs are sought.

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 to answer critical questions focused on functional performance of the mechanisms. In addition, the report shall include recommendations for brassboard or prototype development during Phase II that is directly applicable to a current or future NASA project/program.

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. The prototype shall be designed to conform to a NASA project/program need and include a well-developed flight demonstration and infusion plan. A report shall be written that includes functional, performance, analytical, and test results; and an evaluation of the technology's maturity level (i.e., TRL) including the risk of proceeding with the development.

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 Moon/Mars 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). Operations on the lunar surface will involve the mating/demating of electrical, fluid, and cryogenic connections. Dust on the surface of these connectors will impede their proper function and lead to failures. Solutions are needed to develop connectors that can function in dusty Moon/Mars extreme environments.

Dust-protective enclosures, flexible covers, boots, hatches, and moving covers are needed to protect delicate mechanism components.

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

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Scope Title: Freeze-Tolerant Radiators, Heat Exchangers, and Water Containers

Scope Description:

Proposals are sought to develop freeze-tolerant radiators, heat exchangers, and water containers. The goal is to develop these components 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).
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, temporarily 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).

Developments in freeze-tolerant water containers are sought in these areas:

- 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 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. The prototype shall be designed to conform to a NASA project/program need and include a well-developed flight demonstration and infusion plan. A report shall be written that includes functional, performance, analytical, and test results; and an evaluation of the technology’s maturity level (i.e., TRL) including the risk of proceeding with the development.

State of the Art and Critical Gaps:

State of the art (SOA) ATCSs on human-rated spacecraft like the Apollo Service Module (SM) and International Space Station (ISS) use 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 required small-inner-diameter (0.18-cm, or 0.07-in.) metallic (Inconel or stainless steel) coolant tubes with thick walls (outer diameter of 0.32 cm, or 0.125 in.), 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 mass and counter 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.

SOA contingency water containers (CWCs) used on the space shuttle and the 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 full 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:

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). These temperatures 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 that 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).

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:

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2. Binns, D., and Hager, P., "Thermal Design Challenges for Lunar ISRU Payloads," 50th International Conference on Environmental Systems (ICES), July 12-15, 2021.
3. Samonski, F.H., Jr., and Tucker, E.M., “Apollo Experience Report: Command and Service Module Environmental Control System,” NASA Technical Note (TN) D-6718, March 1, 1972.
4. “International Space Station (ISS) Active Thermal Control System (ATCS) Overview,” https://www.nasa.gov/pdf/473486main_iss_atcs_overview.pdf
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6. Tobias, B., et al., “International Space Station Water Balance Operations,” 41st International Conference on Environmental Systems (ICES), 2011.
7. Li, S., 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
8. 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.

9. Schultz, P.H., Hermalyn, B., Colaprete, A., Ennico, K., Shirley, M., and Marshall, W.S., “The LCROSS Cratering Experiment,” Science, 330, 2010, pp. 468-472.

Scope Title: Actively Controlled Louvers

Scope Description:

NASA plans to develop infrastructure to enable a sustaining human presence on the Moon as part of the Artemis program. Current lunar orbit and surface habitat concepts incorporate conventional single-phase radiators to reject heat, and these habitats will be exposed to ionizing ultraviolet (UV) radiation and lunar dust. The UV and lunar dust environments can significantly degrade the radiator’s Z-93 absorptivity properties and reduce heat rejection capability. In addition, the radiator coolant tubes may rupture when exposed to subfreezing environmental temperatures during transit to lunar orbit and at nighttime in lunar south pole regions. Radiator coating degradation and coolant freezing jeopardize the success of Artemis missions. Louver technology is a promising solution to maintain radiator performance and integrity, but heritage louvers are passively controlled. Active-control louvers are sought to improve thermal response times and allow ground control. The louver design must be compliant with the current ground rules and assumptions (GRAs) as follows:

- Maintain radiator heat rejection capability between 2 and 15 kW.
- Minimum 15-year life.
- Louver shall vary the effective radiator emissivity from 0.14 (blades closed) to 0.74 (blades open).
- Louver blade thickness between 0.5 and 2 cm.
- Electromagnetic charging shall be mitigated.
- Dust-tolerant design that mitigates the effects of a dusty environment.

Specifically, developments in louvers are sought in these areas:

- Lightweight and corrosion-resistant material; ideally less than 1 kg (2.2 lbs.) and compliant with NASA STD-6016A.
- Thermal response time to setpoint changes to less than 15 min.
- Electrically powered and dust-protected actuation.
- Actuation power less than 500 W.

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 14.2 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 small-scale demonstration (no less than 1,400 cm^2) showing technical feasibility and operability (i.e., thermal response time and emissivity range) in a laboratory environment, and a report that includes analytical results in a relevant environment and recommendations for brassboard or prototype development during Phase II. In addition, the report should include a material trade study assessing the louver weight against the emissivity range.

Phase II Deliverables: A brassboard or prototype representing a no-less-than ~7-m^2 radiator panel with louvers in a vacuum environment. The goal is to achieve a TRL of 4 or 5. The testing should demonstrate 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), including the risk of proceeding with the development; and a well-developed flight demonstration and infusion plan.

State of the Art and Critical Gaps:

State-of-the-art (SOA) louver blades are made from aluminum and are passively actuated using a bimetallic spring. The louver blade transition from open to closed or vice versa and resulting thermal response time can take 1 to 2 hr. The louver thermal response time needs to be less than 15 min for human lunar habitats. Studies have shown that 1 to 4 kW of heat power is needed to keep coolant in a 48-m^2 deployable radiator from freezing. Passive louvers are not electrically powered, and active louver power should be less than 500 W. A conventional 14-blade aluminum passive louver weighs ~1 kg (2.2 lb). The active louver mass, including the control mechanism, needs to be less than 0.5 kg (1.1 lb).

Relevance / Science Traceability:

A lunar habitat will be exposed to high-energy, or ionized, UV radiation while traveling through the Van Allen belts and can last from hours to days. Experiments have shown exposure to more than 500 equivalent sun hours (ESH) in the Van Allen belts can degrade the radiator's Z-93 absorptivity from 0.16 to 0.24, or 50%. An absorptivity reduction of 50% results in approximately 9 to 3 kW, or two-thirds reduction in heat rejection capability based on conservation of energy. Conventional aluminum louver blades are approximately 1.3 cm thick, and the UV intensity through the Van Allen belts can be eliminated with this thickness based on the Beer-Lambert law. Lunar dust is copious and highly adhesive. Tests have shown Z-93 absorptivity linearly degrades with the amount of dust coverage on the coating. As little as 20% dust coverage can increase the absorptivity by 75% and decrease the heat rejection capability by 30%. Lunar habitats stationed near the lunar south pole will be exposed to extremely cold environmental temperatures (as low as -213 °C or -351°F) during lunar nights (up to 14 days). The cold environmental temperatures are below the freezing point of heritage or candidate active thermal control system (ATCS) coolants (e.g., ammonia, water, Freon, HFE 7200). Conservation of energy analysis results showed significant heater power (up to 4 kW, or 13,648 BTU/hr) is required to prevent heritage coolants from freezing and maintain operations. Louvers can reduce the radiator's effective emissivity to 0.14 while in the closed position and keep the radiator outlet temperature above the HFE 7200 working and freezing points.

References:

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2. Sawyer, D.M., and Vette, J.I., “AP-8 Trapped Proton Environment for Solar Maximum and Solar Minimum,” NASA Technical Memorandum TM-X-72605, pg. 87, December 1976.
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5. Gaier, J.R., Siamidis, J., et al., “The Effect of Simulated Lunar Dust on the Absorptivity, Emissivity, and Operating Temperature on AZ–93 and Ag/FEP Thermal Control Surfaces,” NASA Technical Memorandum 215492, December 2008.
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Z14.01 Lunar Surface Excavation (SBIR)

Related Subtopic Pointers: T7.04
Lead Center: KSC
Participating Center(s): GRC, JPL

Subtopic Introduction:

NASA is interested in developing excavation and supporting technologies to mine resources by excavating regolith at the Moon's south pole and eventually in other lunar locations, including the lower latitude mare regions. Excavation of lunar regolith is enabling for in-situ resource utilization (ISRU) because the regolith will be the source of many feedstocks that can be used to make needed products in this domain. The use of local resources on the Moon is planned for the NASA Artemis missions, which will contribute to the sustainability goals that have been set in White House Space Policy Directive 1 [1]. For ISRU, excavation technologies are required to mine resources that will have been previously located and identified by resource prospecting methods. For oxygen extraction, the loose top-surface regolith may be mined because the oxygen is ubiquitously present in the form of silicates, whereas volatile resources are thought to be beneath an insulating overburden that may be up to 1 m deep and beyond. Mars mission data (Phoenix, Mars Reconnaissance Orbiter (MRO), etc.) have also shown that there are vast deposits of water ice in the Martian subsurface, providing Mars-forward linkage for subsurface frozen regolith excavation technologies.

Regolith can also be used in bulk form for civil engineering applications, such as constructing berms for landing/launch rocket engine plume impingement ejecta and emplacement of regolith overburden on hangar shell structures to provide radiation protection, thermal stabilization, and meteoroid impact shielding for assets that may be placed inside these hangars for environmental protection and shielding, such as pressurized habitats for astronauts [2].

Furthermore, when the regolith is consolidated, either with a binder material or by fusing it through sintering, vitrification, or melting, a viable concrete-like construction material can be produced and used to build lunar infrastructure and other useful parts, such as ballast blocks for cranes and other equipment that relies on reaction forces provided by gravity [3].

This subtopic is seeking proposals on only the following aspects of lunar regolith excavation and mining systems:
Scope 1: Hauling and Delivery of Excavated Regolith
Scope 2: Modularity of Excavation and Mining Systems
Proposals should be submitted in the context of the following reference concept of operations:

A mobile excavation/hauling/delivery robotic system that will excavate 110,000 tons of surface regolith at an ISRU mining site over a period of 5 years. During this period, this system will travel at least 1,500 km per year while it hauls the regolith to an end-user site for delivery. The same robotic system will then traverse back to the mine, after which it will repeat the ISRU mining. The tailings from ISRU production plants and other processes must also be removed. The system may consist of one or more robotic units working together as a team to optimize functionality. It can be assumed that the robots will work for 16 hr per Earth day and electrically recharge during the remaining 8 hr.

Scope Title: Excavated Regolith Transport

Scope Description:

Hauling:
"Hauling" refers to the act of transporting lunar regolith from one place to another, on the Moon, typically over long lunar distances (>5 km per leg of the trip). The emphasis here is on the robotic transportation itself, focusing on efficiently moving bulk regolith from the point of origin to the destination. The hauling that will be required on the Moon will need to be autonomous because crews will not be there to operate the robotic equipment in situ. Even when crewmembers are present on the Moon, they will be busy with other tasks, such as doing scientific exploration. Hauling also refers to removing the tailings from an ISRU production plant to prevent excessive accumulation.

Delivery:
"Delivery" refers to the final stage of the regolith transportation process. It is the act of bringing regolith to a specific destination or recipient and depositing it in a receiving device, such as a regolith hopper for feeding it into an ISRU plant. Delivery usually involves the leg of the journey where the items are taken from a mining hub to the end user, such as an ISRU plant or a construction site. Special implements, concepts of operations, or methods may be needed to deliver the regolith. For example, regolith may need to be transferred from a transportation vehicle bed container into a stockpile and then picked up again to be used. How will this be accomplished?

Both hauling and delivery will be crucial components of the future lunar logistics and supply chain industry, ensuring that regolith is efficiently moved from quarries and mines to the end users. In Phase I, trade studies are sought to inform which type of autonomous mobility regolith transportation equipment is most efficient and appropriate for an ISRU mining operation. For example, the hauling of regolith could be carried out by a combined excavator/hauler or by a separate hauler that is loaded with regolith by the excavator. What is the maximum distance a combined excavator/hauler can haul a load before it is more efficient to use a dedicated hauler with a separate excavator robot? Loading and unloading of the hauling and delivery system shall be addressed. Should large vehicles be used, or is a fleet of cooperating smaller vehicles appropriate? Concepts, prototype(s) designs, analysis, hardware, test data, and test reports are desired for various types of equipment that can do hauling and/or delivery of regolith for ISRU purposes. A clear justification with rationale should be provided for the equipment that is being proposed. Typical lunar south pole terrain at the NASA Artemis program candidate landing sites and lunar regolith terramechanics of the studied concepts shall be addressed. Energy consumption and optimized operations shall be considered. Systems modeling and performance simulations are desirable.

Surface robotic mobility platforms are the focus of this solicitation. Other non-surface transportation methods, such as rail, gondolas, “launching” resources, or flying hoppers, are out of scope for this solicitation.

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

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
- Software

Desired Deliverables Description:

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

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

A potential Phase III deliverable might include a long-term test campaign (>1 year) in a lunar analogous terrestrial environment in order to subject equipment to realistic work conditions.

State of the Art and Critical Gaps:

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

No dedicated regolith hauling vehicles for lunar surface operations have been prototyped. The NASA Johnson Space Center (JSC) Chariot vehicle could potentially be used as a mobility platform for hauling if a regolith bin was placed on the bed.

Relevance / Science Traceability:

The work desired applies to Technology Taxonomy area 7 (TX07): Exploration Destination Systems. It applies to Strategic Goal 2: Extend Human Presence Deeper into Space and to the Moon for Sustainable Long-Term Exploration and Utilization, from the 2018 NASA Strategic Plan. It also applies to the Plan’s Strategic Objective 3.1: Develop and Transfer Revolutionary Technologies to Enable Exploration Capabilities for NASA and the Nation. It also applies to TX04: Robotic Systems, as the excavation equipment will need to operate without a human crew present during some periods.

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Scope Title: Modularity of Excavation and Mining Systems

Scope Description:

Terrestrial mining subsystem reliability has been extensively studied by industry through tens of thousands of hours of operations working toward equipment efficiency. In terrestrial operations, it has been estimated that equipment maintenance costs range from 20 to 35% of mine operation costs, and 10% of production time is lost due to unplanned maintenance [4]. In one published case study, downtime was logged for subsystem and component maintenance [5], which can be an indicator of which components or subsystems will need greater attention to reduce downtime. Similarly, an ISRU excavation system may need to perform at orders of magnitude greater than the current state of the art for distances traveled, requiring a robust approach to maintenance, resupply, and spare parts management. In order to continue indefinitely, a robotic system must have a continuous supply of energy and spare parts, along with the means to swap out used parts and insert new ones. This scope is focused on modular systems parts that are proposed to represent primitives which the robotic maintenance system can swap but cannot open up to perform repairs inside. For all practical purposes, from the perspective of the robotic maintenance system, the part modules are fully encapsulated black boxes [6]. These modular encapsulated components can then be treated as line-replaceable units (LRUs) and repaired offline so that a negative production impact is minimized. The LRUs can be swapped out by robotic means or by astronaut crews.
X
A LRU is a modular component or subsystem in various mechanical, electronic, or electromechanical systems that can be easily replaced or swapped out for maintenance or repair purposes. LRUs are designed to minimize downtime and simplify maintenance by allowing faulty or damaged units to be quickly replaced on-site without the need for extensive troubleshooting or repair.
Some key characteristics and features of LRUs:

- Modularity: LRUs are standalone components that can function independently and are designed to be easily integrated into a larger system. They are self-contained units with specific functions, such as mechanical latches, standardized structural interfaces, power take-offs, standardized connectors, power supplies, processors, sensors, or communication modules.
- Quick Replacement: When an LRU malfunctions or becomes defective, it can be quickly removed from the system and replaced with a new or refurbished unit. This process minimizes downtime and reduces the need for specialized repair work.
- Plug-and-Play: LRUs are designed to be plug-and-play, meaning they can be easily disconnected and reconnected using standardized connectors, interfaces, or mounting mechanisms.
- Diagnostic Capabilities: Many LRUs come with built-in diagnostic capabilities, allowing the larger system to identify faulty units and provide feedback to maintenance personnel about the specific issues.
- Field Replaceable: LRUs are typically designed to be replaced at the operational site, without requiring specialized tools or a full disassembly of the system.
- Regolith Dust Tolerance: LRUs will be exposed to high levels of dusty regolith during excavation and hauling operations as well as during swapping installation operations. Interfaces must be designed to prevent jamming, contamination, or other fouling of maintenance operations from regolith.

LRUs are commonly used in various industries, including aviation, automotive, telecommunications, and industrial equipment. In aviation, for example, LRUs are widely used in aircraft systems to facilitate easy and efficient maintenance and to reduce aircraft turnaround time between flights. By employing LRUs, organizations can streamline maintenance processes, improve system reliability, and reduce overall maintenance costs.

This scope seeks studies to identify which subsystems and components on a lunar regolith excavator should be LRUs. A functional approach with systems engineering methods and rationale is appropriate to define them in Phase I. Robotic handling and replacement of LRUs is desirable and should be evaluated. In Phase II, concepts, prototype(s) designs, analysis, hardware, test data, and test reports are requested for some of the selected LRUs as potential deliverables. Dust tolerance should be addressed as part of the Phase I concept and Phase II testing and demonstration.

This scope is also seeking studies and technologies that include strategies and designs to allow lunar excavation systems to survive 5 years of continuous operation. Robotic maintenance strategies shall be defined and examined, and methods for robotic servicing shall be identified.

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 07.1 In-Situ Resource Utilization

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

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

Phase II deliverables should be hardware demonstrations at a relevant scale. See Topic Scope Description for additional information about deliverables.

A potential Phase III deliverable might include a long-term test campaign (>1 year) in a lunar analogous terrestrial environment in order to subject equipment to realistic work conditions.

State of the Art and Critical Gaps:

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

Modularity has been performed in terrestrial systems but not for lunar surface systems.

Relevance / Science Traceability:

The work desired applies to Technology Taxonomy area 7 (TX07): Exploration Destination Systems. It applies to Strategic Goal 2: Extend Human Presence Deeper into Space and to the Moon for Sustainable Long-Term Exploration and Utilization, from the 2018 NASA Strategic Plan. It also applies to the Plan’s Strategic Objective 3.1: Develop and Transfer Revolutionary Technologies to Enable Exploration

Capabilities for NASA and the Nation. It also applies to TX04: Robotic Systems, as the excavation equipment will need to operate without a human crew present during some periods.

References:

[1] NASA. New Space Policy Directive Calls for Human Expansion Across Solar System. (2017). https://www.nasa.gov/press-release/new-space-policy-directive-calls-for-human-expansion-across-solar-system

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[9] Mueller, R.P., van Susante, P., Reiners, E., & Metzger, P.T. (April 2021). NASA Lunabotics Robotic Mining Competition 10th Anniversary (2010–2019): Taxonomy and Technology Review. Earth and Space 2021, 497-510. https://ntrs.nasa.gov/citations/20200003009

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Z14.03 Assembly and Outfitting of Tall Truss-Based Power Towers (SBIR)

Related Subtopic Pointers: T7.04
Lead Center: LaRC
Participating Center(s): KSC, MSFC

Subtopic Introduction:

As NASA works to achieve the NASA Moon-to-Mars Objectives, and specifically 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, lunar communications network, launch/landing pads, roads, shelters, and habitats.

Autonomous assembly is a key enabling technology that can provide a low-risk, high-payoff path toward early creation of critical lunar infrastructure (including power and communication towers, blast containment shields, shelters, bridges/walkways, etc.). Important features of assembly include its relative simplicity, versatility, terrestrial experience base, and capability to be accomplished using general-purpose robotic agents. Furthermore, assembly can leverage the use of components derived from in-situ resource utilization (ISRU) in combination with Earth-sourced components. It is envisioned that the ISRU-based components can range from simple shapes, such as trusses, beams, and plates, to more complex 3D-manufactured joints, connections, and mounting features. A properly developed assembly capability should enable an efficient logical transition from Earth-sourced to lunar-sourced components as they become available. The first application of assembly will likely be a tall tower for communications and power generation. However, the developed assembly technologies are extensible to the assembly of other large-scale infrastructure elements, such as launch landing pads (LLPs), blast containment shields, sunshades for propellant depots, and shelters and habitats for crew and asset protection.

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. To the extent reasonable, outfitting can be accomplished autonomously; however, the specific agents (robotic or human) performing the outfitting are part of the codesign of the overall excavation, construction, and outfitting (ECO) system.

To focus efforts, this solicitation seeks solutions to the outfitting of a power tower followed by connection of the tower to a global power grid. Outfitting may occur concurrently with the structural assembly or be fitted after completion of a power tower. A power tower is defined as a 50-m tall by 1-m by 1-m square cross-section four-longeron truss structure with solar arrays suspended from a cross member at the top of the tower. The cross member rotates to follow the Sun when emplaced at the lunar south pole. The truss elements are expected to include composite members when assembled from Earth-sourced materials, transitioning to aluminum members as lunar-derived structural members become available. A fundamental attribute of outfitting is assembly; outfitting is thus distinct from deployment, because deployment does not require assembly. To the extent reasonable, outfitting should be accomplished robotically; however, the specific agents (robotic or human) performing the outfitting are part of the codesign of the overall ECO system.

This subtopic is seeking proposals in the following areas only:
Scope 1: Extraterrestrial Surface Assembly of Tall Truss-Based Towers
Scope 2: Outfitting of Lunar Surface Structures: Truss-Based Power Towers

Phase I efforts will emphasize feasibility studies and proof-of-concept tests to demonstrate key technology functions; Phase II efforts will likely include integrated system testing to demonstrate the assembly or outfitting processes. These demonstrated processes must be scalable to anticipated large-scale lunar surface assemblies and structures.

Scope Title: Extraterrestrial Surface Assembly of Tall Truss-Based Towers

Scope Description:

Autonomous 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) for solar power generation and communications, 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-based structures on the Moon. Specifically, joining technologies and robotic tools are required to enable efficient and reliable autonomous/automated assembly of these structures, which are often composed of hundreds of individual elements.

Proposals are invited for the development of robotic assembly and joining concepts and the corresponding robotic tools required to assemble a tall truss-based tower (specific tower design information is provided below). However, extensibility of the robotic tools and joining concepts to other structural assemblies is highly 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 0.5 and 2.0 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. Over time, however, it is expected that ISRU-based 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 of particular interest. Finally, it is also assumed that a commercial general-purpose, space-capable robotic manipulating arm will be available and that proposals shall concentrate on the development and integration of specialized robotic end-effectors and tooling required for assembly; however, it is desirable for proposers to specify the commercial robot capabilities and other support equipment assumed in their concept (reach, payload capacity, power consumption, etc.).

Note: The tower, joining approach, and robotic assembly system is not expected to be flight qualified, but it should have a clear path to flight.

Focused application for development - Assembly of a tall lunar tower:

- Lunar tower height: 50-m class lunar tower (10-m-tall lunar tower segment assumed for ground demonstration).
- Lunar tower payload: 1,500 kg at top of tower (250 kg Earth equivalent for 1/6 gravity loads for ground demonstration).

- Tower 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 reference concept of operations (ConOps) = Module build and lift assembly approach (i.e., assemble a truss module or bay, lift up and assemble the next module below, repeat until tower is fully erected).

Truss element geometries:

- Truss element lengths: 0.5 to 2.0 m (it can be assumed that intermediate lengths can be obtained if necessary).
- Truss element cross section:
  - Angle: flange length 10 mm, 20 mm, 40 mm; flange thickness 2.0 mm, 4.0 mm, 6.0 mm;
  - Square rod: 10 mm^2, 15 mm^2, 20 mm^2

(It can be assumed that trusses can be modified to aid in the assembly process if necessary, e.g., additive or subtractive manufacturing.)

Truss element materials:

- Earth-sourced = aluminum 6061, graphite-epoxy
- ISRU-based = 98% pure aluminum (properties similar to 1-series untempered aluminum; E = 10 Msi, yield ~5 ksi)

Phase I efforts are expected to focus primarily on system design and feasibility studies and proof-of-concept tests to identify and demonstrate key technology functions such as robotic truss manipulation, joint design, joining, etc.; Phase II efforts will be used to mature these technologies and concepts and to conduct a ground demonstration to robotically assemble a 10-m-tall tower. The resulting assembly system and demonstrated assembly process must be scalable to a 50- to 80-m-tall lunar power and communications tower.

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

- Robotic tools for assembly that are compatible with commercially available robotic manipulator arms.
- 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) are desired.
- Joining concepts for assembly of composite and/or aluminum truss structures (including the joining method and any necessary fittings/tooling/jigging).
- Joint/node designs. In situ manufacturability, robotic assembly considerations, inspection.
- Concept of operations describing process to assemble a tall tower using the robotic tools and joining methods developed.
- In situ certification and proof testing.
- 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.

- Discuss application of technology to the assembly of other truss-based structures, e.g., walls, arches, and domes.

Note: Proposal does not have to produce space-rated equipment; however, the concept and processes shall be extensible to the lunar environment. The lunar daytime environment should be considered for assembly operations (1/6 gravity, temperature, radiation, vacuum, lighting, power requirements). Justification of design choices shall be included.

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

Primary Technology Taxonomy:

- Level 1: TX 07 Exploration Destination Systems
- Level 2: TX 07.X Other Exploration Destination Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I must include the design and test of critical elements associated with the proposed robotic technologies and joining methods needed to assemble truss-based structures, leading to a 10-m-tall tower ground assembly demonstration in Phase II. For example, proposed truss configuration and joint designs, structural analysis and design justification, and a summary of assembly trials and test results from Phase I must be included. Phase I must also include a ConOps for the assembly of the tower and the design and test plan of the robotic assembly system functions needed for Phase II. 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 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 final robotic assembly system design, tower and joint design, and a ground demonstration of a 10-m-tall tower assembly. The tower is expected to be constructed using robotic systems and implements and joint designs developed in Phase I. Clear evidence of the extensibility and scale-up of the ground demonstration system concept to 50- to 80-m-tall lunar towers shall be provided. Structures and systems must be developed to a minimum of TRL-5. Phase II assembly shall also consider the integration and deployment of a surrogate 100-kWe solar array or other relevant elements.

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-4 Industrial Scale Construction Capabilities—Roads with Autonomous Navigation Aids and 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 and outfitting of infrastructure directly addresses the following:

- NASA Moon to Mars Objectives*:* LI-1 Development of a Global Power Grid, and LI-4 Industrial Scale Construction Capabilities—Roads With Autonomous Navigation Aids and Assembly of Towers.
- STMD Strategic Thrust: “Live: Sustainable Living and Working Farther from Earth.”

References:

1. Lunar Surface Innovation Initiative: https://www.nasa.gov/directorates/spacetech/Lunar_Surface_Innovation_Initiative
2. Persistent Assets in Zero-G and on Planetary Surfaces: Enabled by Modular Technology and Robotic Operations, Doggett et al.: https://arc.aiaa.org/doi/pdf/10.2514/6.2018-5305

Scope Title: Outfitting of Lunar Surface Structures: Truss-Based Power Towers

Scope Description:

Assembly and outfitting 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 manual structural outfitting on Earth is a well-established construction approach, many technology gaps exist for the automated outfitting of truss infrastructure on the Moon—specifically, technologies for routing and securing cables and tubing to a truss structure, as well as the robotic tools to enable autonomous/automated outfitting of these structures.

Proposals are invited for the development of concepts to outfit a vertical truss tower, including routing of electrical cables; securing cables along the truss structure; and connection of equipment such as communication packages, cameras, lights, and antenna. Proposals should include concept of operations and associated robotic tools required to outfit truss power towers. The primary focus of this activity is the assembly of a tall truss-based tower. A power tower is defined as a 50-m-tall, four-longeron truss structure with solar arrays suspended from a cross member at the top of the tower. The cross member rotates to follow the Sun when emplaced at the lunar south pole. The truss elements are expected to include composite members when assembled from Earth-sourced materials, transitioning to aluminum members as lunar-derived structural members become available. Thus, concepts that support assembly of Earth-sourced and ISRU-based truss elements are favored. Extensibility of the outfitting concepts and robotic tools to other structural assemblies is desirable. Proposals to the current solicitation can assume that the truss elements being assembled are as described below. 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: cable routing; securing cables to truss tower; and securing equipment such as communication packages (20-kg boxes, 50 x 50 x 100 cm), cameras, lights, and antenna (in the 10-kg class), including securing electrical connection of equipment as well as strain relief.
Truss tower geometries:

- Truss element lengths: 0.5 to 2.0 m (it can be assumed that intermediate lengths can be obtained if necessary).
- Truss element cross section:
    - Square rod: 10 mm^2, 15 mm^2, 20 mm^2
    - Angle: flange length 10 mm, 20 mm, 40 mm; flange thickness 2.0 mm, 4.0 mm, 6.0 mm

(It can be assumed that trusses can be modified to aid in the outfitting process if necessary, e.g., additive or subtractive manufacturing.)

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 12.4 Manufacturing

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I must include the design and test of critical elements associated with the proposed outfitting of a 50-m-tall power tower, including robotic technologies to route and secure cabling and support equipment such as communication packages, cameras, lights, and antenna. Phase I must also include a concept of operations for outfitting of the tower and the proposal for design and testing of the outfitting concept. Phase II proposals should result in at least TRL-5 tools for outfitting of a power tower. Phase II should concentrate on demonstrating key technologies in realistically sized tests of the proposed concept of operations along with required robotic tools utilizing available terrestrial robots. Phase II deliverables must include demonstration of outfitting a 10-m section of a 50-m tower, including installation and connection of representative equipment.

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.

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. To transition these structures into useable facilities, utility outfitting must be accomplished to establish electrical power, fluid lines (installed for hydraulics, potable and nonpotable water, etc.), and environmental control utilities. This outfitting is the focus of this topic. To accomplish outfitting (i.e., utility installation), robotic routing, connection, and penetration sealing of cables and tubing must occur, followed by joining technologies to connect these systems to operational components.

NASA Moon to Mars Objectives: LI-1 Development of a Global Power Grid, and LI-4 Industrial Scale Construction Capabilities—Roads With Autonomous Navigation Aids and Assembly of Towers.
The NASA Space Technology Mission Directorate (STMD) STARPort database currently includes four technology gaps related to assembly of structures:

- Assemble truss-based tower.
- Structural elements for assembly.
- Structural joints/joining technology.
- Autonomy and robotics to assemble the tower.

Relevance / Science Traceability:

This technology is very much applicable in STMD support of its NASA, Government, and industry customers.

- STMD for SMD: Radio telescope structural support (back side of the Moon).
- ESDMD and SOMD (formerly HEOMD): Human Habitats, space infrastructure as in buildings, landing pads, roads, berms, radiation protection, and custom building sizes and shapes.
- ARMD and Earth-based Government agencies: In situ construction capabilities both locally and remote.
- Industry or Earth-based Government agencies: Rapid construction - small building within 24 hours.

References:

1. 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

TX08: Sensors and Instruments

This area covers technologies for instruments and sensors, including remote observation capabilities.

A3.05 Advanced Air Mobility (AAM) Integration (SBIR)

Related Subtopic Pointers: T10.01, T8.07
Lead Center: HQ
Participating Center(s): LaRC

Subtopic Introduction:

Advanced Air Mobility (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 is 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 operations (e.g., infrastructure inspection or search missions), and medical transport, are also of interest. Responses to this subtopic are not limited to strictly any single AAM mission but are focused on aspects that would either benefit multiple missions or integrate across aspects of the ecosystem, such as air traffic management and vehicle operations.

Scope Title: Improving Awareness of Icing Potential for Near-Term AAM Operations

Scope Description:

The goal of this scope is two-fold: to improve the safety of current operations and to provide data for the benefit of the AAM ecosystem, such as developing standards and refining forecasting models. Although most current operations will avoid flight where there is the potential for icing, this effort is targeting developing and improving the accuracy of icing observations to improve the safety of AAM high-risk operations, such as those for lifesaving or national security purposes. Note that icing avoidance and mitigation technologies are not within the scope of this subtopic. Leveraging an understanding of current icing observational and forecasting techniques, efforts under this SBIR proposal would be directed at improving icing observational methods and/or forecasting techniques. These improvements and techniques should be suited to commercialization in the near term while also be positioned to benefit broader efforts, such as those of NOAA, the FAA, and Standards Development Organizations (SDOs). This effort, combined with improved forecasts, icing mitigation technologies, and improved icing observational equipment and methods, will be a step along the path towards safer and more reliable AAM operations.

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

Primary Technology Taxonomy:

- **Level 1:** TX 08 Sensors and Instruments
- **Level 2:** TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

Phase I of this scope would include an assessment of the state of the art of observational methods, forecasting techniques, existing observational data sources, and the current challenges that need to be addressed to enable the next step-change in improving situational awareness of potential icing for AAM operations. Phase I would also begin to design a potential system architecture that would leverage existing and new data sources to provide icing observations that can be utilized for current operations and to improve forecasting models. Lastly, Phase I should be used to identify users of the data produced by this architecture, including AAM operators, forecasting model developer(s), and/or SDO working group(s).

Phase II of this scope would be to refine this system architecture and build an initial instantiation to demonstrate the feasibility, the ability to provide new, relevant and beneficial information, and assess its commercialization potential.

State of the Art and Critical Gaps:

Current methods for addressing the issues associated with icing focus on a conservative risk posture and avoiding potential icing conditions. This conservative approach is necessary as actual observational data is sparse and resulting forecasting models consequently take a low-risk approach. As AAM operations increase and companies work to reduce costs while maintaining reliability, better tools will be needed to determine the actual likelihood of encountering icing conditions, so that operations are not negatively impacted unnecessarily, and appropriate safety measures are taken based upon the mission risk profile and the vehicle configuration/capability; these tools must also be more accurate, regarding the potential for actual icing conditions.

Relevance / Science Traceability:

This subtopic seeks to complement past and future efforts under the A1 subtopic for icing avoidance and mitigation technologies. Although that subtopic focuses on decision-support tools and technologies to better avoid icing and technologies to reduce the likelihood of icing (e.g., surfaces that prevent ice from forming), this scope is focused on reducing the volume of airspace where icing is likely, by improving observations and forecasting. Together, these efforts offer a multipronged approach to this challenge.

References:

None

Scope Title: Mobile AAM Weather Information Systems

Scope Description:

The goal of this scope is to increase safety for near-term AAM operations by providing a mobile weather information system that can be tailored and relocated depending on the use case while meeting the anticipated American Society for Testing and Materials (ASTM) standard for Weather Information Providers. The vision for the mid- and far-term outlook calls for much more prevalent and locality-specific systems that balance safety, performance, cost, and other system attributes. To meet aviation weather standards in the near term, AAM operations will rely on existing FAA-certified systems or private and experimental observations, visual line-of-sight operations, waivers, or having a pilot on board the aircraft. The goal of this scope is to enable cost-effective safety improvements to AAM operations away from airports that provide weather information by having systems available for purchase that meet the draft ASTM standard. This will allow companies to obtain weather information, increasing safety while also allowing them to transport these systems to various locations, reducing the need for permanently installed infrastructure. The mobile aspect could also allow the systems to be utilized in areas where other infrastructure is lacking or where it is currently unavailable. Being mobile, the system should address all aspects necessary for operations, from collecting and/or obtaining locally relevant data to processing the data for display and potentially providing recommendations. An Uncrewed Aerial System (UAS) could be considered as a component of a mobile weather system, but it could not comprise the entire envisioned mobile weather system under this solicitation. This is partly because a weather information system relying solely on a single observation and not providing data processing for display or providing recommendations would likely not provide a compelling business case. It is not anticipated that the system will be able to be operate autonomously initially. It is also anticipated that the ASTM standard will be published before Phase II proposals are due.

Expected TRL or TRL Range at completion of the Project: 1 to 7

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:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

The Phase I deliverable would be a designed mobile system tailored for one or more use cases, and an expression of potential interest from one or several customers. The use cases could be short-term fast response uses such as disaster relief, support aviation operations during firefighting or search and rescue, or a system for planned activities such as infrastructure inspections, "drone shows" at events, or transport of medical lab samples. Such systems should be able to meet the draft ASTM Weather Information Provider standard.

Phase II would be to build and test the system desired by one of the several customers for potential sale and operational use.

State of the Art and Critical Gaps:

Other than at airports, there currently are no weather observation systems that take observations relevant to AAM operations, essentially at altitudes of less than 10,000 ft. Given the size of the United States, it will require decades and a vast amount of funding before these systems can be designed and installed. This SBIR solicitation is focused on providing the value enabled by having this information at a sustainable cost to the user.

Relevance / Science Traceability:

This effort has greater applicability to the AAM ecosystem or potentially as a supporting capability to NASA science missions conducted at low altitudes on Earth.

References:

None

S11.01 Lidar Remote-Sensing Technologies (SBIR)

Related Subtopic Pointers: T10.01, T8.07
Lead Center: LaRC
Participating Center(s): GSFC

Subtopic Introduction:

Lidar continues to be a key technology for NASA interests in Earth science, planetary science, and spacecraft navigation. Many technology advances are on the horizon for lidar that can be effectively used for NASA science interests. The subtopic nomination includes encouragement of these advances, such as hybrid laser architectures, photonic integrated circuits, optical phased arrays, metamaterials, and detection beyond classical limits and assists proposing firms to match technology development with NASA needs. This subtopic has a long history in developing new technologies and commercial products as identified below. Many such technologies have been incorporated into NASA lidar designs, including successful airborne demonstrators and space flight instruments. At the end of Phase II, the technology must be a viable solution for airborne and/or space-flight applications in the near future.

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 as well as particulates in the ocean 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
- Research
- Analysis

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 a 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 or to enable detection beyond classical limits. 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 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. Nonmechanical scanners (beam steering) >50 cm are also desired. Integrated receivers for Doppler wind measurement at 1550 or 1650 nm wavelengths 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. Similarly, proposals for the development of detector technology should be submitted to a different subtopic (S11.04) unless the innovation specifically targets a particular lidar application. Receivers for direct detection wind lidar are not sought this year.
- New three-dimensional (3D) mapping and hazard-detection lidar are sought 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 wildfire 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. Ground- and low-Earth-orbit- (LEO-) based lidar systems used for the detection and tracking of orbital debris targets are also of interest. 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 SMD, including:

- Atmospheric water vapor: Profiling of tropospheric water vapor supports studies in weather and dynamics, radiation budget, clouds, and aerosol processes.
- Aerosols: Profiling of atmospheric aerosols and how aerosols relate to clouds and precipitation.
- Atmospheric winds: Profiling of wind fields to support studies in weather and atmospheric dynamics on Earth and atmospheric structure of planets.
- Topography: Altimetry to support studies of vegetation and the cryosphere of Earth, as well as the surface of planets and solar system bodies.
- Greenhouse gases: Column measurements of atmospheric gases, such as methane, that affect climate variability.
- Hydrocarbons: Measurements of planetary atmospheres.
- Gases related to air quality: Sensing of tropospheric ozone, nitrogen dioxide, or formaldehyde to support NASA projects in atmospheric chemistry and health effects.
- Automated landing, hazard avoidance, and docking: Technologies to aid spacecraft and lander maneuvering and safe operations.

References:

1. NASA missions are aligned with the National Research Council's decadal surveys, with the latest survey on Earth science published in 2018, "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 and https://science.nasa.gov/earth-science/decadal-pbl
2. 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
3. Description of NASA lidar instruments and applications can be found at:
    - https://science.larc.nasa.gov/lidar/
    - https://science.gsfc.nasa.gov/sci/

S11.02 Technologies for Active Microwave Remote Sensing (SBIR)

Related Subtopic Pointers: T10.01, T8.07
Lead Center: JPL
Participating Center(s): GSFC

Subtopic Introduction:

Advancements and continued development of 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 areas are deemed to be of high importance to support advancements in future missions for NASA in the next decade. Success factors for each area after Phase

II are for mission injection though a Decadal Survey formulation effort via Surface Deformation and Change (SDC), Surface, Topography, and Vegetation (STV), or Planetary Boundary Layer (PBL). Key technology gaps that have not been solved motivate each topic area and are described in detail in the scopes.

1. SDC science is a continuing Decadal Survey topic, and follow-ons to the science desired for NASA-ISRO Synthetic Aperture Radar (NISAR) are already being planned. Cloud, water, and precipitation measurements increase capability of measurements to smaller particles, enabling much more compact instruments. Advancements in components are needed to support these advance measurements.
2. Low-frequency-band electronics and antennas are of great interests to subsurface studies, such as those completed by the Mars Advanced Radar for Subsurface and Ionosphere Sounding and the Shallow Radar (MARSIS and SHARAD, respectively) for Mars and those planned for Europa by the Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON) on the Europa Clipper. Studies of the subsurface of other icy worlds are of great interest to 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. Advanced 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 radio-frequency (RF) optics and stabilization systems are needed to support multiple upcoming applications including STV and PBL.

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 Transceivers

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— fiber-coupled Rydberg integrated RF-optics sensor head, arrayed vapor cell systems for atom-based Rydberg detectors, and compact Rydberg coupler laser stabilization systems to access target RF transitions in S-band through K-band.

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.
- Switches with high power (>100 W peak and >10 W average), speed (20 KHs events) and isolation (>25 dB) are also desired with low insertion loss of <0.4 dB and <0.5 dB at V-band (64 to 70 GHz) and W-band (95 GHz +/- 200 MHz), respectively.
- 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. Although 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. Approaches that do not require MMIC development are desired.

Quantum radar/radio components or subsystems to support STV:

- 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.
- Fiber-coupled vapor cells for Rb and Cs systems with efficiency >40% that, through use of a dichroic, delineate the probe from coupler signal and solve the problem of collimating lens and fiber sharing.
- Arrayed-vapor-cell systems that can permit spatially separated detection of RF fields to support K-band focal plane detectors with reflector antennas. Requested are 5x5 arrays with spacing less than a wavelength. Techniques to obtain a spatially reconfigurable array within a vapor cell is also desired.
- Optimized frequency-stabilization subsystems for a compact Rydberg laser package with a coupler laser wavelength tunable to access target RF transitions at S-band through K-band with absolute frequency stability at the 100-kHz level or better (goal: 10kHz) for operation under typical vibration conditions in suborbital flight.

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 SDC are strongly desired for Earth remote sensing, land use, natural hazards, and disaster response. NISAR is a flagship-class mission, but it is 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 spatiotemporal 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 STV 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 (very high frequency) to Ka-band: 50 MHz to 40 GHz) with different configurations sensitive to amplitude, phase, or polarization of signals to enable vertical profiling with high accuracy, high spatiotemporal resolution, and tomography capability. In addition to STV, Rydberg sensors could play a key role in PBL. The PBL, also known as the atmospheric boundary layer or peplosphere, is the lowest part of the atmosphere, and its behavior is directly influenced by its contact with a planetary surface. Remote sensing through active/passive radars are needed to observe the PBL. Rydberg techniques support broad spectrum remote sensing of the PBL.

Relevance / Science Traceability:

SDC science is a continuing Decadal Survey topic, and follow-ons to the science desired for NISAR mission are already being planned. Cloud, water, and precipitation measurements increase capability of measurements to smaller particles and enable much more compact instruments. STV is a Decadal Survey topic that will have significant impact in the following decade and that will require new and nonconventional technologies. STV touches multiple science goals, including solid earth, ecosystems, climate, hydrology, and weather, and is challenging to fit within the cost cap. PBL is a decadal survey topic that will have a significant impact in understanding and monitoring the lowest part of the atmosphere where the behavior is directly influenced by its contact with a planetary surface.

References:

1. NISAR follow-on for Surface Deformation and Change: https://science.nasa.gov/earth-science/decadal-sdc
2. NASA: "Radar in a CubeSat (RainCube)," https://www.jpl.nasa.gov/cubesat/missions/raincube.php

3. National Academies Press: "Global Atmospheric Composition Mission," https://www.nap.edu/read/11952/chapter/9
4. NASA: "Global Precipitation Measurement Mission," https://gpm.nasa.gov
5. NASA Surface Topography and Vegetation Incubation Study: https://science.nasa.gov/earth-science/decadal-stv

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Scope Title: Deployable and/or Steerable Aperture Technologies

Scope Description:

Solutions for the following technology needs are sought:
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. For low-frequency tomographic radar requirements: Deployable antenna with ~2:1 bandwidth, good pulse (transient) response, deployed volume ~1/3 wavelength at the lowest frequency (~MHz). For distributed aperture radars there is a need for daughter-craft antennas for the distributed radar covering a frequency of about 40 to 50 MHz with a gain of at least 5 dBi and with low mass, compact stow, and reasonable cost. Designs need to be temperature tolerant; that is, not changing performance parameters drastically over flight temperature ranges of ~100 °C.

High-frequency (V-band/W-band) deployable antennas for SmallSats and CubeSats: small-format, deployable/inflatable antennas are desired (for 65 to 70 GHz, 94 GHz, or 250 to 350 GHz) with an aperture size of ~1+ m^2 (>1.6 m for 250 to 350 GHz) 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, are highly desired.

Technologies enabling low-mass steerable technologies, especially for L- or S-bands, including—but not limited to—antenna or 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 thus are deployable, even for large spacecraft. For SmallSats/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 SmallSat/CubeSat form factors.

High-frequency antennas can often be hosted without deployment, but a ~1-m^2-diameter antenna on a SmallSat/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 and SHARAD 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 deployables, see similar missions (on much larger platforms):

1. REASON: https://www.jpl.nasa.gov/missions/europa-clipper/
2. REASON: https://europa.nasa.gov/spacecraft/instruments/reason
3. MARSIS: https://mars.nasa.gov/express/mission/sc_science_marsis01.html

For high-frequency deployables, see the similar, but lower frequency mission:

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

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Scope Title: Low-Power W-Band Transceivers

Scope Description:

Required is 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, particularly for Earth science applications, will be less extreme in radiation.

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

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

Phase I: Paper study/design.
Phase II: Prototype.

State of the Art and Critical Gaps:

Low-power-consumption transceivers for W-band are critical for studies of atmospheric science, pressure sounding, and atmospheric composition for both Earth and planetary science. Such transceivers currently do not exist.

Relevance / Science Traceability:

- ACE (Advanced Composition Explorer): https://solarsystem.nasa.gov/missions/ace/in-depth/
- Planetary Terminal Descent and Landing Radar Final Report: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19710011019.pdf

References:

Missions for atmospheric science and altimetry applications:

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

2. Mars Science Laboratory: https://descanso.jpl.nasa.gov/monograph/series13/DeepCommo_Chapter8--141029.pdf

S11.03 Technologies for Passive Microwave Remote Sensing (SBIR)

Related Subtopic Pointers: T10.01, T8.07
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:

- 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 5 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, power, and cost (SWaP-C). Components, methods, or manufacturing techniques utilizing novel techniques are desired, such as additive manufacturing (AM), that include interconnect technologies that enable highly integrated, low-loss distribution networks that integrate active components and passive devices such as power splitters, couplers, filters, antenna arrays, and/or isolators in a compact package with significant volume reduction. 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 5 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 from G-band up to 1 THz with >6 dB ENR (excess noise ratio).
- Broad-band (multi-octave) packaged low-noise amplifiers covering up to 70 GHz.
- Low-noise amplifiers that operate at 1.2 THz with >10% bandwidth.

- Technologies, processes, or methods, such as AM, that are able to reduce SWaP-C while achieving radio-frequency (RF) performance on par with or superior to traditional manufacturing 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:

- 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-C. Critical gaps depend on specific frequency and application.

Gaps include technologies to reduce 1/f noise with submillimeter amplifier-based receivers, particularly those 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.

Technologies, such as AM, are sought that can result in significant volume/cost reduction with performance comparable or superior to current technologies. For example, technologies that can integrate X-, Ku-, or Ka-band transmit/receive modules with antenna arrays and/or local oscillator (LO) distribution networks for F- and/or G-band receiver arrays. Several publications have demonstrated the feasibility of additively manufactured RF to millimeter-wave circuitry; however, there is a notable gap in research that specifically examines its reliability and effectiveness in environments pertinent to NASA and space applications. Furthermore, the current body of work predominantly focuses on subcircuits or a restricted number of parts, without adequately demonstrating the desired repeatability and reproducibility required for the development of intricate multimodule circuit networks needed for space instrumentations. There is also a gap for additive manufacturing technologies with fabrication tolerances, repeatability, and material properties that enable electronic devices (e.g., mixer blocks, corrugated horn antennas, etc.) that operate in the 0.5 to 1.5 THz regime with RF performance on par with traditional manufacturing methods.

Relevance / Science Traceability:

Critical need: Creative solutions to improve the performance of future Earth-observing, planetary, and astrophysics missions. The wide range of frequencies in this scope are used for numerous science measurements such as Earth science temperature profiling, ice cloud remote sensing, and planetary molecular species detection.

References:

1. Ulaby, Fawwaz; and Long, David: *Microwave radar and radiometric remote sensing*, Artech House, 2015.
2. 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.
3. Racette, P.; and Lang, R.H.: "Radiometer design analysis based upon measurement uncertainty," *Radio Science*, 40(05), pp. 1-22, 2005.
4. 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.
- Electro-optic modulators that operate up to 600 GHz.
- In current technology, phase and amplitude modulations on laser outputs are implemented in two separate photonic devices. It is desirable to develop a compact device to support versatile waveform with both phase and amplitude modulations. It is also desirable for the modulation input signal to operate up to 1 GHz with bandwidth >100 MHz, low phase noise, and high frequency stability.
- ASIC-based solutions for digital beamforming, creating one or more beams to replace mechanically scanned antennas.
- Digitizers for spectrometry starting at 40 Gsps, 20 GHz bandwidth, 8-bit or more resolution, and with a simple interface to a FPGA.

- ASIC implementations of polyphase spectrometer digital signal processing with <1 W/GHz, >10-GHz-bandwidth spectrometer with 8192 channels, and radiation-hardened and minimized power dissipation.

All systems or subsystems should also focus on low-power, radiation-tolerant broadband microwave spectrometers for NASA applications. Proposals should compare predicted performance and SWaP to conventional radio-frequency 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 receivers with increased bandwidth or resolution for 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.

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1. Ulaby, Fawwaz; and Long, David: *Microwave radar and radiometric remote sensing*, Artech House, 2015.
2. Chovan, Jozef; and Uherek, Frantisek: "Photonic Integrated Circuits for Communication Systems," *Radioengineering*, 27(2), pp. 357-363, 2018.
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5. Le Vine, David M.: "RFI and Remote Sensing of the Earth from Space," *Journal of Astronomical Instrumentation,* 8.01, 2019, https://ntrs.nasa.gov/citations/20170003103

Scope Title: Advanced Deployable/Inflatable 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/inflatable antenna technology is extremely limited, particularly above Ka-band. NASA requires low-loss deployable antenna apertures with high compaction ratio (small, stowed volume) at frequencies up to 200 GHz or beyond. Deployed aperture diameters of 0.5 to 2 m 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 broadband deployable or compact antenna feeds with bandwidths of two octaves or more. Frequencies of interest start at 500 MHz and extend to 5 THz. Loss should be as low as possible 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.

Broadband feedhorns with the target frequency range of 10 to 200 GHz are also desired.

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 64-70 GHz, 95 GHz, 167-175 GHz, or near 215 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 and 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:

1. Passive remote sensing such as performed by the Global Precipitation Mission (GPM) Microwave Imager (GMI): https://gpm.nasa.gov/missions/GPM/GMI
2. Chahat, N. et al.: "Advanced CubeSat Antennas for Deep Space and Earth Science Missions: A review," *IEEE Antennas and Propagation Magazine*, 61(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)

Related Subtopic Pointers: T10.01, T8.07
Lead Center: JPL
Participating Center(s): ARC, GSFC, LaRC, MSFC

Subtopic Introduction:

NASA is seeking innovative new technologies or improvements to existing technologies to meet the detector needs of future missions, as described in the most recent National Academies' decadal surveys. Areas of particular interest this year to this Subtopic are:

(1) Low-power and low-cost readout integrated electronics:
  (a) In-pixel digital readout integrated circuits (DROIC) for high-dynamic-range IR imaging and spectral imaging focal plane arrays.
  (b) Microwave kinetic inductance detector/transition-edge sensor (MKID/TES) detectors.
  (c) Low-power, low-noise, cryogenic multiplexed readouts for large-format 2D bolometer arrays.
(2) Far-IR/submillimeter-wave detectors:
  (a) New or improved technologies leading to measurement of trace atmospheric species or broadband energy balance in the IR and far-IR from geostationary and low-Earth orbital platforms.
  (b) Robust wafer-level packaging/integration technologies that will allow high-frequency-capable interconnects and allow two dissimilar substrates to be aligned and mechanically "welded" together.
  (c) Advanced terahertz receiver components.

Note that technologies for visible detectors and lidar detectors are not being solicited this year. For 2024 and 2025 the focus is on low-cost readouts and heterogeneous integration of semiconductors to enhance performance of far-IR detectors.

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 that can be accessed at this link (link is external): https://science.nasa.gov/about-us/science-strategy/decadal-surveys Selected components are needed for room-temperature operation, and other components for cryogenic temperature operation. 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 2024, emphasis will be placed on Earth-science-related technologies (IR and far-IR detectors and technologies).

Low-power and low-cost readout integrated electronics:

- Photodiode arrays: In-pixel 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.
- MKID/TES detectors: A radiation-tolerant, digital readout system is needed for the readout of low-temperature detectors such as MKIDs or other detector types that use microwave-frequency-

domain multiplexing techniques. Each readout channel of the system should be capable of generating a set of at least 1,500 carrier tones in a bandwidth of at least 1 GHz with 14-bit precision and 1-kHz frequency placement resolution. The returning-frequency multiplexed signals from the detector array will be digitized with at least 12-bit resolution. A channelizer will then perform a down-conversion at each carrier frequency with a configurable decimation factor and maximum individual subchannel bandwidth of at least 50 Hz. The power consumption of a system consisting of multiple readout channels should be at most 20 mW per subchannel or 30 W per 1-GHz readout channel. That requirement would most likely indicate the use of a radio-frequency (RF) system on a chip (SoC) or application-specific integrated circuit (ASIC) with combined digitizer and channelizer functionality.

- Bolometric arrays: Low-power, low-noise, cryogenic multiplexed readout for large-format two-dimensional (2D) bolometer arrays with 1,000 or more pixels, operating at 65 to 350 mK. We require a superconducting readout capable of reading two 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 (QWs).
- 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 research, analysis, 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 QW 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 the National Institute of Standards and Technology (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).
- Earth radiation budget measurement per 2007 decadal survey Clouds and Earth's Radiant Energy System (CERES) Tier-1 designation to maintain the continuous radiation budget measurement for climate modeling and better understand radiative forcings.
- Astrophysical missions such as OST will need IR and far-IR detector and related technologies.
- LANDSAT Thermal InfraRed Sensor (TIRS), Climate Absolute Radiance and Refractivity Observatory (CLARREO), BOReal Ecosystem Atmosphere Study (BOREAS), Methane Trace Gas Sounder, or other IR Earth-observing missions.
- Current science missions utilizing 2D large-format cryogenic readout circuits:
    - HAWC+ (High Resolution Airborne Wideband Camera Upgrade), for SOFIA (Stratospheric Observatory for Infrared Astronomy) future missions.
    - PIPER (Primordial Inflation Polarization Experiment), balloon-borne.
    - PICO (Probe of Inflation and Cosmic Origins), a probe-class cosmic microwave background mission concept.

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S11.05 Suborbital Instruments and Sensor Systems for Earth Science Measurements (SBIR)

Related Subtopic Pointers: T10.01, T8.07
Lead Center: LaRC
Participating Center(s): ARC, GSFC, JPL

Subtopic Introduction:

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 annual NASA Research Opportunities in Space and Earth Science (ROSES) solicitations. 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, unpiloted 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 of the art.

Scope Title: Sensors and Sensor Systems Targeting Aerosols and Clouds

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 annual NASA ROSES solicitations. 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, UAS, balloons, or ground networks; or end-to-end solutions providing needed data products from mated sensor and airborne/surface/subsurface platforms. An important goal is to create sustainable measurement capabilities to support NASA's Earth science objectives, with infusion of new technologies and systems into current/future NASA research programs. Instrument prototypes as a deliverable in Phase II proposals and/or field demonstrations are highly encouraged.

Complete instrument systems are generally desired, including features such as remote/unattended operation and data acquisition, and minimum size, weight, and power consumption. All proposals must summarize the current state of the art and demonstrate how the proposed sensor or sensor system represents a significant improvement over the state of the art.

Specific desired sensors or mated platform/sensors include:

- Small, low-cost multi-angle and multi-spectral (350 to 1600 nm wavelengths) imager suitable for airborne observations of cloud fraction and stereo-derived structure.
- High-size- and high-time-resolution measurements of the dry aerosol electrical mobility size distribution (10 to 1000 nm diameter) at 1 Hz suitable for deployment on aircraft from the surface to 43,000 ft altitude.
- Aerosol absorption coefficient covering the 400 to 800 nm spectral range for deployment on aircraft from the surface to 43,000 ft altitude; non-filter-based techniques (e.g., photoacoustic

spectroscopy) are preferred over filter-based instruments, but the instrument must be robust to temperature and pressure changes encountered during airborne operation.

- Aerosol scattering or extinction coefficient covering the 400 to 800 nm spectral range for deployment on aircraft from the surface to 43,000 ft altitude, where the instrument is robust to temperature and pressure changes encountered during airborne operation.
- Aerosol scattering as a function of scattering angle (phase function or, preferably, phase matrix).
- Aerosol complex refractive index.
- Aerosol and cloud particle number and size distribution covering the diameter size range of 0.01 to 200 µm with 10% accuracy under ambient (i.e., unperturbed) temperature, relative humidity, and pressure conditions. Probes targeting cloud particles in the lower end of this size range (0.01 to 5 µm) are particularly encouraged.
- Cloud probes able to differentiate and quantify nonsphericity and phase of cloud particles.
- Liquid and ice water content in clouds with calibrated accuracy and precision.
- Liquid and ice water path in relevant tropical, midlatitude, and/or polar environments, including data inversion and analysis software.
- Spectrally resolved cloud extinction.
- Static air temperature measured from aircraft to better than 0.1 °C accuracy.
- Isokinetically controlled aircraft aerosol inlets able to transmit both submicron-sized particles as well as those greater than 5 µm in diameter at airspeeds typical of the NASA P-3B, 777-200ER, and G-III/IV/V aircraft.
- Autonomous aerosol optical depth (AOD) ultraviolet-visible-near-infrared (UV-vis-NIR) (340 to 900 nm) hyperspectral plus short-wave-IR- (SWIR-) band sensor for shipboard-based measurements.
- Innovative, high-value sensors directly targeting a stated NASA need (including trace gases and ocean hyperspectral UV-vis-NIR water-leaving radiance and inherent optical properties) may also be considered. Proposals responding to this specific bullet are strongly encouraged to identify at least one relevant NASA subject matter expert.

The S11.05 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 and Change, and Carbon Cycle and Ecosystems focus areas as well as Applied Sciences. In situ and ground-based sensors inform NASA ship and airborne science campaigns led by programs in these focus areas and provide important validation of the current and next generation of satellite-based sensors (e.g., PACE, TEMPO, OCO-2, OCO-3, MAIA, GLIMR, SBG, and AOS). The solicited measurements will be highly relevant to future NASA campaigns (Arctic-COLORS), with objectives and observing strategies similar to past campaigns (e.g., ARCSIX, ASIA-AQ, CAMP2EX, FIREX-AQ, KORUS-AQ, DISCOVER-AQ, NAAMES, and EXPORTS).

Expected TRL or TRL Range at completion of the Project: 4 to 7

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

The ideal Phase I proposal would demonstrate a clear idea of the problem to be solved, potential solutions to this problem, and an appreciation for potential risks or stumbling blocks that might jeopardize the success of the Phase I and II projects. The ideal Phase I effort would then address and hopefully overcome any major challenges to (1) demonstrate feasibility of the proposed solution and (2) clear the way for the Phase II effort. These accomplishments would be detailed in the Phase I final report and serve as the foundation for a Phase II proposal.

The ideal Phase II effort would build, characterize, and deliver a prototype instrument to NASA, including necessary hardware and operating software. The prototype would be fully functional, but the packaging may be more utilitarian (i.e., less polished) than a commercial model.

State of the Art and Critical Gaps:

The subtopic is and remains highly relevant to NASA SMD and Earth Science research programs; in particular, the Earth Science Atmospheric Composition, Climate Variability and 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, OCO-3, MAIA, TEMPO, GLIMR, SBG, AOS; see links in References). The solicited measurements will be highly relevant to current and future NASA campaigns with objectives and observing strategies similar to past campaigns (e.g., ACTIVATE, NAAMES, EXPORTS, CAMP2EX, FIREX-AQ, KORUS-AQ, and DISCOVER-AQ; see links in References).

Relevance / Science Traceability:

The subtopic is and remains highly relevant to NASA SMD and Earth Science Division (ESD) research programs; in particular, the Earth Science Atmospheric Composition, Weather and Atmospheric Dynamics, Climate Variability and 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, OCO-3, MAIA, TEMPO, GLIMR, SBG, A-CCP; see links in References). The solicited measurements will be highly relevant to future NASA campaigns with objectives and observing strategies similar to current and past campaigns (e.g., ARCSIX, ASIA-AQ, ACTIVATE, NAAMES, EXPORTS, CAMP2EX, FIREX-AQ, KORUS-AQ, DISCOVER-AQ; see links in References). The need horizon of the subtopic sensors and sensors systems is both near-term (<5 yr) and midterm (5 to 10 yr).

Relevant programs and program officers include:

- NASA ESD Radiation Sciences Program (Hal Maring, HQ Program Scientist)
- NASA ESD Tropospheric Composition Program (Barry Lefer, HQ Program Scientist)
- NASA ESD Upper Atmosphere Research Program (Ken Jucks, HQ Program Scientist)
- NASA ESD Ocean Biology and Biogeochemistry Program (Laura Lorenzoni, HQ Program Scientist)
- NASA ESD Weather and Atmospheric Dynamics Program (Tsengdar Lee and Will McCarty, HQ Program Scientists)
- NASA ESD Earth Surface and Interior Program (Ben Phillips and Kevin Reath, HQ Program Managers)
- NASA ESD Airborne Science Program (Bruce Tagg, HQ Program Scientist)

References:

NASA Airborne Science Program aircraft include: https://airbornescience.nasa.gov/aircraft

Relevant current and past satellite missions and field campaigns include:

1. Decadal Survey recommended Atmosphere Observing System (AOS) mission focusing on aerosols, clouds, convection, and precipitation: https://science.nasa.gov/earth-science/decadal-surveys
2. OCO-2 satellite mission that targets spaceborne observations of carbon dioxide and the Earth's carbon cycle: https://ocov2.jpl.nasa.gov/mission/
3. OCO-3 satellite mission that extends NASA's study of carbon from the International Space Station (ISS): https://ocov3.jpl.nasa.gov/
4. MAIA (Multi-Angle Imager for Aerosols) Mission that will make radiometric and polarimetric measurements needed to characterize the sizes, compositions and quantities of particulate matter in air pollution: https://www.jpl.nasa.gov/missions/multi-angle-imager-for-aerosols-maia
5. TEMPO satellite mission focusing on geostationary observations of air quality over North America: http://tempo.si.edu/overview.html
6. PACE satellite mission that focuses on observations of ocean biology, aerosols, and clouds: https://pace.gsfc.nasa.gov/
7. SBG satellite mission focuses on observations of aquatic and terrestrial ecology: https://sbg.jpl.nasa.gov/
8. GLIMR satellite mission observes and monitors coastal ocean biology, biogeochemistry and ecology: https://eos.unh.edu/glimr
9. ARCSIX airborne field campaign targeting the Arctic surface-aerosol-cloud-radiation system: https://espo.nasa.gov/arcsix/content/ARCSIX
10. ASIA-AQ airborne field campaign targeting pollution and urban air quality in Asia: https://espo.nasa.gov/asia-aq/
11. Arctic-COLORS field campaign studies land-ocean interactions in a rapidly changing Arctic coastal zone, and assesses vulnerability, response, feedbacks and resilience of coastal ecosystems, communities, and natural resources to current and future pressures (field work to begin in 2025 and extend to 2028): https://arctic-colors.gsfc.nasa.gov/
12. CAMP2Ex airborne field campaign focusing on tropical meteorology and aerosol science: https://espo.nasa.gov/camp2ex
13. 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/
14. ATom airborne field campaign mapping the global distribution of aerosols and trace gases from pole-to-pole: https://espo.nasa.gov/atom/content/ATom
15. 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
16. DISCOVER-AQ airborne and ground-based campaign targeting pollution and air quality in four areas of the United States: https://www-air.larc.nasa.gov/missions/discover-aq/discover-aq.html
17. NAAMES Earth Venture suborbital field campaign targeting the North Atlantic phytoplankton bloom cycle and impacts on atmospheric aerosols, trace gases, and clouds: hhttps://www-air.larc.nasa.gov/missions/naames/index.html
18. EXPORTS field campaign targeting the export and fate of upper ocean net primary production using satellite observations and surface-based measurements: https://oceanexports.org

S12.01 Exoplanet Detection and Characterization Technologies (SBIR)

Related Subtopic Pointers: T10.01, T8.07

Lead Center: JPL
Participating Center(s): GSFC

Subtopic Introduction:

The characterization of exoplanets, planets orbiting stars other than our Sun, is one of the highest priorities set forth in the National Academies Astro2020 Decadal Survey. Characterization in this context means the study of a planet's atmospheric constituents, its mass, and its orbit. The National Academy of Sciences (NAS) recommended that NASA pursue a large space telescope with coronagraphic capabilities that would enable it to directly image Earth-like exoplanets in visible and near-infrared light. There are two complementary approaches to doing this. A coronagraph is an instrument mounted behind the telescope that uses a set of masks and deformable mirrors to control diffraction and scatter so that starlight is largely eliminated while passing the faint exoplanet light through to a sensitive detector. A starshade, on the other hand, is a large diffractive flower-shaped screen on a spacecraft positioned thousands of kilometers in front of the telescope, where it blocks the starlight. Both of these approaches rely on a priori knowledge of which stars have planetary systems. Extreme precision radial velocity (EPRV) is the most promising technique for providing this knowledge. EPRV measures the line-of-sight motion of stars as they react to orbiting planets with a precision of cm/sec over periods of years. This subtopic develops key technologies for coronagraphs, starshades, and EPRV instruments. Notably, coronagraphs and starshades must reduce the starlight to one part in 10 billion, while EPRV measures the velocity relative to the speed of light to a part in 10 billion as well.
General NASA astrophysics references:

1. National Academies Decadal Survey, "Pathways to Discovery in Astronomy and Astrophysics in the 2020s," 2021. https://nap.nationalacademies.org/catalog/26141/pathways-to-discovery-in-astronomy-and-astrophysics-for-the-2020s
2. NASA Astrophysics: https://science.nasa.gov/astrophysics
   This page has an overview that will provide context for proposers, and many useful links, including the Astrophysics Fleet Mission Chart and the Decadal Survey.
3. The Astrophysics Technology Development archive: https://www.astrostrategictech.us/
   This is a searchable database of non-SBIR-funded proposals (e.g., SATs, APRAs) that will show proposers where NASA is investing in technology.
4. The NASA Astrophysics biennial Technology Development report: https://apd440.gsfc.nasa.gov/technology.html
   This includes the list of prioritized NASA Astrophysics technology gaps: https://apd440.gsfc.nasa.gov/tech_gap_priorities.html

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, and thermal variations and to otherwise estimate the accuracy of high-dynamic range apodizing masks.
- Methods to distinguish the coherent and incoherent scatter in a broadband speckle field.

Wavefront control technologies:

- Small-stroke, high-precision, deformable mirrors scalable to 10,000 or more actuators (both to further the state of the art towards flight-like hardware and to explore novel concepts). Multiple deformable-mirror technologies in various phases of development and processes are encouraged to ultimately improve the state of the art in deformable-mirror technology. Process improvements are needed to improve repeatability, yield, power consumption, connectivity, stability, and performance precision of current devices.
- High-precision, stable, deformable mirrors whose nominal surface can carry optical prescriptions for dual use as imaging optics such as off-axis parabolas and apodizing elements. Similar to other technologies, scalable actuator arrays between hundreds and thousands of actuators are encouraged.
- Driving electronics, including multiplexers and application-specific integrated circuits (ASICs) with ultra-low power dissipation for electrical connection to deformable mirrors.

Optical coating and measurement technologies:

- Instruments capable of measuring polarization crosstalk and birefringence to parts per million.
- Polarization-insensitive coatings for large optics.
- Methods to measure the spectral reflectivity and polarization uniformity across large optics.

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

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II:

- Research

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

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, LUVOIR, starshades, and any space telescopes that could potentially be used for exoplanet imaging and characterization.

References:

1. Exoplanet Exploration—Planets Beyond Our Solar System: https://exoplanets.nasa.gov
2. Exoplanet Exploration Program: https://exoplanets.nasa.gov/exep/
    - Specifically, the technology pages and those addressing coronagraphs: https://exoplanets.nasa.gov/exep/technology/technology-overview/
    - Key documents: https://exoplanets.nasa.gov/exep/resources/documents/
3. High-Contrast Imaging Testbeds: https://arxiv.org/abs/1907.09508
4. 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, 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:

1. Starshade 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 (2022) and Science Mission Directorate Science Plan (2020) 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 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:

1. NASA Strategic Plan 2022: https://www.nasa.gov/wp-content/uploads/2018/01/2022_nasa_strategic_plan_0.pdf
2. NASA Science Mission Directorate Science Plan: https://smd-cms.nasa.gov/wp-content/uploads/2023/09/2020-2024-nasa-science-plan-yr-23-update-final.pdf

Precision radial velocity:

1. Fischer et al.: "State of the Field: Extreme Precision Radial Velocities," 2016, https://ui.adsabs.harvard.edu/abs/2016PASP..128f6001F/abstract
2. Plavchan et al.: "Radial Velocity Prospects Current and Future: A White Paper Report prepared by the Study Analysis Group 8 for the Exoplanet Program Analysis Group (ExoPAG)," 2015, http://adsabs.harvard.edu/abs/2015arXiv150301770P
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4. EPRV Working Group report. See this website for preliminary information and the final report from this group due in mid-August: https://exoplanets.nasa.gov/exep/NNExplore/EPRV/

Photonics in astronomical instrumentation:

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S12.03 Advanced Optical Systems and Fabrication/Testing/Control Technologies for Extended- Ultraviolet/Optical to Mid-/Far-Infrared Telescopes (SBIR)

Related Subtopic Pointers: T10.01, T8.07
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), CubeSat, rocket, Pioneer, and balloon) 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 optiomechanical 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), Prioritized Technology Gaps (https://apd440.gsfc.nasa.gov/tech_gap_priorities.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.

This subtopic has three Scopes. Scopes #1 and #2 solicit technologies for all potential missions: Scope #1 seeks mirror-system solutions, and Scope #2 seeks technologies to manufacture, test, and control mirror surfaces. Scope #3 solicits narrowly defined special topics changes every 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 Flagship) operating at any wavelength from ultraviolet/optical (UV/O) to mid-/far-infrared (IR). A mirror system is defined as the substrate (material and core structure) and supporting structure along 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 STOP modeling.

The primary near-term need is technologies to enhance/enable the Habitable Worlds Observatory (HWO). HWO desires a 6-m aperture telescope 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, to enable coronagraphy, the HWO 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 coefficients of thermal expansion (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 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 $3.5 M/m^2.

Potential balloon science missions are either in the extreme UV (EUV), UVO, or in the IR/far-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 low CTE, homogenous CTE, and high thermal conductivity; metal alloy, nanoparticle composite, carbon fiber, graphite composite, ceramic, or SiC materials; or additive manufacture or direct precision machining. CubeSat missions need low-cost, compact, scalable, diffraction-limited, and athermalized off-axis reflective and on-axis telescopes. One potential mission is for near-IR-/short-wave-IR- (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. Although detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.

An ideal Phase II project 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 the 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 $100 thousand and $1 million per square meter.

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:

1. NASA Astrophysics Division: https://science.nasa.gov/astrophysics
2. 2022 Astrophysics Biennial Technology Report: https://apd440.gsfc.nasa.gov/technology.html
3. 2022 Astrophysics Prioritized Technology Gaps: https://apd440.gsfc.nasa.gov/tech_gap_priorities.html
4. 2022 Exoplanet Exploration Program Gap List: https://exoplanets.nasa.gov/internal_resources/2269/
5. NASA Astrophysics Technology Development archive: https://www.astrostrategictech.us/
6. Dankanich et. al.: “Planetary Balloon-Based Science Platform Evaluation and Program Implementation - Final Report,” NASA/TM-2016-218870, available from https://ntrs.nasa.gov/
7. For additional information about scientific balloons: https://www.csbf.nasa.gov/docs.html
8. 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
9. 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

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

Scope Description:

Although the primary focus of this scope is the Habitable World Observatory, 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 reduce cost—particularly for large mirrors. Technology that increases remove rate (to reduce processing time) while producing smoother surfaces (less mid- and high-spatial frequency error) are potentially enhancing. Potential technologies for improvement include (but are not limited to): computer-controlled grinding/polishing, electrolytic in-process dressing (ELID) processes, electrochemical processes, on-machine in-process metrology feedback, 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 use nonscience light rejected by the coronagraph to estimate drifts in the system wavefront during observations. These techniques are limited by the low stellar photon rates of the dim objects being observed (~5 to 11 Vmag), leading to tens of minutes between wavefront control updates. New methods may include 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 meet 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 James Webb Space Telescope (JWST) and Nancy Grace Roman Space Telescope 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. Wavefront (WF) sensing and control for coronagraphs, including electric field conjugation and low-order WF sensing (LOWFS), is at TRL 4 and is being developed and demonstrated by the Wide Field Infrared Survey Telescope Coronagraph Instrument (WFIRST/CGI). However, none of these technologies have the precision and frequency bandwidth to enable <3 pm rms stability needed for exo-Earth coronography.

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 state of the art (SOA) is defined by the JWST actuators. They provide ample range for far-IR applications but have more precision than necessary and are expensive. Furthermore, they are not adequate for UV/optical (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 WF 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:

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

Scope Title: Special Topics: Polarization Birefringence Mapper, Integrated Flexure Interface and Near-Angle Scatter

Scope Description:

Special Topic #1: Polarization Birefringence Mapper
To detect and characterize exo-Earths around Sun-like stars, the Habitable World Observatory (HWO) requires mirrors with polarization birefringence uniformity on the order of 1% over its full aperture. This special topic solicits an instrument to map polarization birefringence for the purpose of qualifying flight mirror coating processes and acceptance testing flight mirrors after coating. Flight mirrors may have diameters from 1.5 to 6 m. It is desired to characterize polarization properties at scientifically relevant wavelengths with 20% spectral bandwidth between 350 and 1800 nm (stretch goal of 100 to 2500 nm).

Special Topic #2: Integrated Flexure Interface
Investigate integration of flexures or otherwise complaint mounting interfaces into a mirror substrate over 1 m in diameter. The goal is a reduction in overall mass and size of the substrate and support structure by taking advantage of new manufacturing technologies to reduce part count. A successful project will show

minimal mirror surface deformation when mounted to an over-constrained (nonkinematic) interface at various gravity orientations.

Special Topic #3: 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.

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:

- Prototype
- Hardware
- Software

Desired Deliverables Description:

Special Topic #1: Polarization Birefringence Mapper
Phase I will demonstrate a process to map polarization properties of an optical surface that enables quantification of the reflected wavefront's spatial polarization uniformity with a 0.1% accuracy (nominal). The process will be demonstrated on a 150-mm mirror (nominal diameter with a to-be-determined (TBD) radius of curvature) with relevant protected aluminum-coated (i.e., Al:MgF, Al:LiF, or other) mirror provided by NASA with 25-mm spatial sampling (nominal) at scientifically relevant wavelengths defined by NASA with 20% spectral bandwidth between 250 and 1000 nm.

Phase II will deliver an instrument to map polarization properties of an optical surface that enables quantification of the reflected wavefront's spatial polarization uniformity with a 0.1% accuracy (nominal). Process will be demonstrated on a 0.5-m mirror (nominal diameter with TBD radius of curvature) with relevant protected aluminum-coated (i.e. Al:MgF, Al:LiF, or other) mirror provided by NASA and software that can stitch sub-aperture maps into a full aperture polarization birefringence map of a primary mirror at least 6 m in diameter with 25-mm spatial sampling (nominal) at scientifically relevant wavelengths defined by NASA with 20% spectral bandwidth between 250 and 1000 nm.

Special Topic #2: Integrated Flexure Interface
Phase I Ideal deliverable would be an integrated mirror and compliant interface at least 0.25 m in diameter with properties that can be modeled and verified by testing.

Phase II Ideal deliverable would further advance the technology by producing a flight-qualifiable integrated mirror and compliant interface greater than 0.5 m in diameter (with a TRL in the 4 to 5 range).

Phase I and II hardware deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing the properties of the materials.

Special Topic #3: Near-Angle Scatter
Phase I details a theoretical analysis of how to predict near-angle scatter in the 40 to 500 mAs region and an implementable test plan to validate the model.

Phase II provides data that validates with greater than 85% confidence a model for predicting near-angle scatter in the 40 to 500 mAs region.

State of the Art and Critical Gaps:

Special Topic #1: Polarization Birefringence Mapper
Single-point and small-area characterization of polarization properties of optical surfaces and coatings over wavelengths from 250 to 1000 nm with ~0.1% accuracy is a mature technology with multiple commercial instruments. This technology has been integrated into commercial instruments for characterizing large flat panel liquid crystal displays (LCDs) (i.e., flat-panel televisions) as large as 3 m. The purpose of this Special Topic is to leverage these commercial capabilities for a specific NASA need—characterizing polarization properties of 1.5- to 6-m-diameter mirrors of 10- to 15-m radius of curvature and having space-qualified coatings with high reflectivity from 100 to 2500 nm—for the purpose of qualifying mirror coating processes and acceptance testing flight mirrors after coating.

Special Topic #2: Integrated Flexure Interface
New technologies such as additive manufacturing and computer numerically controlled (CNC) electrodischarge machining have opened the possibility of combining what traditionally have been separate components into a single part. Reducing part count not only saves mass and space, but also assembly, alignment, and all associated fixtures and procedures. In all previous cases, the investments have been in the mirror substrate only. The next logical step is to investigate how to integrate flexure interfaces between these mirrors and mounting systems.

Special Topic #3: Near-Angle Scatter
Rayleigh-Rice surface scatter theory is widely accepted for smooth surfaces but is physically unrealistic for describing near-angle scatter in the 40 to 500 mAs 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 mAs. It is unclear if current commercial straylight modeling software (of which there are at least two) can perform the required analysis.

Relevance / Science Traceability:

Mirror technology is enabling for all potential SMD science.
Special Topic #1 is enabling for the potential HWO mission science.
Special Topic #2 has applicability to any mission requiring a large-aperture low-mass stiff mirror system.
Special Topic #3 is enabling for potential HWO mission concept trade studies.

References:

1. 2022 Astrophysics Biennial Technology Report: https://apd440.gsfc.nasa.gov/technology.html
2. 2022 Exoplanet Exploration Program Gap List: https://exoplanets.nasa.gov/internal_resources/2269/
3. Breckenridge/Chipman SAT final report: https://exoplanets.nasa.gov/internal_resources/1686/

S12.04 X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UVOIR (Ultraviolet-Optical- Infrared), and Free-Form Optics (SBIR)

Related Subtopic Pointers: T10.01, T8.07
Lead Center: GSFC
Participating Center(s): JPL, MSFC

Subtopic Introduction:

The National Academy Astro 2020 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 2014-2033 Roadmap identifies the coating technology for space missions to enhance the rejection of undesirable spectral lines and to improve space/solar-flux durability of extreme UV (EUV) optical coatings as well as coating deposition to increase the maximum spatial resolution: https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/2014_HelioRoadmap_Final_Reduced_0.pdf

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, ultra-stable, 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 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. Additionally, we need epoxies that impart little to no stress on the mirrors during application and curing. For silicon mirrors, the epoxies should absorb 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 \$4M to \$6M 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 sub elements of this subtopic is an x-ray optical mirror system—demonstration, analysis, reports, software, and hardware prototype:

- Phase I deliverables: Reports, analysis, and demonstration.

  Analysis: Please use modeling and analytical techniques to predict the suitability of the proposed design.
  Demonstration: Please show that the end product proposed is achieving the specified requirement.

- Phase II deliverables: Analysis, demonstration, and prototype. Please provide a breadboard and test results that show sufficient data verifying the performance of the proposed design.

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, ultra-stable 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 2020 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.

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:

1. NASA Astrophysics: https://science.nasa.gov/astrophysics. This page has an overview that will provide context for proposers, and many useful links including the Astrophysics Fleet Mission Chart and the Decadal Survey.
2. The Astrophysics Technology Development archive: https://www.astrostrategictech.us/. This is a searchable database of non-SBIR funded proposals (e.g., SATs, APRAs) that will show proposers where NASA is investing in technology.
3. The Astrophysics Biennial Technology report: https://apd440.gsfc.nasa.gov/technology.html. This includes the list of prioritized Astrophysics technology gaps: https://apd440.gsfc.nasa.gov/tech_gap_priorities.html

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Scope Title: Coating Technology for X-Ray-UVOIR (Ultraviolet-Optical-Infrared)

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 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-IR (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: Reports, analysis, and demonstration. Analysis: Please use modeling and analytical techniques to predict the suitability of the proposed design. Demonstration: Please show that the end product proposed is achieving the specified requirement.

- Phase II deliverables: Analysis, demonstration, and prototype. Please provide a breadboard and test results that show sufficient data verifying the performance of the proposed design.

State of the Art and Critical Gaps:

Coating technology (for a wide range of wavelengths from x-ray to IR:

- Habitable Worlds Observatory (HWO) needs a process to be developed and validated that can deposit coatings with high reflectivity from 100 to 2500 nm on concave mirrors of diameter from 1.5 to 6 m with approximately 1% reflectance and 1% polarization form birefringence uniformity over at least 100 x 100 spatial sampling. The range described as 100 to 250 nm is relevant to HWO, and the ideal coating UV reflectivity should be close to unity across those wavelengths. HWO is seeking a high throughput.
- Astro2020 has placed pursuit of a new constellation of Great Observatories as the top national priority for the future of space astrophysics. The report envisions a new strategy for the development of these large missions in the form of the Great Observatories Mission & Technology Maturation Program (GOMaP), whose first entrants are to be a "~6-m IR/O/UV Observatory optimized for exoplanet imaging/spectroscopy and general astrophysics", followed by a high spatial and spectral resolution X-ray Great Observatory, and a Far-Infrared Great Observatory.
- Current EUV is defined by Heliophysics (80% reflectivity from 60 to 200 nm).
- Current X-Ray-UVOIR (Ultraviolet-Optical-Infrared) 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:

- 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 Roadmap 2014-2033, https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/2014_HelioRoadmap_Final_Reduced_0.pdf 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:

1. 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
2. HEASARC: Upcoming Missions (nasa.gov)
3. ATHENA (nasa.gov)
4. Concepts for Future High Energy Astrophysics Future Missions (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 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: Reports, analysis, and demonstration. Analysis: Please use modeling and analytical techniques to predict the suitability of the proposed design. Demonstration: Please show that the end product proposed is achieving the specified requirement.
- Phase II deliverables: Analysis, demonstration, and prototype. Please provide a breadboard and test results that show sufficient data verifying the performance of the proposed design.

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 because of 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 HWO (Habitable Worlds Observatory), currently being proposed for the 2020 Astrophysics Decadal Survey have demonstrated improved optical performance over a larger field of view afforded by free-form optics. Such programs will require advances in free-form metrology to be successful.

References:

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

S12.06 Detector Technologies for Ultraviolet (UV), X-Ray, and Gamma-Ray Instruments (SBIR)

Related Subtopic Pointers: T10.01, T8.07
Lead Center: JPL
Participating Center(s): GSFC, MSFC

Subtopic Introduction:

This subtopic covers detector requirements for a broad range of wavelengths from ultraviolet (UV) through gamma ray for applications in Astrophysics, Earth Science, Heliophysics, and Planetary Science. Requirements across the board are for greater numbers of readout pixels, lower power, faster readout rates, greater quantum efficiency, single-photon counting, and enhanced energy resolution.

Scope Title: Detectors

Scope Description:

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 Habitable Worlds Observatory (HWO) that is under development based on recommendation of 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/sec; 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/sec), low dark (<<1 count/cm^2/sec); quantum efficiency (QE) >30% between 100 and 200 nm; solar blind; and radiation hard.
- High-dynamic-range, high-efficiency detectors in ultraviolet/optical/near-infrared (UV/O/NIR), narrowband (UV only), and broadband (UV to NIR).
- 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 $>10\times10^6$ 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/sec/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 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/
- Heliophysics: https://science.nasa.gov/heliophysics

Mission studies developed as part of Astro2020 Decadal Survey:

- 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 (Lunar Reconnaissance Orbiter 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:

1. NASA Cosmic Origins (COR): https://cor.gsfc.nasa.gov/
2. NASA Planetary Missions Program Office: https://www.nasa.gov/planetarymissions/
3. NASA Explorers and Heliophysics Projects Division (EHPD): https://ehpd.gsfc.nasa.gov/
4. NASA Astrophysics: https://science.nasa.gov/astrophysics
5. The Astrophysics Technology Development archive: https://www.astrostrategictech.us/
6. The Astrophysics Biennial Technology report https://apd440.gsfc.nasa.gov/technology.html, including the list of prioritized Astrophysics technology gaps: https://apd440.gsfc.nasa.gov/tech_gap_priorities.html
7. NASA Astrophysics Technology Gap list: https://apd440.gsfc.nasa.gov/tech_gaps.html; https://apd440.gsfc.nasa.gov/tech_gap-descriptions.html#tieronetop
8. NASA Heliophysics Strategic Mission Programs: https://science.nasa.gov/heliophysics/2024_decadal_survey/heliophysics-strategic-mission-programs
9. 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
10. "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
11. 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

S13.03 Extreme Environments Technology (SBIR)

Related Subtopic Pointers: T10.01, T8.07
Lead Center: JPL
Participating Center(s): GRC, GSFC, LaRC

Subtopic Introduction:

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. However, these developments are still at the early stages and need to be advanced to higher 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 systems with low size, weight, and power (SWaP) and high efficiency that can readily survive and operate in these extreme environments without the need for the environmental protection systems.

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 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 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).

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 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 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 and low-temperature-capable 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 and low temperature capable, radiation-hard sensors and actuators for autonomous robotic missions.
- Wide-temperature-range and low-temperature-capable feedback sensors with subarcsecond/nanometer precision.
- Wide-temperature-range and low-temperature-capable long-life, long-stroke, low-power, and high-torque force actuators with subarcsecond/nanometer precision.
- Wide-temperature-range and low-temperature-capable 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, low- and wide-operating-temperature, low-noise mixed-signal electronics for spaceborne systems such as guidance and navigation avionics and instruments.
- Radiation-tolerant/radiation-hardened, low- and wide-operating-temperature power electronics and energy storage devices.
- 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. However, these developments are still at the early stages and need to be advanced to higher 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 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.

References:

1. Selected publications from the IEEE Aerospace Conference: https://ieeexplore.ieee.org/xpl/conhome/1000024/all-proceedings (or via IEEE *Xplore* Digital Library).
2. Selected publications from the Outer Planets Assessment Group (OPAG): https://www.lpi.usra.edu/opag/

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

Related Subtopic Pointers: T10.01, T8.07
Lead Center: JPL
Participating Center(s): ARC, GRC, GSFC, MSFC

Subtopic Introduction:

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) and/or in the "Artemis III Science Definition Team (SDT) Report." 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.

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

Scope Description:

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 on 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 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 (direct-current) 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 capability 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-4 (BSL-4) conditions. This fly-through sampling focus is distinct from S13.01, which solicits sample collection technologies from surface platforms.
- Instruments for quantifying the lunar regolith for meeting in-situ resource utilization (ISRU) and in-situ construction needs. The technologies must characterize at least one of the following key properties of regolith, which are thought to affect the operation of ISRU and construction processes: (1) mineral phase composition and elemental analysis, (2) softening and melting points, and (3) melt viscosity. The target performance metrics are (1) temperature stability of +/- 5 °C and (2) system stability and repeatability <3%. The major mineral phases of interest are those found in the lunar highlands regolith, which is primarily composed of anorthosite rock. The quantification of mineral phases such as pyroxenes, olivine, iron sulfides (Troilite), apatite, and anorthite are desired. The instruments sought are envisioned to run in batch mode to periodically sample the lunar regolith feed into ISRU and construction processes and must be able to operate for at least 1 year with a goal of 5 years without substantial maintenance in the dusty regolith environment. The proposed instruments must be able to operate on the lunar surface in temperatures (with thermal mitigations) of up to 110 °C (230 °F) during sunlit periods and as low as -170 °C (-274 °F) during periods of darkness.

Please note that detector technologies for visible, infrared (IR), far-IR, and submillimeter are excluded from this subtopic and should be submitted to the S11.04 Subtopic “Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter.”

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 SMD 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, such as 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:

1. 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
2. NASA Roadmap for ocean worlds exploration: http://www.lpi.usra.edu/opag/ROW
3. In situ instruments and technologies for NASA's ocean worlds exploration goals: https://www.nasa.gov/specials/ocean-worlds/
4. NASA technology solicitation ROSES 2023/C.12 Planetary Instrument Concepts for the Advancement of Solar System Observations(PICASSO) call: https://nspires.nasaprs.com/external/solicitations/summary.do?solId={FAA785AB-5F8F-608A-7507-41FF8AE9EE50}&path=&method=init
5. NASA technology solicitation ROSES 2023/C.19 Development and Advancement of Lunar Instrumentation (DALI) call: https://nspires.nasaprs.com/external/solicitations/summary.do?solId={60CAE906-CC40-2CED-B173-1EE21373C346}&path=&method=init

6. Needed instrument technologies as listed on the website of NSAS's Planetary Exploration Science Technology Office (PESTO): ww1.grc.nasa.gov/space/pesto/instrument-technologies-future/
7. Artemis III Science Definition Team (SDT) Report: https://www.nasa.gov/sites/default/files/atoms/files/artemis-iii-science-definition-report-12042020c.pdf
8. Papike, J. J., Taylor, Lawrence A. , Simon S. B., Heiken Grant, Vaniman David, French, Bevan. M. "Lunar Sourcebook: A User's Guide to the Moon," Cambridge University Press, 1991, pp 121–182: http://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/Chapter05.pdf

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

Related Subtopic Pointers: T10.01, T8.07
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.

Space-qualifying new commercial sensor technologies for Heliophysics observations is an approach that can both reduce accommodation needs as well as bring improved measurement capabilities. For a list of

currently operating and past missions, see https://science.nasa.gov/missions-page?field_division_tid=5&field_phase_tid=All.
Other relevant references include:

- 2013 Heliophysics Decadal Survey: https://www.nationalacademies.org/our-work/a-decadal-strategy-for-solar-and-space-physics-heliophysics
- NASA Heliophysics Roadmap (2014-2033): https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/2014_HelioRoadmap_Final_Reduced_0.pdf
- 2023 Heliophysics Strategic Technology Office (HESTO) Gap and Trend Analysis: https://zenodo.org/record/8091762

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:

- Technologies to enable remote sensing of magnetic fields in the solar corona. For example, technologies that enable high-SNR (signal to noise ratio) observation of off-limb Ly-Alpha.
- Technologies that enable remote sensing of neutral winds in the upper atmosphere. This may include:
    - Light detection and ranging (LIDAR) systems for high-power, high-frequency geospace remote sensing, such as sodium and helium lasers.
    - Technologies for precise radiometry at THz bands corresponding to upper atmosphere thermal emissions in the 1-5 THz range, particularly at 4.7 THz. This includes, but is not limited to:
        - Technologies that reduce size, mass, and power of THz radiometry instrumentation, for example by increasing the operating temperature of THz detectors.
        - Technologies that enable THz spectroscopy, for example by use of THz local oscillator for heterodyne mixing.
        - Technologies that improve signal-to-noise ratio of THz instrumentation, particularly at 4.7 THz.
        - Technologies to enable imaging of THz radio observations.
    - Nitric oxide sensors which can quantify NO abundances in both daytime and nighttime conditions in Earth’s mesosphere-lower thermosphere.
- Technologies or components enabling auroral, airglow, geospace, and solar imaging at visible, far and extreme ultraviolet (FUV/EUV), and soft x-ray wavelengths (e.g., mirrors and gratings with high-reflectance coatings, multilayer coatings, narrowband filters, blazed gratings with high ruling densities, and diffractive and metamaterial optics).
- Electromagnetic sounding of ionospheric or magnetospheric plasma density structure at radiofrequencies from kHz to >10 MHz.
- Passive sensing of ionospheric and magnetospheric plasma density structure using transmitters of opportunity (e.g., global navigation satellite system (GNSS) or ground-based transmissions).
- Technologies that enable observations of bright solar flares without saturation in wavelength range from EUV to x-rays. This includes, but is not limited to:

  - Fast-cadence solid-state detectors or camera systems (e.g., charge-coupled device (CCD), complementary metal-oxide semiconductor (CMOS)) for imaging in the EUV with or without intrinsic ion suppression.
  - Fast-cadence solid-state detectors or camera systems for imaging soft or hard x-rays (~0.1 to hundreds of keV), preferably with the ability to detect 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 improve or enable very long focal lengths or imaging spatial resolutions in the EUV to x-ay range, particularly those that are suitable for observing very bright sources.
  - Technologies to improve focusing optics for hard x-rays in the 1 to 300 keV range.
- Technologies to either reduce the size, complexity, or mass or to improve the imaging resolution of solar telescopes used for imaging solar x-rays such as those that enable smoothly laminating silicon micropore optics with materials that enhance the grazing incidence reflectivity of soft x-rays in the energy range from 0.1 to 2 keV.
- Technologies to improve or enable the rejection of background x-rays in the 1 to 300 keV range such as those that:
  - Shield or block background particles from a detector.
  - Provide anticoincidence detection of background x-rays.
- Technologies, including metamaterials and micro-electro-mechanical systems (MEMS) that enable polarization, wavelength, or spatial discrimination without macroscale moving parts.
- Technologies to improve upon coronagraphs, such as those that
  - Improve solar occultation technologies, including solar shades for UV and EUV observations.
  - Reduce the size, mass, and power.
  - Better enable solar coronagraphs to be used in deep-space missions (beyond earth orbit).

Proposers are strongly encouraged to relate their proposed development to NASA's future heliophysics goals as set out in the references provided. Proposed instrument components and/or architectures should be as simple, reliable, and low risk as possible, while enabling compelling science. Novel instrument concepts (e.g., quantum sensors) are highly 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 08.1 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 LWS and 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:

1. For example, missions, see "NASA Science Missions," https://science.nasa.gov/missions-page?field_division_tid=5&field_phase_tid=All
2. For details of the specific requirements, see the National Research Council’s "Solar and Space Physics: A Science for a Technological Society," http://nap.edu/13060
3. For details of NASA's Heliophysics roadmap, see the "NASA Heliophysics Science and Technology Roadmap for 2014-2033," https://explorers.larc.nasa.gov/HPSMEX/MO/pdf_files/2014_HelioRoadmap_Final_Reduced_0.pdf
4. 2013 Heliophysics Decadal Survey: https://www.nationalacademies.org/our-work/a-decadal-strategy-for-solar-and-space-physics-heliophysics

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

Scope Description:

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) and ultra-high-voltage power supplies for space (50 to 100 kV), including approaches that lead to the reduction in size, mass, and power of high-voltage power supplies.

- Technologies for the development of magnetic core material suitable for incorporation into science-grade flux-gate magnetometers.
- Technologies for the development of compactly stowed, lightweight, long, straight, and rigid booms compatible with CubeSats or SmallSats.
- Technologies for the rapid and cost-effective fabrication of electrostatic analyzer components.
- Technologies for improved detection of low-energy (<10 keV) ions and electrons.
- Technologies for the efficient conversion of neutrals (<1 keV) to charged particles.
- Technologies for reduction in size, mass, and power of electric and magnetic field wave instrumentation.

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:

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. High voltage in charged-particle instrumentation is typically limited to ~10 kV. Higher voltage supplies are needed to enable instrumentation capable of improved composition and heavy-ion measurements. The availability of high-voltage optocouplers (HVOCs) suitable for spaceflight are severely limited. Metal-oxide-semiconductor field-effect transistor (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. In addition, the reduction of size, mass, and power associated with state-of-the-art <10 kV power supplies is needed for the next generation of mission concepts.
- 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.
- Electrostatic analyzer components are typically manufactured using traditional machining techniques. New technologies (e.g., additive machining, new analyzer concepts) are needed to enable cost-effective fabrication and assembly of multiple instruments for new multispacecraft mission concepts.
- Low-energy (<10 keV/e) charged particle measurements are typically achieved through secondary electron multiplication via channel electron multipliers (CEMs) or microchannel plates

(MCPs). New technologies are needed to enable the detection of low-energy charged particles with reduced need for high-voltage and/or significant contamination-control requirements.
- Conversion efficiencies for neutral particles for energetic neutral atom (ENA) instrumentation are currently very low for particles under 1 keV. New technologies are needed to improve the detection efficiency of lower energy ENAs.
- New technologies are needed to reduce mass, power, and size of electric and magnetic field wave instruments for the next generation of Heliophysics mission concepts.

Relevance / Science Traceability:

Particle and field instruments and technologies are essential bases to achieve the 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 applications 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:

1. National Research Council: "Solar and Space Physics: A Science for a Technological Society," 2013: http://nap.edu/13060
2. Example missions (e.g., NASA Magnetospheric Multiscale (MMS) mission, Fast Plasma Investigation, Solar Probe, Solar Terrestrial Relations Observatory (STEREO), and Geospace Dynamics Constellation): http://science.nasa.gov/missions

S15.01 Plant Research Capabilities in Space (SBIR)

Related Subtopic Pointers: T10.01, T8.07
Lead Center: KSC
Participating Center(s): ARC, JPL

Subtopic Introduction:

Plants are essential for NASA's space exploration campaigns because they provide fresh and nutritious food for the crew and decrease dependence on Earth as missions become more complex. Furthermore, plants are expected be an important component of future bioregenerative-based, environmental control, and ecological life support systems (ECLSS) because they generate oxygen, remove carbon dioxide, purify water, and recycle waste. Last but not the least, plants provide psychological benefits to the crew as mission duration and isolation from Earth increases.
This subtopic focuses on developing technologies for plant research in space to enable a mechanistic understanding of their biology under various spaceflight stressors, while also providing a tool for

successful crop cultivation in microgravity and controlled environment agriculture systems, greenhouses, and farmer's fields on Earth. The wearable plant sensors developed through this solicitation would be complementary to NASA Earth Science's efforts in airborne remote sensing technologies of vegetation for SMART agriculture and ecosystem management.

Scope Title: Plant Research Capabilities in Space and on Earth, Wearable Sensors for Monitoring Plant Performance and Health in Space and on Earth

Scope Description:

Agriculture on Earth benefits from sensor technologies that help farmers make decisions on the time to plant, water, fertilize, harvest, and treat crop diseases. These sensor technologies have tremendous potential for plant research hardware and crop production systems in future space missions and habitats. Like farmers on Earth, astronauts need technology that will allow them to identify problems early so they can take corrective action before crop health, productivity, and safety are negatively affected.

Furthermore, the ability of these sensors to monitor the experimental environment will help crew prevent adverse impacts on model plant organisms so more reliable/reproducible basic science research outcomes are achieved.

NASA is interested in wearable or attachable sensors that can detect water, nutrient, and disease stress in plants. Water stress could include consequences of too much (e.g., hypoxic) or too little (e.g., drought) water in the plants. Proposals should describe plant sensor technologies that can be attached directly to the plant or integrated into existing spaceflight plant growth hardware (Veggie or the Advanced Plant Habitat). Sensors should be miniaturized, preferably wireless, and clearly describe the output signal or measurement and link It to the physiological process and/or stress being measured.

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

Primary Technology Taxonomy:

- Level 1: TX 08 Sensors and Instruments
- Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype

Desired Deliverables Description:

Phase I should demonstrate the proof of concept and provide a written report describing initial testing of the technology or principles in the laboratory or a plant growth system or relevant agricultural setting. The path toward hardware development in Phase II, along with a possible demonstration on the International Space Station (ISS) should be stated, and an assessment of the technology business case (i.e., cost and revenue forecast, market size, potential customers, etc.) is also required.

At the end of Phase II, a deliverable would be a working prototype or engineering development unit to demonstrate a sensor that can be attached to a plant growing on space hardware, such as the Vegetable

Production System (Veggie), the Advanced Plant Habitat (APH) or future crop production systems (e.g., Ohalo III).

State of the Art and Critical Gaps:

State of the art is compact sensors driven by artificial intelligence (AI) and advanced engineering that will enable crew to decide on best management approaches to space crop cultivation and basic plant biology research.

Relevance / Science Traceability:

This Subtopic will support Biological and Physical Sciences mandate of thriving in deep space and transformative science through in situ monitoring of the physiology and microenvironment of model plants. Moreover, NASA's exploration campaigns will be advanced by enabling sustainable food production in space in the form of edible crops.

References:

1. Di Tocco J, Lo Presti D, Massaroni C, Cinti S, Cimini S, De Gara L, Schena E. (2023) Plant-Wear: A Multi-Sensor Plant Wearable Platform for Growth and Microclimate Monitoring. *Sensors (Basel).* 23(1):549. doi: 10.3390/s23010549.

2. Hossain NI, Tabassum S. (2023) A hybrid multifunctional physicochemical sensor suite for continuous monitoring of crop health. *Sci Rep.* 13(1):9848. doi: 10.1038/s41598-023-37041-z.

3. Ibrahim H, Moru S, Schnable P, Dong L. (2022) Wearable Plant Sensor for In Situ Monitoring of Volatile Organic Compound Emissions from Crops. *ACS Sens.* 7(8):2293-2302. doi: 10.1021/acssensors.2c00834.

4. Lee G, Hossain O, Jamalzadegan S, Liu Y, Wang H, Saville AC, Shymanovich T, Paul R, Rotenberg D, Whitfield AE, Ristaino JB, Zhu Y, Wei Q. (2023) Abaxial leaf surface-mounted multimodal wearable sensor for continuous plant physiology monitoring. *Sci Adv.* 9(15):eade2232. doi: 10.1126/sciadv.ade2232.

5. Li Z, Paul R, Tis TB, Saville AC, Hansel JC, Yu T, Ristaino JB, Wei Q (2019) Non-invasive plant disease diagnostics enabled by smartphone-based fingerprinting of leaf volatiles. *Nat. Plants* 5:856-866.

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

Related Subtopic Pointers: T10.01, T8.07
Lead Center: GRC
Participating Center(s): ARC, KSC, MSFC

Subtopic Introduction:

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. Many materials used in our daily lives are processed in the liquid state and only work because they are free of pores caused by trapped gas bubbles. Eliminating porosity on Earth is easy: the trapped gas flows upward. However, in microgravity the trapped gas stays within the liquid, leading to porosity. Controlling porosity in space affects all work with liquids, solid-to-liquid phase changes, and liquid-gas interfaces. Porosity control affects many potential commercial processes, but early work will most likely benefit structural manufacturing (welding, brazing/soldering, metal addition) and aqueous technologies, including Environmental Control and Life Support Systems (ECLSSs), bioreactors (nutrition), and cleaning. Materials development, both application-targeted work and research into fundamental phenomena, delivers a kind of novelty that could touch any industry. From a minor tweak to a major disruption, a new material capability or manufacturing technology can drive a wide variety of products. Advanced materials have the potential to provide weight reductions, reduce the burden on launch vehicles, and allow more strength and flexibility.

Scope Title: Enabling Materials Science Technology

Scope Description:

This subtopic seeks proposals to develop systems appropriate for the challenges common to materials science experiments requiring elevated temperatures. Challenging experimental requirements could include precise observation and control of the gaseous environment, accommodating and controlling high temperatures, porosity control, and strategies for integration into spacecraft environments with limits on thermal output, power input limitations, and process gas supply. Additional human safety considerations apply to any experiments designed for crewed environments; however, research that utilizes high-pressure, high-temperature, or radiation environments are unlikely to take on crewed platforms but merit consideration.

Although a wide variety of designs is possible, proposals must identify a science research concept and the relevance of the hardware capabilities to achieving that research; they must also identify one or more target destinations, such as commercial ,low-Earth-orbit (LEO) destinations (CLDs) or beyond-LEO flight platforms among the following: Commercial Lunar Payload Services (CLPS) lunar lander, Lunar Gateway, free-flyer, and Artemis.

The scope does not require the development of a complete system—it can focus on a component or collection of components that satisfy experimental needs as part of a larger system, such as the following:

- Develop a scalable gas-environment processor that can handle difficult mixed effluent for particulate removal and thermal control. Similarly, ideas that could take existing systems and expand their useful temperature range or reduce the need for consumables, such as disposable particulate filters, would be considered.
- Develop a subsystem that can recover noble gasses from filtered gasses for reuse.
- Control porosity by either eliminating, minimizing, or preferentially positioning pores or voids.
- Develop automated and compact scientific observation and measurement systems relevant to experimental profile (microscopy, inductively couple plasma (ICP), mass spectrometry, pH, airborne particle counting, extreme temperatures, etc.).
- Control precisely the pressure and temperature in open and closed reaction volumes.
- Develop automated sample handling that avoids cross contamination of liquid samples.

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 08.3 In-Situ Instruments/Sensor

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. Deliver a model of the potential for the concept to scale or adapt to experimental needs, emphasizing how the concept exceeds the state of the art in relevant metrics; for example, cost, thermal budget, power budget, required consumables (filters, process gasses, etc.), and experiment scale. 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 scaled in cooperation with relevant scientific stakeholders, development and test of an engineering development unit and prototype 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 a manned or unmanned orbital platform are especially valuable.

State of the Art and Critical Gaps:

Existing physical science experiments performed at high temperatures are often limited to very small samples sizes or limited numbers of samples because of processing hardware limitations. These limitations steer experiments into sealed ampoules with limited control of the experimental atmosphere, sample size, and temperature controls. Experiments involving pyrolysis; rapid quenching; the use of purges, cover gasses and forming gas; and structural changes observed over large cross sections rarely get consideration because of these limits. Experimental platforms often also depend on resupply for items such as filters or noble gasses; decreasing these dependencies will help reduce costs and enable experimentation at larger scales or higher cadences. Controlling porosity in space affects all work with liquids, solid-to-liquid phase changes, and liquid-gas interfaces. Porosity control affects many potential commercial processes, but early work will most likely benefit structural manufacturing (welding, brazing/soldering, metal addition) and aqueous technologies including ECLSSs, bioreactors (nutrition), and cleaning.

Some critical limitations result from the infrastructure available on the ISS and the elevated needs for safety in a crewed environment. With future science potentially leveraging uncrewed robotic platforms or more capable commercial infrastructure with more power, better heat removal, and more capable waste gas systems, the time to consider how to optimize for future capabilities is now.

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 and beyond LEO. 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:

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3. J. Moraes Neves, P.J. Collins, R.P. Wilkerson, R.N. Grugel, and A. Radlinska: Microgravity Effect on Microstructural Development of Tri-calcium Silicate (C_3S) Paste, Front. Mater., 6 (2019), pp. 1–12, https://doi.org/10.3389/fmats.2019.00083

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:

Phase I requirements are, as a minimum, development and test of a bench-top prototype and a written report both 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:

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, it 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:

1. 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.
2. 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.
3. 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: Experimental Hardware for Autonomous Biological Research in the Space Environment

Scope Description:

This subtopic seeks proposals that develop technologies capable of providing life support to experimental organisms and generating measurements necessary for studying their growth and activity autonomously. Hardware should accommodate a model organism(s) relevant to the NASA's science goals, which include microorganisms, plants, or mammalian cell culture and organoids. As a wide variety of designs is possible, proposals shall identify a science research concept and the relevance of the hardware capabilities to achieving that research; they shall also identify one or more target platforms among the following: beyond-low-Earth-orbit (BLEO) platforms (Commercial Lunar Payload Services (CLPS) lunar lander, Lunar Gateway, free-flyer, Artemis) or LEO platforms (International Space Station (ISS), commercial space station). Hardware designed for LEO platforms shall also meet all requirements below.

Instruments that are modular (allow users to easily interchange sensors, growth chambers, or other components) and extensible (allow easy addition of new capabilities) are strongly desired.

Requirements

The instrument shall be capable of:

- Autonomous operation: Control system enabling full experiment execution and data storage without user intervention once it is activated. Systems that can also accommodate "on-the-fly" remote modification of execution scripts, modification between individual experiments, and/or real-time control for troubleshooting are encouraged; at minimum, the system shall be capable of fully autonomous operation for one experiment.
    - Control of environmental conditions including the following: temperature, lighting, ambient CO_2 and O_2, humidity, pressure, pH, ionic strength, dissolved gases, dissolved nutrients, waste products, agitation, etc. Proposals shall specify the model organism and target platform. Concepts shall not fully depend on environmental control to be provided by the platform.
    - Measurement of parameters in real time, appropriate to the model organism; e.g., changes in dissolved gases or metabolites in growth medium, optical absorbance and fluorescence, imaging, nucleic acid extraction and sequencing/gene-expression analysis, protein extraction and analysis, cytometry, fluorescence-activated cell sorting (FACS), and gene and protein microarray analysis (with appropriate sample preparation).
- Independent operation from the gravity environment: Full function at any gravitational level from micro-g up to terrestrial gravity or even hypergravity, if relevant.
    - Storage and control, including metering or dilution series as warranted, of appropriate growth media and experimental reagents such as dyes, antagonists, drugs, etc.
    - Appropriate mitigation of bubble formation in fluidic systems, whether due to physical setup and conditions or organismal respiration.
    - Dry/lyphilized storage combined with capability for rehydration/reconstitution/revitalization of sensitive reagents, nutrients, or microorganisms where necessary to support long-duration experimental scenarios.
- Late load capability: Capacity for organisms and perishable reagents to be loaded and/or replenished in a sterile manner, without complete disassembly of the instrument.

Additional desired features

The instrument shall also be capable of one or more of the following:

- Capability for continuous culture or multigeneration iterative culture.
- Feedback control: Ability for growth measurements or other biological data to feed back into control parameters; e.g., for chemostat implementation, triggering subculturing, etc.
- Systems that support statistical robustness through replicate experiments; e.g., in multiwell formats where suitable.
- 1g/partial g control: Built-in centrifuge to create artificial gravity at relevant levels (e.g., Moon, Mars, Earth as control) if deployed in a low-gravity environment.
- Capability for post-experiment sample preservation, including cell fixation, preservation of nucleic acids/proteins, tissue preservation, seed storage, etc.

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 08.3 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 is required as is a written report detailing evidence of demonstrated autonomous prototype technology in the laboratory 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.

Phase II would involve a prototype and a report containing detailed science requirements; results of testing; and design, concept of operations, development, and testing of the prototype. 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:

Fundamental research in the biological response to the space environment is crucial for assessing and mitigating health risks to human explorers. The need for new technology to support this research is especially keen for BLEO platforms; recent examples include the BioExp-1 and BioSentinel experiments associated with Artemis I. These experiments were conducted without human crew present, and a key limitation characterizing upcoming BLEO research opportunities is very limited availability crew time (e.g., Artemis, Gateway) or none at all (e.g., free flyers, CLPS landers). Other constraints of research beyond LEO include limitations placed on mass and power consumption; limitations in data transfer rates; the need for self-sufficiency in controlling the incubation environment (e.g., temperature, gas composition); and the need to be able to maintain organisms in stasis during lengthy pre-launch and transit periods, prior to experiment initiation. Many such flight opportunities will not allow sample return; experimental hardware should therefore be capable of taking measurements sufficiently complex to enable hypothesis testing without the return of samples for analysis on Earth. Platforms within LEO (ISS and upcoming commercial space stations) will also benefit from versatile and adaptable instruments capable of autonomous biological experimentation.

Many experimental hardware suites already designed for use on the ISS meet the functionality requirements listed above but not the requirement for autonomous operation. Many biological CubeSats meet the requirement for autonomy but do not have the diverse experimental capabilities. Most existing instruments for biological research in space have been custom built for a specific organism or set of experiments and lack the desired modularity and extensibility.

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 and on other space platforms. The hardware capabilities will be used to further stimulate the demand for commercial product development and strengthen U.S. leadership.

References:

1. NRC (National Research Council). Recapturing a future for space exploration: Life and physical sciences research for a new era. Washington, DC: The National Academies Press, 2011. doi:10.17226/13048.
2. National Aeronautics and Space administration. Space Biology Science Plan 2016-2025, 2016. https://www.nasa.gov/sites/default/files/atoms/files/16-03-23_sb_plan.pdf
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7. Zea L, Santa Maria SR, Ricco AJ. 7 - CubeSats for microbiology and astrobiology research. In: Cappelletti C, Battistini S, Malphrus BK, editors. Cubesat Handbook. Academic Press, 2021, pp. 147–162. doi:10.1016/B978-0-12-817884-3.00007-2.
8. National Aeronautics and Space administration. Space Station Research & Technology: ISS Researcher's Guide Series, 2023. https://www.nasa.gov/international-space-station/space-station-research-and-technology/opportunities-information-for-researchers/iss-researchers-guide-series/

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

Related Subtopic Pointers: T10.01, T8.07
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 submillimeter through x-ray photons. Thus, cryogenics will play an important role in many of NASA’s advanced missions in astrophysics and Earth science and in the exploration of the solar system. Advances in the development of miniature, low-power coolers will greatly enhance the science capability of SmallSats and CubeSats for Earth and lunar observations, including swarm arrays of SmallSats for high-resolution remote sensing. They also enhance the capability of small in situ instruments on rovers. 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, this 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-infrared (IR) instruments on SmallSats and CubeSats for Earth and lunar observations as well as 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 < 4 K), advances in magnetic coolers enable the use of large arrays 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; this includes 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, (2) advanced thermal insulation systems, and (3) 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 increase efficiency and reduce complexity and cost are desirable.

Examples of target missions include several concepts currently under study for far-IR and x-ray-probe-class observatories recommended in the 2020 Astrophysics Decadal Survey. The use of low-temperature detectors is also under consideration for the large near-IR/optical/UV (ultraviolet) flagship mission recommended by the 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 or a CubeSat platform would be highly advantageous. Low-cost cryocooler electronics are also sought that are sufficiently radiation hard for lunar or planetary missions.

To support advanced instruments using MgB_2 superconducting nanowire single-photon detectors (SNSPDs), MgB_2 kinetic Inductance bolometers, low-noise amplifiers, and cryogenic microwave and millimeter-wave mixers, NASA is seeking advanced multistage cryocooler technologies that will enable these sensors to operate in a SmallSat platform. The typical cooling power required for these instruments is approximately 100 mW at 20 K. The cryocooler input power must be compatible with available power in a 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 and lower operating temperature 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. The need for these coolers is emphasized by the fact that "Advanced cryocoolers" are listed as a Tier 1 Technology Gap in the latest (2022) Astrophysics Biennial 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 the Tier 1 Technology Gap in the 2022 Astrophysics Biennial 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. In addition, low-temperature detectors are under consideration for an exoplanet characterization instrument on the large near-IR/optical/UV flagship mission recommended by the Decadal Survey.

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 IR detectors.

In planetary science, progress on cryogenic coolers will enable the use of far- to mid-IR sensors with orders-of-magnitude improvement in sensitivity for outer planetary missions. These will allow thermal mapping of outer planets and their moons. In addition, miniature coolers enable more capable in situ instruments on landers and rovers.

References:

Examples of mission concepts for the far-IR probe include:

1. PRIMA (which is based on the GEP): see Moore, et al., Proc. SPIE 10698, 1069858 (2018); doi.org/10.1117/12.2314237
2. Line Emission Mapper (LEM): see Kraft, et al., https://arxiv.org/abs/2211.09827

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.
- Thermal insulation is critical to reduce cooling power requirements for optics and detectors in cryogenic instruments. At low temperatures (<70 K), thermal conduction across layers in multilayer insulation (MLI) dominates the heat leak (Ross, 2015). The emissivity of conventional MLI with thin aluminum coatings increases at low cryogenic temperatures and the MLI effectiveness decreases (Tuttle, 2008). Areas of interest include innovative discrete thermal radiation insulation approaches suitable for the temperature range of 100 to 20 K. Another area of interest is radiation insulation approach for bi-pods supporting cryogenic payloads. The single-layer insulation (SLI) used on these bipods has a very large thermal gradient along the axis of the struts, causing appreciable conduction heat leak from the warm end to the cold end of the bipods, and thus the heat loads on the cryocooling system.
- Reliable solid-state conductors with variable thermal conductance ranging from 0.05 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 the cryogenic instrument calibration stage, significantly reducing cryogenic 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.

Advanced insulation: State-of-the-art radiation insulation technologies include spacerless blankets (Bugby, 2021) and radiation insulation systems with discrete structural spacers to reduce axial conduction heat leak.

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, heat dissipation in actuators can be a significant design problem.

References:

1. Ross, R.G.; Quantifying MLI Thermal Conduction in Cryogenic Applications from Experimental Data, *IOP Conf. Ser.: Mater. Sci. Eng.* 101, 012017, 2015.
2. Tuttle, J.; DiPirro, M.J.; Canavan, E.R.; Hait, T.P.: Thermal properties of double-aluminized kapton at low temperatures, *AIP Conference Proceedings* 986, 34–41, 2008.

3. Bugby, D.C.; Rivera, J.G.; Britton S.R.: Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE) Project Year One Results, 50th International Conference on Environmental Systems, 2021.

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 an imposed B field of 500 µT on the inside of the shield to <1 µT at a distance of 10 cm outside the shield exterior. 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 sec. 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 three-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-hr 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-IR and X-ray-probe-class missions recommended in the 2020 Astrophysics Decadal Survey, as well as future far-IR and X-ray flagship missions.

References:

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

1. Shirron, et al.: "Thermodynamic performance of the 3-stage ADR for the Astro-H Soft-X-ray Spectrometer instrument," *Cryogenics,* 74, pp. 24-30, 2016, and references therein.

For articles describing magnetic sub-Kelvin coolers and their components:

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

S16.08 Quantum Sensing: Atomic sensors, optical atomic clocks, and solid-state systems (SBIR)

Related Subtopic Pointers: T10.01, T8.07
Lead Center: GSFC
Participating Center(s): JPL

Subtopic Introduction:

Quantum information science and technology (QIST) has been identified as a critical technology for U.S. national security and leadership in cutting-edge science and technology. The 2018 National Quantum Initiative Act and subsequent strategy documents specifically point to quantum sensors as the nearest term technology infusion with applications across defense, terrestrial industry, and space-based remote sensing. Of the quantum sensing technologies currently being developed, atomic sensors are the most ready for infusion into NASA missions and have use-cases to enable ground-breaking science within the next 5 to 10 years. For example, cold atomic sensors will enable ultraprecise time-variable gravity field measurements of Earth and other planetary bodies, ultrastable optical clocks will enable deep-space navigation and searches for dark matter and dark energy, and atom-based electromagnetic sensors can span huge swaths of the electromagnetic spectrum in a single miniaturized package. This subtopic will seek to accelerate the development and maturation of atomic sensors and the critical subsystems required to enable NASA missions and transition these technologies from the laboratory to commercialization.
In particular, this subtopic has three main scopes:

- Optical atomic clocks: subsystems and architectures to enable space-qualifiable, compact and low-power optical atomic clocks with long-term stability better than 10^{-16}. In particular, NASA requires compact optical frequency combs that span greater than an octave and optical clock architectures that minimize the number of lasers and wall-plug power consumption.
- Atomic interferometry: subsystems and architectures to enable space-qualifiable atom interferometers for gravimetry and gradiometry in Earth orbit and beyond. In particular, high brightness ($>10^7$ atoms) and ultracold (<10 nK) Rb or Cs sources are critical gaps in these technologies as well as the laser and optical systems required to achieve these temperatures and atom numbers.
- Atomic and solid-state defect sensors: Electromagnetic sensors that can achieve ultrawide frequency tuning in a compact form factor (such as Rydberg atomic sensors) or robust, small size, weight and power (SWaP) vector magnetometers (atom or defect based).

Scope Title: Optical Atomic Clocks

Scope Description:

The ability to precisely measure time is a critical enabling technology across NASA technology and space applications. In particular, navigating in cislunar space and in Global-Positioning-System- (GPS-) denied environments terrestrially has increased the need for more precise time-keeping technologies. Clocks based on atomic transitions have been the worldwide time standard for several decades, and recent technological advances in the ability to control, trap, and measure atoms and ions have pushed the stability of these clocks to extraordinary levels. Recently, the Deep Space Atomic Clock (DSAC) mission successfully flew a space-qualified clock based on the microwave transition of a mercury ion, demonstrating a long-term stability of 10^{-15}. However, atomic clocks based on optical transitions intrinsically improve that sensitivity level by 3 orders of magnitude, as demonstrated in laboratory and terrestrial field environments. At a precision level of 10^{-17} or better, space-based optical atomic clocks would enable one-way time transfer for deep-space missions and navigational precision within a foot over months without requiring a time update. Optical clocks with this level of precision would enable dark matter and dark energy searches and could be the basis for the next gravitational wave observatory.

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:

In order to mature optical atomic clock technologies, NASA seeks to fill the following technical gaps:

- 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 sec (wavelengths for Yb+, Yb, and Sr clock transitions are of special interest).
- Rugged, fiber-based self-referenced optical frequency combs that span greater than an octave.
- 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.

Relevance / Science Traceability:

Optical atomic clocks with long-term stabilities better than 10^{-15} and beyond will be required for manned missions to Mars and for cislunar navigation. Time transfer and synchronization of terrestrial optical atomic clocks over long distances requires space-based timekeeping with similar sensitivities. Space-based optical atomic clocks at stabilities better than 10^{-17} will enable groundbreaking science such as searches for solar dark matter halos, deviations of fundamental constants, and gravitational wave detection at frequencies not accessible to LIGO (Laser Interferometer Gravitational-Wave Observatory) or LISA (Laser Interferometer Space Antenna).

References:

1. 2020 NASA Technology Taxonomy: https://go.nasa.gov/3hGhFJf
2. 2017 NASA Strategic Technology Investment Plan: https://www.nasa.gov/wp-content/uploads/2015/06/2017-8-1_stip_final-508ed.pdf

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Scope Title: Cold Atom Interferometry

Scope Description:

Sensors based on cold-atom interferometry can enable ultraprecise measurements of gravitational and other inertial accelerations. Terrestrial applications have emerged utilizing laser-cooled atom sensors for inertial navigation units and gyroscopes for aviation and maritime units and gravity field mapping for mining and natural resource discovery. The microgravity environment of space presents an opportunity to leverage these sensors to improve measurements of gravity by orders of magnitude. Cold-atom-based gravity gradiometers in Earth orbit will enable 10x to 100x improvement in spatial and mass resolution of time-variable gravity, improving our understanding of mass change processes on the Earth. Cold-atom gravity gradiometers will enable precise measurements of the gravity fields of the Moon and other planetary bodies in a single satellite, enabling safe landing of spacecraft. Deploying these systems into space will require the technological development of several key enabling technologies, to include compact, efficient narrow-linewidth laser sources; complex laser optical systems to deliver controlling pulses; ultrahigh vacuum systems; compact, bright ($>10^6$ atoms), ultracold (<5 nK) atom sources; and simulations and analytical tools for space-borne atom sensors.

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 (> 2 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:

Some of the identified key challenges are (but not limited to):

- Space-qualifiable high-flux ultracold atom sources, related components, and methods (e.g., $>1\times10^6$ total atoms near the point at <5 nK). In particular, high-brightness ultracold sources are required for Rb or Cs. Other alkali species may be considered if applicable to a particular design.
- 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-state-of-the-art photonic components at wavelengths for atomic species of interest. 852 nm (Cs) and 780 nm (Rb) in particular are desired.
    - Efficient acousto-optic modulators: e.g., low radio-frequency (RF) power ~200 mW, low thermal distortion, and ~80% or greater diffraction efficiency.
    - Efficient electro-optic modulators: e.g., low-bias drift, residual amplitude modulation (AM), and return loss; fiber-coupled preferred.
    - Miniature optical isolators: e.g., ~30 dB isolation or greater, ~ -2 dB loss or less. Required wavelengths at 852 and 780 nm are highly desired.
    - 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. 852 nm (Cs) and 780 nm (Rb) are highly desired. 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 interferometry and clock measurements in space.

Relevance / Science Traceability:

The technologies and enabling subsystems advanced by this subtopic are critical to realizing cold-atom interferometric sensors for next-generation science missions. In particular, the 2017 Earth Science Decadal study points to cold-atom gravity gradiometry as a path toward the next generation of Mass Change missions for time-variable gravity recovery. This mission is slated to launch within the next 10 years, and technological maturation is required now. Additionally, future fundamental physics measurements such as dark matter and dark energy and gravitational wave detection utilizing cold-atom interferometers are in mission concept development. Small, compact cold-atom systems are also being developed to provide inertial navigation and positioning for systems to operate in Global-Positioning-System- (GPS-) denied environments or cislunar space.

References:

1. 2017 NASA Strategic Technology Investment Plan: https://www.nasa.gov/wp-content/uploads/2015/06/2017-8-1_stip_final-508ed.pdf
2. 2015 NASA Technology Roadmaps: https://go.usa.gov/xU7sy

Scope Title: Atomic and solid-state quantum sensors

Scope Description:

As indicated by the 2018 National Quantum Initiative Act and subsequent funding for research and development, NASA has identified quantum sensors as a critical area of technological maturation for future space and aviation missions. This scope has been added to SBIR 16.08 in order to solicit technological development of quantum sensors based on laser-cooled or thermal atoms or on solid-state systems beyond optical atomic clocks and cold-atom interferometers. In particular, NASA is interested in the development of low-SWaP, rugged magnetometers and electromagnetic sensors based on these platforms. Examples include, but are not limited to, Rydberg atom sensors enabling ultrawide bandwidth tunability without external antennae; atom-vapor magnetometers enabling in situ calibration and high sensitivity; and solid-state defect magnetometers enabling vector magnetometers in a chip-scale, environment-tolerant form factor.

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 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I could include relevant studies, bench-scale experiments, or breadboard demonstrations of the relevant techniques and technologies required for these quantum sensors. A typical study would include the theoretical analysis of the proposed techniques that include a discussion of the technological maturation required to develop a prototype system with a path to space qualification.

Phase II would include the delivery of a prototype system to a relevant NASA research center to enable further maturation and engineering integration into higher TRL test units and demonstrations.

State of the Art and Critical Gaps:

Relevant technological gaps include the following:

- Rydberg sensors or their subsystems/components for electric field or microwave measurements. Rydberg sensors have the potential to enable tunability from direct-current (DC) signals into the GHz in a single aperture. However, gaps include full continuous tunability in the microwave regime relevant to Earth science and atmospheric signals and to configurations that would allow directional receiving without external antennae.
- Space-qualifiable chip-scale atomic magnetometers. Atomic vapor magnetometers have significant benefits over flux-gate or other conventional magnetic-field-sensing systems in terms of in situ calibration (not requiring spacecraft maneuvers to calibrate), long-term drift, and sensitivity. However, the complexity of these systems must be reduced and the size and power minimized to be relevant to near-term missions.
- Solid-state defect magnetometers or electromagnetic sensors: The ability to engineer spin-active defects in solid-state systems (for instance the nitrogen vacancy in diamond or silicon defects in SiC) has enabled chip-scale electromagnetic sensing. Devices based on these defects have the promise to enable ultracompact form factors and all-electric (i.e., no laser required) systems. Additionally, the ability to build these systems from diamond or SiC may provide exquisite environmental tolerance in high temperatures or high radiation for planetary missions. However, technological maturation must continue with these defects to improve sensitivities to compete with existing technologies (such as flux-gate) and to design vector magnetic field capabilities.
- Other innovative atomic quantum sensors for high-fidelity field measurements that have space applications and can be developed into a space-qualifiable instrument.

Relevance / Science Traceability:

These sensors have direct relevance to future missions, including Earth science balloon and small-satellite missions, to study atmospheric composition using microwave signals. Enabling magnetometry with atom vapor or solid-state sensors can enable planetary missions to extremely hostile environments such as Venus or for heliophysics missions to analyze space weather and solar activity.

References:

1. 2020 NASA Technology Taxonomy: https://go.nasa.gov/3hGhFJf
2. 2017 NASA Strategic Technology Investment Plan: https://www.nasa.gov/wp-content/uploads/2015/06/2017-8-1_stip_final-508ed.pdf

Z4.05 Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis (SBIR)

Related Subtopic Pointers: T10.01, T8.07
Lead Center: LaRC
Participating Center(s): GSFC, MSFC

Subtopic Introduction:

Nondestructive evaluation (NDE) is the use of nondestructive interrogating energy (e.g., electromagnetic waves, acoustic excitation, or thermal impulse) 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 structural or nonstructural. Example materials systems suggested for inspection include (but are not limited to) Inconel, titanium, aluminum, carbon fiber, thermoplastic composites, Avcoat, Alumina Enhanced Thermal Barrier (AETB), Phenolic Impregnated Carbon Ablator (PICA), lunar regolith, thermal blanket structures, and other common aerospace materials.

This SBIR subtopic contains two separate scopes to address targeted areas of focus for NDE development with a focus on in-space NDE.

The first scope supports development and deployment of in-space inspection tools. These inspection tools should target inspection of in-space welded and/or bonded structures. Development efforts should target any set of common aerospace materials in structural configurations, such as truss structures and stiffened structures. Other NDE developments can also be proposed in this scope supporting in-space inspection. The second scope supports advanced inspection of aerospace components, including components produced via additive manufacturing and advanced in-space manufacturing. Specifically, this scope will target inspection of additively manufactured lunar regolith structures and advanced-manufactured lunar regolith structures. Inspection of lunar regolith structures and subcomponents can be accomplished by observing the layer-by-layer build process (in situ) or as a final inspection of the built structure. Other technologies supporting inspection of materials, structures, and components used in and/or produced by additive and/or advanced in-space manufacturing processes, including in-situ resource utilization (ISRU) raw materials (e.g., core samples), will be considered as well.

As NASA strives for longer duration space missions, these new tools need to be developed to support NASA's Strategic Framework (https://techport.nasa.gov/framework) to address in-space manufacturing and advanced manufacturing.

Scope Title: Development and Deployment of In-Space Inspection Tools

Scope Description:

Technologies sought under this SBIR scope include those related to in-space NDE. Two areas of particular interest include automated inspection of in-space welded assemblies and inspection of bonded structures. Instrument development for compact, low-mass, portable 3D imaging tools are of high interest. These include, but are not limited to, x-ray computed tomography (CT), 3D visual inspection techniques, and other tools that are applicable to volumetric inspection of space-based structures.

On-orbit NDE of structures includes platforms on International Space Station (ISS), lunar surface, Gateway, Martian, and 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 emerging 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 Gateway must ultimately (after final development) be able to meet Gateway 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, consideration must still be given to system size, mass, power, and data rate, to the extent that it makes the technology feasible for infusion 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-power, low-mass, compact microfocus x-ray sources or innovative detector technologies). 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 scope is aimed at technologies for conventional NDE inspection of relevant components in space, meaning detection of commonly known defects in materials (cracks, pores, delamination, foreign object debris (FOD), impact damage, etc.), rather than analytical tools aimed at determining chemistry, composition, or other properties of materials. This scope is primarily targeting inspection of welded and bonded structures in space, but other 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. As such, if an NDE technique can be developed that can inspect bonded and welded structures but is applicable to other in-space components, be sure to include them, as this would be considered a multifunctional NDE tool.

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: Laboratory 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 I 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 spaceflight. 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 highly 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 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:

1. 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. https://ntrs.nasa.gov/citations/20170004934
2. 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. https://ui.adsabs.harvard.edu/abs/2018AIPC.1949m0002L/abstract
3. 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. https://ntrs.nasa.gov/citations/20180006282
4. 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.
5. 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.
6. 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.

7. 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.
8. 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/api/citations/20190001865/downloads/20190001865.pdf
9. Hodges, K.; Burke, E.; Jones, J.; Lanigan, E.; Duquitte, D.: Challenges and Prospects for NASA's In-space Inspection Needs. https://ntrs.nasa.gov/citations/20230011117
10. Burke, E.; Jones, J.; Lanigan, E.; Lecky, C.; Wells, D.: NASA's Agency Wide Efforts To Improve Nondestructive Evaluation Methods for Additive Manufacturing and In-Space Inspection. https://ntrs.nasa.gov/citations/20230000742
11. Cramer, K. E.: NASA's Emerging Needs in NDE for Space Exploration, CNDE Webanair October 19, 2023. https://iastate.box.com/s/xiuautyr4g79wcgesmquiuognxqienim

Scope Title: Advanced Inspection of Regolith-Based Structures and Additively Manufactured Aerospace Components

Scope Description:

Of particular interest in this NDE subtopic scope are technologies that advance the inspection of as-built regolith-based structures (i.e., those fabricated using regolith as a parent material and adapted for structural use via a binder or other process). These inspection techniques can function both as an in situ process and as a direct inspection of as-built regolith structures. NDE techniques within this scope can target both ISRU and in-space manufacturing (using regolith or non-regolith materials).

Inspection of regolith structures should utilize inspection techniques that scale well to larger structures. Inspection of additive manufacturing (AM) should target parts that could be manufactured in an AM cabinet system that fits in an International Space Station EXPRESS (EXpedite the Processing of Experiments to the 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. Prioritization will be given to NDE tools or enabling technologies that work on low or accessible power and are compact and easy for astronauts to carry.

Also of high importance are in situ inspection methodologies for highly complex regolith structures and AM parts, and development of inspection methods that can be used during the manufacturing or build process. These in situ inspection techniques can provide layer-by-layer inspection information as AM parts are manufactured. These in situ systems should also obtain information that can be directly used to interrogate the AM build and can possibly be used for a closed-loop feedback system. In situ systems should also have an anomaly logging capability that relates the in situ data to specific areas of the build that may require focused inspection post build. Lastly, the in situ system should provide a final part anomaly inspection report that could be used as final certification documentation for an AM part.

Expected TRL or TRL Range at completion of the Project: 1 to 5

Primary Technology Taxonomy:

- Level 1: TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
- Level 2: TX 12.1 Materials

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I Deliverables:
For proposals focusing on NDE sensors: Laboratory 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 I 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:

Currently there is no path for certification of AM fracture-critical components for spaceflight. Additionally, there is no method for using in situ systems for certification of AM fracture-critical components for spaceflight. These systems will be required to safely manufacture AM components in space. It is acceptable to address metallic components, but the current focus considers regolith inspections a higher priority. These gaps have been identified in the STMD Strategic Framework under Advanced Materials.

Relevance / Science Traceability:

Many of NASA's current programs involving spaceflight are looking to infuse additively manufactured parts. These programs include, but are not limited to, Space Launch System, Artemis, and NASA Transformational Tools and Technologies (TTT). This also includes many NASA commercial crew partners. Developments in this critical area will support future operations in ISRU as well as advanced in-space manufacturing.

References:

1. 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. https://ntrs.nasa.gov/citations/20170004934
2. 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. https://ui.adsabs.harvard.edu/abs/2018AIPC.1949m0002L/abstract
3. 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. https://ntrs.nasa.gov/citations/20180006282
4. 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.
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6. 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.
7. 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.
8. 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/api/citations/20190001865/downloads/20190001865.pdf
9. Hodges, K.; Burke, E.; Jones, J.; Lanigan, E.; Duquitte, D.: Challenges and Prospects for NASA’s In-space Inspection Needs. https://ntrs.nasa.gov/citations/20230011117
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11. Cramer, K. E.: NASA’s Emerging Needs in NDE for Space Exploration, CNDE Webanair October 19, 2023. https://iastate.box.com/s/xiuautyr4g79wcgesmquiuognxqieni

TX09: Entry, Descent, and Landing

This area covers entry, descent, and landing technologies needed to enable both current and future missions.

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

Related Subtopic Pointers: T9.03
Lead Center: ARC
Participating Center(s): GSFC, 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 technologies for wireless sensor systems that can be implemented onboard a spacecraft to collect measurements on vehicle performance during atmospheric entry.

Scope Title: Wireless Sensors for EDL Flight Performance Data

Scope Description:

Measurements onboard a spacecraft during the EDL phase of a mission provide benchmark data for understanding flight performance and validating design tools. There is a significant need to advance the state-of-the art toward sensor systems with lower size, weight, and power. The mass of cable harnesses across sensor interfaces and routing to the electronics system can be a significant percentage of the overall mass of the sensor system as a whole—greater than 50% in some cases. NASA is seeking wireless sensor systems capable of functioning onboard a spacecraft during EDL and which eliminate the point-to-point wiring between the central electronics system and the individual sensors. Desired characteristics of the wireless sensor system include the following:

- Temperature sensors with a range up to 1,260 °C.
    - Proposals are encouraged to address extensibility of the system to other analog sensors, such as heat flux sensors.
- Capable of being awakened instantly.
- Minimum of 10 sensor nodes, scalable to a larger number of nodes.
- Data acquisition and communication powered by a battery:
    - Operating range for the battery powering the sensors: From -40 to 125 °C.
    - Battery life: Hibernation for at least 2 years and active for at least 30 days.

Additional desired characteristics of the wireless sensor system supporting electronics:

- Weight per outer node (sensor location): 0.25 lb. or less.
- Total mass of the system: 10 lb. or less.
- Size of the central node: 100 in^3 or smaller.
- Size of the outer node excluding the antenna: 3 in^3 or smaller.
- Measurement resolution: 14-bit or higher.
- Acquisition rate per measurement: 8 Hz or higher.

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
- Software

Desired Deliverables Description:

Phase I Goals: Assessment study of potential wireless sensor system, including definition of the wireless sensor network architecture, modularity, and the approach to identify a product solution that meets desired technical characteristics.

Phase II Goals: Prototype wireless sensor system demonstration with hardware delivery to NASA.

State of the Art and Critical Gaps:

There is currently no commercial off-the-shelf wireless sensor system at a sufficiently high TRL capable of being implemented for flight EDL applications. Current NASA EDL missions implement wired instrumentation systems with harness cable masses that, in some cases, comprise more than 50% of the total instrumentation system mass.

Relevance / Science Traceability:

Since 2014, NASA has required competed EDL missions to propose an Engineering Science Investigation plan for onboard flight instrumentation. Data from instruments onboard the spacecraft are crucial for supporting NASA's future robotic and human exploration missions. Furthermore, NASA's STMD strategic framework has identified development of low size, weight, power, and cost (SWaP-C) instrumentation as a need for Ice Giant entry systems.

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1. Sebastian V. Colum and Magnus A. Haw (2023), "Open-Source Wireless Sensor Network (Wi-Se Net) for Flexible Deployment." AIAA 2023-1540. AIAA SCITECH 2023 Forum, January 2023.
2. E. Martinez, J. Santos, R. David, and M. Mojarradi (2014), “Challenge of Developmental Flight Instrumentation for Orion Exploration Flight Test 1: Potential Benefit of Wireless Technology for Future Orion Missions,” Proc. of IEEE International Conf. on Wireless in Space and Extreme Environments (WiSEE), October 2014.

Scope Title: Component Technologies for Lidar Sensors 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 that will be utilized within 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 the development of lidar technologies that provide either terrain mapping (range point cloud) capability or direct velocity measurement. The continued maturation of these technologies is targeting (1) reduction of size, mass, and power of terrain mapping and velocity sensors; (2) multimodal operation (i.e., combining mapping and velocimetry functions); and (3) advanced component technologies for enhancing operational robustness and/or expanding operational envelope.

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 the following:

- 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 1.5-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 5-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 0.5 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).

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 PL&HA 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). 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 (2009), “Analysis and Testing of a LIDAR-Based Approach to Terrain Relative Navigation for Precise Lunar Landing,” AIAA.
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 (2015), “Imaging Flash Lidar for Safe Landing on Solar System Bodies and Spacecraft Rendezvous and Docking,” Proc. SPIE, Vol 9465.
6. Nikolas Trawny, Andres Huertas, Michael Luna, Carlos Y. Villalpando, Keith E. Martin, John M. Carson III, Andrew E. Johnson, Carolina Restrepo, and Vincent E. Roback (2015), “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.

Z7.03 Entry and Descent System Technologies (SBIR)

Related Subtopic Pointers: T9.03
Lead Center: LaRC
Participating Center(s): ARC

Subtopic Introduction:

NASA is advancing deployable aerodynamic decelerators and 3D-woven thermal protection system (TPS) concepts to enhance and enable robotic and human space missions involving entry and aerocapture phases. Applications include Mars, Venus, and Titan in addition to suborbital and return to Earth. The benefit of deployable decelerators is that the entry vehicle structure and TPS 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. The benefit of a 3D-woven TPS is having a highly reliable thermal-structural component suitable for use in part or in whole on a heat shield. A 3D-woven TPS enables return of human and robotic missions from the Moon and Mars.

This subtopic area solicits innovative technology solutions applicable to both deployable and 3D-woven TPS concepts. Specific technology development areas include the following:
(1) Gas Generators of Noncombustible Gas for Hypersonic Inflatable Aerodynamic Decelerators (HIADs).
(2) Improved Resin Infusion Technique for Large 3D-Woven Preforms.
(3) Material Selection and Development to Improve Deployable Solutions.

Scope Title: Gas Generators of Noncombustible Gas 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 reduced 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. Note that higher temperature gas deliveries require rapid deployment of additional gas to account for mass collapse at the onset of g-loading. 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.

Generator delivery of a noncombustible gas (e.g., nitrogen) is highly desired for near-term applications. 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 suborbital missions but 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 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. 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 45 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 Aero assist 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 can be subscale component development and 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, or launch vehicle asset recovery.

State of the Art and Critical Gaps:

The current state of the art for gas generators is still limited due to the novelty of this technology. Previous awards have mostly developed hydrogen gas generators. Near-term applications desire generator delivery of a noncombustible gas. 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 are 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 in addition to suborbital and return to Earth. 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:

1. Hughes, S.J., et al., “Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development Overview,” AIAA Paper 2011-2524.

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

Scope Title: Improved Resin Infusion Technique for Large 3D-Woven Preforms

Scope Description:

Large, fully densified 3D-woven composites are increasingly important for high-reliability structural components in aerospace applications. An example of this is the 3D orthogonally woven quartz fiber/cyanate ester resin composite invented by NASA, known as the 3D-Multifunctional Ablative Thermal Protection System (3D-MAT), that is a crucial structural part of the Orion heat shield for all Artemis missions. While this TRL-9 technology has successfully flown on Artemis I, there are still challenges associated with the manufacture of 3D-MAT, particularly in achieving full densification (<2% void volume) via resin transfer molding on parts measuring at least 13 x 12 x 3 in. A systematic study of how resin infusion processing parameters such as infusion method, pressure, and preform conditioning affect the densification process and quality of the final composite using large 3D preforms is of significant interest to NASA and the aerospace community. While the 3D-MAT system with its 3D-orthogonal construction with high fiber volume (>55%), quartz yarn, and Toray® EX-1510 cyanate ester resin is of particular interest, all fully dense fiber/resin composite systems are relevant to further understand the influence of processing parameters on the quality of the composite structure. Nondestructive evaluation (NDE) techniques such as computed tomography (CT) scan or x-ray are crucial to determining the presence or absence of void pockets. Additional mechanical property characterization of any void pockets would add to the understanding of their impact. The focus of Phase I development can be material coupons and/or subscale manufacturing demonstrations that show proof of technique and lead to Phase II manufacturing scale-up and testing.

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 Aero assist 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 material coupons, techniques, hardware, or prototypes that are designed and developed.
The focus of Phase I development can be material coupons and/or subscale manufacturing demonstrations that show proof of technique and lead to Phase II manufacturing scale-up and testing. At the end of Phase II, the technique should be ready for potential adoption by NASA missions.

State of the Art and Critical Gaps:

While some fully dense fiber/resin composite systems are TRL-9 technology (e.g., 3D-MAT, which has successfully flown on Artemis I), there are still challenges associated with their manufacture, particularly in achieving full densification (<2% void volume) of large (i.e., at least 13 x 12 x 3 in.) 3D-woven preforms. A systematic study of how resin infusion processing parameters such as infusion method, pressure, and preform conditioning affect the densification process and quality of the final composite using large 3D preforms is of significant interest to NASA and the aerospace community.

Relevance / Science Traceability:

NASA needs advanced 3D-woven high-reliability structural components to enhance and enable robotic and human space missions. Applications include Mars, Venus, and Titan in addition to suborbital and return to Earth. ESDMD (Exploration Systems Development Mission Directorate), STMD (Space Technology Mission Directorate), and SMD (Science Mission Directorate) can benefit from this technology for various exploration missions.

References:

1. 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 Improve Deployable Solutions

Scope Description:

Advancements are desired in textile manufacturing technologies that can be used to simplify production (e.g., weave architectures, weavability, joining techniques), reduce cost (e.g., lower cost fibers and materials for less severe environments), reduce mass (e.g., improved insulations), improve performance (e.g., larger inflation ports and hoses, low-outgassing adhesives), and improve or reduce the stowed volume of mechanically deployed structures, inflatable structures, or their thermal protection systems (TPSs).

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 low Earth orbit (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. 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, Venus, and Titan in addition to suborbital and return to Earth.

NASA's Hypersonic Inflatable Aerodynamic Decelerator (HIAD) concept was successfully demonstrated by the Low Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) project. However, there are still several challenges associated with the manufacture and assembly of HIAD technologies, particularly with flexible and packable inflation hoses and ports for the inflatable structure and with low-outgassing adhesives that are desired for most spaceflight missions. Increasing inflation hose and port sizes from the current 1/2-in. diameter to 1- and 2-in. diameters would significantly improve HIAD inflation time performance. Hoses and ports need to be compliant for packing and avoid sharp edges and features that could potentially damage the inflatable aeroshell. Ports will need to integrate and attach to inflatable aeroshell structure elements that are constructed with a fabric exterior and an inner gas barrier material, such as silicone and polytetrafluoroethylene films. The hoses and ports need to be designed for gas to be delivered from compressed gas storage tanks or gas generators with gas temperatures up to 200 °C. Hoses and ports are typically located on the aft side of the inflatable aeroshell and exposed to temperatures up to 400 °C for short durations from the peak heat pulse during atmospheric entry flight. To suit many spaceflight applications, adhesives used for construction need to be low outgassing. The focus of Phase I development can be investigation of suitable materials, demonstration of construction methods and features, testing of complete hose and port assemblies to show proof of concepts, and lead to Phase II manufacturing scale-up and efficiencies for inflatable aeroshell 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 Aero assist and Atmospheric Entry

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Reports documenting analysis and development results, including description of any materials, hardware, or prototypes investigated or developed.

The focus of Phase I development can be investigation of suitable materials, demonstration of construction methods and features, and testing of complete assemblies to show proof of concepts, leading to Phase II manufacturing scale-up and testing in relevant environments for applications related to Mars, Venus, and Titan in addition to suborbital and return to Earth.

State of the Art and Critical Gaps:

ADEPT and subsequent DMA concepts have been developed primarily to facilitate probes and landers at Venus (ADEPT) and small spacecraft as secondary payloads of opportunity (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 are still several challenges associated with the manufacture and assembly of HIAD technologies, particularly with flexible and packable inflation hoses and ports for the inflatable structure and with low-outgassing adhesives, which are desired for most spaceflight missions. Therefore, continued advancements are desired in textile manufacturing technologies that can decrease cost, enable rapid manufacturing, improve performance, and provide options that are compatible with these entry environments, which 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 in addition to suborbital and return to Earth. 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:

1. Hughes, S.J., et al., “Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology Development Overview,” AIAA Paper 2011-2524.
2. Bose, D.M, et al., “The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Mission Applications Study,” AIAA Paper 2013-1389.
3. Hollis, B.R., “Boundary-Layer Transition and Surface Heating Measurements on a Hypersonic Inflatable Aerodynamic Decelerator with Simulated Flexible TPS,” AIAA Paper 2017-3122.
4. Olds, A.D., et al., “IRVE-3 Post-Flight Reconstruction,” AIAA Paper 2013-1390.
5. Del Corso, J.A., et al., “Advanced High-Temperature Flexible TPS for Inflatable Aerodynamic Decelerators,” AIAA Paper 2011-2510.
6. Cassell, A., et al., “ADEPT, A Mechanically Deployable Re-Entry Vehicle System, Enabling Interplanetary CubeSat and Small Satellite Missions,” SSC18-XII-08, 32nd Annual AIAA/USU Conference on Small Satellites.
7. Cassell, A., et al., “ADEPT Sounding Rocket One Flight Test Overview,” AIAA Paper 2019-2896.
8. 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.
9. 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.
10. 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.

Z7.07 Plume-Surface Interaction (PSI) Technologies (SBIR)

Related Subtopic Pointers: T9.03
Lead Center: LaRC
Participating Center(s): GRC, MSFC

Subtopic Introduction:

This subtopic is focused on advancing NASA capabilities in PSI modeling, testing, instrumentation, and supplemental technologies. Development of tools or abilities to predict, characterize, and analyze the induced landing environment from a terminal landing phase of flight is desired, along with further development of tools that can ingest PSI-ejecta field data to predict the effects on a vehicle and local surface environment for mission planning and design. Flight instrumentation and sensors that are specifically designed to capture data relevant to PSI or allow sensor performance in environments obscured by regolith liberated and lofted during descent and landing are also sought. Development of propulsion modeling capabilities and systems; dust mitigation; guidance, navigation, and control (GNC) sensors; and surface operations and infrastructure are not within scope for this subtopic.

Scope Title: PSI Instrumentation, Ground Testing, and Analysis

Scope Description:

As NASA and commercial entities prepare to land robotic and crewed vehicles on the Moon and other planetary bodies, characterization of the environments induced by propulsive descent and landing is critical to identifying and verifying requirements for landing systems, including descent and landing concept of operations, engine configuration, instrument and sensor placement and protection, vehicle stability, and surface and proximity infrastructure and operations. The ability to predict the extent to which regolith is liberated and transported in the vicinity of the lander is critical to understanding the risks posed by these PSI environments' effects and for safe and reliable vehicle performance assessment. Knowledge of the surface erosion and characteristics, behavior, and trajectories of ejected particles during the landing phase is important for designing effective sensor systems and PSI risk mitigation approaches. Mission applications include lunar and planetary destinations, robotic and crewed landers, and pulsed and throttled propulsion systems.

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 the time-evolving surface topography and 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 analyses 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 and mission destinations. 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:

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:

Critical gaps relevant to PSI center on the need for validated capabilities to predict PSI environments for both lunar and planetary destinations. Past SBIR investments have yielded significant progress toward closing these gaps through advanced high-fidelity modeling tools, unique experimental and measurement techniques, and prototype sensors and flight instrumentation. These capabilities are crosscutting, directly supporting the design, development, and eventual certification of flight systems for both vacuum and atmospheric environments. PSI is a critical part of entry, descent, and landing (EDL). Ground testing, modeling and simulation, and flight testing/data in combination are a cornerstone of NASA's extensive, successful experience on EDL missions.

Missions are challenged by PSI risks derived from large extrapolations of existing models to flight conditions and uncertainties in fundamental knowledge of relevant gas-granular physics. Variation in characteristics of regolith and atmosphere (or lack thereof), propulsion system configuration, and concept of operations all pose challenges in applying capabilities developed for one mission application to another. Accurate predictions of PSI environments are also needed to support other efforts focused on surface operations and infrastructure, vehicle sensor design, and degraded performance potential.
The current state of the art for PSI relies on subscale, terrestrial ground testing to provide data for both semi-empirical erosion model development and validation of modeling methodologies across a range of fidelities. Modeling tools and approaches span engineering-level to fully coupled, highly parallelized, computationally expensive simulation frameworks, each with effort to go on validation and improvements to extend applicability. In situ measurement techniques are in development for unique flight instrumentation and sensors to directly characterize PSI physics and provide model validation data without or through minimizing the environmental limitations of terrestrial ground testing.

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.
- Ascent vehicles operating in non-terrestrial environments and with unprepared launch sites.

References:

1. Watkins, R. N., et al., “Understanding and Mitigating Plume Effects During Powered Descents on the Moon and Mars,” *white paper submitted to the Planetary Science Decadal Survey 2023-2032*, 2021.
2. Metzger, P. T., et al., “Phenomenology of Soil Erosion due to Rocket Exhaust on the Moon and the Mauna Kea Lunar Test Site,” *J. Geophys. Research*, Vol. 116, E6, June 2011.
3. Metzger, P. T., et al., “Jet-Induced Cratering of a Granular Surface with Application to Lunar Spaceports,” *Journal of Aerospace Engineering*, June 2009.
4. Mehta, M., et al., “Thruster Plume Surface Interactions: Applications for Spacecraft Landings on Planetary Bodies,” *AIAA Journal*, 51(12), pp. 2800-2818, 2013.
5. Alexander, J. D., et al., “Soil Erosion by Landing Rockets Final Report,” NASA Contract NAS9-4825, July 1966.
6. Land, N. S., and Scholl, H. F., “Scaled Lunar Module Jet Erosion Experiments,” NASA TN D-5051, April 1969.
7. Scott, R. F. and Ko, H-Y., “Transient Rocket-Engine Gas Flow in Soil,” *AIAA Journal*, Vol. 6, No. 2, pp. 258-264, Feb. 1968.
8. Romine, et al., “Site Alternation Effects from Rocket Exhaust Impingement During a Simulated Viking Mars Landing, Part 1: Nozzle Development and Physical Site Alteration,” NASA CR-2252, July 1973.
9. Leahy, F. B., et al., “Cross-Program Design Specification for Natural Environments (DSNE) Revision 1,” SLS-SPEC-159, Oct. 2021.

Z8.13 Space Debris Prevention for Small Spacecraft (SBIR)

Related Subtopic Pointers: T9.03
Lead Center: MSFC
Participating Center(s): ARC, GSFC

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) and to a rapidly increasing population in higher orbit regimes. Since 2013, the flight heritage reflects that small spacecraft numbers have increased by over 30%, and small spacecraft are currently the primary source to space access for commercial, government, private, and academic institutions. As of 2013, 247 CubeSats and 105 other non-CubeSat small spacecraft under 50 kg had been launched worldwide, representing less than 2% of launched mass into orbit over multiple years. In 2013 alone, around 60% of the total spacecraft launched had a mass under 600 kg, and of those under 600 kg, 83% were under 200 kg and 37% were nanosatellites [1]. Of the total 1,849 spacecraft launched in 2021, 94% were small spacecraft with an overall mass under 600 kg, and of those under 600 kg, 40% were under 200 kg and 11% were nanosatellites [1]. The total number of spacecraft launched in the past 10 years is 5,681, and 45% of those had a mass under 200 kg [1]. To date, this number continues to grow, with some companies planning and/or 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" [2, 3, 4].

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)" [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 [5], as well as significant strain on the current space traffic management architectures to prevent such scenarios [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 all of these plans materialize, the population of operational satellites in LEO would jump by over a factor of ten—from ~1,000 today to over 16,000 within the next 10 to 20 years," and this population "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. In fact, this concern is applicable to higher orbit regimes such as cislunar international missions, based upon increases in missions and more diverse orbits supporting future lunar 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. Space Traffic Management in the Age of New Space, Aerospace Corps, 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.

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 threats of space debris are increasing with the launch of multiple-satellite constellations, particularly in low Earth orbit (LEO). Currently, the general guideline is that satellites in LEO must deorbit or be placed in graveyard orbit within a maximum of 25 years after the completion of their mission [1]. However, on September 29, 2022, the Federal Communications Commission (FCC) adopted a new rule to reduce this requirement to 5 years for U.S.-licensed satellites, as well as those from other countries that seek to access the U.S. market [9,11]. Therefore, spacecraft under 2,000 km in altitude will have to deorbit as soon as it is applicable, and no longer than 5 years after end of mission. This requirement will apply to spacecraft launched 2 years after the rule is approved. Up to the date of publication of this report, this rule does not specifically apply to NASA satellites that are not licensed through the FCC. Current discussions at the Agency and Federal level are ongoing to determine the final policies [9,10].

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 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 highly 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 operational mission 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 or conjunction risk—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 2022 NASA State of the Art of Small Spacecraft Technology report [9], Section 13.0, 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. As a result of most nontraditional deorbit devices, uncertainties exist related to when and where space objects will come out of their established orbit due to natural causes (e.g., atmospheric drag, solar pressure) or when deorbit is initiated. To achieve precise prediction of deorbit trajectories and satellite behavior in that phase, improved methods of prediction and control are desired, possibly including real-time, closed-loop modeling and/or control, and deorbit initiation systems.

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. SmallSat by the Numbers, Bryce and Space Technology, 2022. https://brycetech.com/reports/report-documents/Bryce_Smallsats_2022.pdf
2. 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.
3. U.S. National Space Policy, 1988.
4. U.S. National Space Policy, 2020.
5. Space Traffic Management in the Age of New Space, Aerospace Corps, 2018.
6. State of Space Environment, H. Krag, Head of ESA’s Space Debris Office, 25 June 2019.
7. 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.
8. Process for Limiting Orbital Debris, NASA, 2012. https://standards.nasa.gov/standard/nasa/nasa-std-871914
9. State of the Art of Small Spacecraft Technology, NASA, 2022. https://www.nasa.gov/smallsat-institute/sst-soa
10. Process for Limiting Orbital Debris, NASA-STD-8719.14C, 2021. https://www.nasa.gov/sites/default/files/atoms/files/process_for_limiting_orbital_debris.pdf
11. Operational Progress Update on the ELSA-D Debris Removal Mission, Forshaw et al., 73rd Astronautical Congress, 2022.

Scope Title: Enhanced Space Traffic Management Technologies for Small Spacecraft Swarms and Constellations

Scope Description:

Objective: Develop enhanced technological solutions that relate to the safe operations of SmallSat swarms and constellations, with the aim of reducing the strain on space traffic management architectures. While the challenges posed by space debris and the management of large constellations is a multidimensional problem with multifaceted solutions, this subtopic scope focuses on enhanced technical solutions 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 ability to track small spacecraft, especially just after launch and beyond low earth orbit, 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. There is a need for technologies that enable tracking and identification immediately following separation from the launch vehicle, as well as tracking beyond LEO. Tracking options that are passive (work regardless of functionality of spacecraft bus) allow tracking through demise and are thus preferable to solutions that require an operator to intervene, as most operators are not funded beyond the useful life of the spacecraft.
- 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. Solutions should include the ability to incorporate current conjunction assessment processes via the 19th Space Defense Squadron (19 SDS) processes as defined on Space-Track.org, as maneuvering without screening for close approaches creates risk of collision.
- 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. Solutions should include the ability to incorporate current conjunction assessment processes via the 19 SDS processes as defined on Space-Track.org, as maneuvering without screening for close approaches creates risk of collision. Also included are software applications and/or network applications that enable:
    - Efficient information exchange between individual spacecraft.
    - Minimal reliance on ground commanding.
    - Efficient use of space-qualified computing architectures.
    - 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.

This scope does not solicit trajectory prediction algorithms. Any such solutions should be submitted through subtopic H9.03.

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 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 coordination 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 19th Space Control Squadron provides conjunction data messages (CDMs) to virtually all space operators worldwide following tracking measurements taken with its assets. These are used to create orbit determination solutions that comprise the space object catalog. The operators then assess and weigh the risks to their assets posed by the event described by the CDM against the resources to be expended to mitigate those risks, as well as consider the non-close-approach risks of taking mitigating action. This is a time-consuming process, typically on timescales that do not allow for rapid reaction to a rapidly evolving threat.

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 [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 [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 are needed in all orbit regimes, including the rapidly growing cislunar environment.

- 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.
    - Autonomous maneuvering is not synonymous with real-time maneuvering. All autonomous maneuvering solutions must allow time and capability to screen planned maneuvers via existing close-approach screening methods at 19 SDS (see Space-Track.org for more information) to share planned information with other operators and thus prevent causing a collision.

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. Space Traffic Management in the Age of New Space, Aerospace Corporation, 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

TX10: Autonomous Systems

This new area covers technologies that (in the context of robotics, spacecraft, or aircraft) enable the system to operate in a dynamic environment independent of external control.

A2.02 Enabling Aircraft Autonomy (SBIR)

Related Subtopic Pointers: T10.05, T6.09
Lead Center: AFRC
Participating Center(s): ARC, GRC, LaRC

Subtopic Introduction:

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 variable and changing levels of autonomous operations with respect to different forms of human interaction and supervisory control.

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. These breakthroughs in autonomous capabilities would also benefit the Advanced Capabilities for Emergency Response Operations (ACERO) in the wildfire response efforts. Consider these examples:

1. Detect-and-avoid algorithms, sensor fusion techniques, robust trajectory planners, and contingency management systems.
2. Autonomous contingency management systems have a need for fault detection, diagnostics, and prognostics capabilities.
3. Autonomous systems that can assist pilots and/or ground operators, reducing human workload and increasing overall safety and mission success.
4. Low size, weight, and power (SWaP) packages that enable autonomous capabilities across a variety of unmanned aircraft systems (UASs), which can be tailored for specific applications.

This subtopic is intended to address these needs with innovative and high-risk research, enabling appropriate use of autonomy in NASA research, civil aviation, emergency response aviation, and ultimately the emerging AAM market.
The scope in this subtopic will target applications of autonomy in air vehicles that will address one or more of the barriers described above. Any proposed technology must address the scope.

Scope Title: Autonomy for Disaster Response

Scope Description:

Technologies developed under this scope will advance the utility of autonomy in emergency response applications that use aircraft. The NASA and the Advanced Capabilities for Emergency Response Operations (ACERO) project is specifically looking for technologies that will aid in wildfire response. Autonomy in disaster response includes technologies that:

- Help autonomous and piloted flight in areas with degraded visibility.
- Support unmanned logistic operations, such as moving supplies to different areas.
- Support wildfire suppression and management missions.
- Support 24/7 operations.

These technologies would need to be either platform-agnostic or easily adaptable to different vehicles as a variety of aircraft are used for disaster and emergency response.
These autonomous technologies would need to be tailored for the type of disaster involved. For this scope, proposed technologies must be tailored for wildfire response.
Flying to respond to emergency situations can necessitate that vehicles enter areas with low visibility for piloted aircraft or into a loss of line of sight for remotely piloted and autonomous vehicles. Autonomous systems can be used to mitigate the hazards of flying in this environment and still respond to the missions assigned to the vehicle. For instance, in wildfire response, operations in high smoke or at night could use various perception systems to continue firefighting efforts while lowering risk to pilots and aircraft. Low size, weight, and power perception systems that are adaptable to varying sizes and types of UASs would allow for responders to take existing aircraft and make them ready for hazardous, low-visibility operations. These technologies could also enable safer and increased night-time operations for wildfire response. For example, these technologies would be used for safer and efficient fire retardant drops in low-visibility conditions.

For response support, autonomous systems can enable faster and safer logistics operations. For instance, in wildfire response, supplies such as axes would need to be dropped off to various areas for responders to use. Autonomous technology from this subtopic could allow for supply UASs to determine the areas that need supplies, find the optimal path to those spots, and drop off the supplies under variable conditions that might limit control and oversight from ground operators and/or pilots. Other logistics technologies could track and assess the status of the various personnel and aircraft to assist with coordination efforts in responding to the wildfire.

Autonomous technologies that support wildfire suppression efforts are another key area of interest for ACERO. Technologies that can assess the fire-retardant drop line clearance and drop efficiency and provide real-time information to pilots and operations centers are also highly desired. Other technology examples include tracking of personnel, automated retardant drops, retardant clearance and drop assessment, as well as visualization of assets via displays and VR options.
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. Proposers wanting to focus on services or technologies to coordinate airborne operations across a wildfire area should submit their proposal to A3.02: Advanced Air Traffic Management for Nontraditional Airspace Missions, under Scope 2: Nontraditional Aviation Operations for Wildfire Response.

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 written plan to continue the technology development and/or to infuse the technology (i.e., sensors and algorithms). This may be included in the final report.
- 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 technology demonstration in a simulation environment that clearly shows the benefits of the technology developed.

Phase II deliverables should include, but are not limited to:

- A usable/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 National Airspace System (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 scope, 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:

1. Advanced Capabilities for Emergency Response Operations (ACERO) https://www.nasa.gov/aeroresearch/programs/aosp/acero-project-description
2. Strategic Implementation Plan for NASA's ARMD: https://www.nasa.gov/directorates/armd/armd-strategic-implementation-plan/
3. 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
4. UAS Integration in the NAS Project (concluded Sept 2020): https://www.nasa.gov/directorates/armd/past-armd-projects/uas-in-the-nas/#:~:text=The%20Unmanned%20Aircraft%20Systems%20(UAS,tests%20in%20a%20relevant%20environment.
5. NASA Explores "Smart" Data for Autonomous World: https://www.nasa.gov/aeroresearch/nasa-explores-smart-data-for-autonomous-world
6. Autonomous Systems Research at NASA's Armstrong Flight Research Center: https://www.nasa.gov/feature/autonomous-systems

S17.03 Fault Management Technologies (SBIR)

Related Subtopic Pointers: T10.05, T6.09
Lead Center: GRC
Participating Center(s): ARC, JPL, MSFC

Subtopic Introduction:

NASA's Science Mission Directorate seeks to answer many long-standing questions about our planet, Sun, solar system, and beyond as well as enable space exploration. 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 is a critical enabling factor in autonomous systems to determine proper corrective actions after an unplanned event, large disturbance, or fault.

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

Scope Description:

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. Challenges related to linear, nonlinear, discrete, or continuous systems must be considered in the design of the approach. For example, critical subsystems such as the electric power system (EPS) and attitude control systems (ACS) require advanced FM techniques to achieve extremely high levels of mission reliability. Furthermore, interactions between subsystems should also be investigated, as the effect of faults may propagate from one critical system to another.

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 FM 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 FM.

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

1. FM operations approaches: This category encompasses FM "in-the-loop," including algorithms, computing, state estimation/classification, machine learning, model-based reasoning, and digital twin technologies. Further research into fault detection and diagnosis, prognosis, fault recovery, and mitigation of unrecoverable faults is needed to realize greater system autonomy and resiliency.
2. FM 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, open-source software 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 subtopic if, and only 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 preprocessing, 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.
- Compare distributed versus centralized FM implementation.
- 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 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 a minimum a report describing the technical accomplishments of the Phase I award and how these results support the underlying commercial opportunity. Describing the commercial potential is best done through experiment: Ideally the Phase II report should describe results of a prototype implementation to a relevant problem, along with lessons learned and future work expected to adapt the technology to other applications. Further demonstration of commercial value and advantage of the technology can be accomplished through steps such as the following:

- Delivery of the technology in software form, as a reference application, or through providence of trial or evaluation materials to future customers.
- Technical manuals, such as functional descriptions, specifications, and 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 on ground analysis capabilities to predict system response and optimize observation schedule. Enable reliable operations while out of direct contact (e.g., deliberately occluded from Earth to reduce photon, thermal, and radio-frequency background).

References:

1. NASA's approach to FM and the various needs are summarized in the NASA Fault Management Handbook: http://everyspec.com/NASA/NASA-NASA-HDBK/NASA-HDBK-1002_Draft-2012_48286/
2. Additional information is included in the talks presented at the 2012 NASA Spacecraft Fault Management Workshop: https://www.nasa.gov/offices/oce/documents/2012_fm_workshop.html
    - Particularly, “Coalescing NASA’s Views of Fault and Health Management” by Brian Muirhead 637595main_day_1-brian_muirhead.pdf (nasa.gov)
3. Another resource is the NASA Technical Memorandum "Introduction to System Health Engineering and Management for Aerospace (ISHEM)": https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060003929.pdf
    - This is greatly expanded in the following publication: Johnson, S. (ed), "System Health Management: with Aerospace Applications," Wiley, 2011: https://www.wiley.com/en-us/System+Health+Management+with+Aerospace+Applications-p-9781119998730
4. FM technologies are strongly associated with autonomous systems as a key component of situational awareness and system resilience. A useful overview was presented at the SMD 2018 Workshop on Autonomy for Future NASA Science Missions, archiving a number of talks on mission challenges and design concepts: https://science.nasa.gov/technology/2018-autonomy-workshop

TX11: Software, Modeling, Simulation, and Information Processing

This area covers modeling, simulation, and information technology as well as software technologies that increase NASA’s understanding and mastery of the physical world and are the basis of new solution paradigms across the breadth of NASA’s missions.

A1.06 Vertical Take-Off and Landing (VTOL) Vehicle Technologies - Multimodal Design Tools (SBIR)

Related Subtopic Pointers: T11.06
Lead Center: GRC
Participating Center(s): AFRC, ARC, LaRC

Subtopic Introduction:

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 proposed UAM vehicles have more than four rotors or propellers, have electric propulsion, carry two to six passengers, fly more like a helicopter (vertical takeoff and landing) than a fixed-wing aircraft and will fly relatively close to the ground and near buildings. There are many technical challenges facing industry‘s development of safe, quiet, reliable, affordable, comfortable, and certifiable UAM vehicles and vehicle operations. This SBIR subtopic focuses on vehicle technologies associated with those challenges. The subtopic is also focused on the future generations of UAM vehicles and the technologies that would extend the VTOL aircraft use for other missions. Each year, the subtopic focuses on different technologies, areas, and/or applications for VTOL aircraft, such as propulsion, handling qualities, structures, acoustics, weather tolerance, cabin environment, and so on. This year, the subtopic targets the challenges associated with the assessment of system architectures and conceptual vehicle design in a complex design space.

Scope Title: Discontinuous and Multimodal Design-Space Exploration Tools for eVTOL Aircraft Conceptual Design

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 proposed UAM vehicles have more than four rotors or propellers, have electric propulsion, carry two to six passengers, fly more like a helicopter (vertical takeoff and landing) than a fixed-wing aircraft and will fly relatively close to the ground and near buildings. There are many technical challenges facing industry‘s development of safe, quiet, reliable, affordable, comfortable, and certifiable UAM vehicles and vehicle operations. One of those challenges is the subject of this SBIR subtopic, namely, the assessment of system architectures and conceptual vehicle design in a complex design space. There are commercial tools available for integrating software tools and for performing optimization; using these tools in a manner as customized as envisioned here will likely cost a similar amount for the development of unique software.

At present, there are tools such as OpenMDAO, which manage continuous-variable trades in highly dimensional design space but do not have an outer-loop tool for managing multiple disconnected parts of the design space in a simultaneous design study. There is also a need for a tool to help manage the description of an instance of an aircraft across disciplines and through permutations and excursions and versions. The application of the requested technologies should be relevant to the NASA Revolutionary Vertical Lift Technology (RVLT) project’s reference concept vehicles [Refs. 1-2], which embody some key vehicle characteristics of the UAM vehicle configurations being designed throughout industry, and which help illustrate the breadth of the design space. For instance, vehicles may have disparate topologies, discrete variables, and multiple modes during the course of flight (e.g., helicopter, conversion, and airplane modes). Vehicles are described at a conceptual level, which often allows parameterization with dozens or hundreds of design parameters and with text-based descriptions or descriptions accessible via Application Programming Interface (API) calls to the various discipline tools in a toolchain [Ref. 3]. The key features of the desired solution include:

- Ability to manage trades involving changes to vehicle topology and discrete-value parameters as design variables.
- Execution of multi-objective trades.
- Ability to implement multiple simultaneous constraints.
- Managing disparate vehicles as part of a single study.
- Managing excursions.
- Managing versions.
- Python application programming interface.
    - Interoperability with the RCOTOOLS Python library (wrapper for several rotorcraft design and analysis tools [Ref. 6].
- Management of vehicle description data in a persistent storage solution for archiving and querying.

Additional desired features include:

- Visualizing results while cases run and after completion.
- Tolerance to failed cases in subdiscipline analysis: tools for debugging and robustness to failed cases.
- Parent/child flowdown of components (e.g., edits to a component in a part library will offer the opportunity to update dependencies and to rerun cases).
- Distributed and multiuser collaboration on a design study.
- Design with margins and probabilistic values for parameters and metrics.
- Interfacing with gradient-based local optimization (e.g., OpenMDAO [Ref. 4], CADDEE [Ref. 5]).
- Headless (command-line or via API call) setup and execution.
- Graphical user interface (GUI) features for managing studies.
- Operability on workstations and on high-performance computing clusters.

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

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:

- Analysis
- Research
- Prototype

Desired Deliverables Description:

Phase I should develop a software architecture and demonstrate interaction for a sample design study of limited scope.
Phase II should further develop the software and demonstrate execution of design studies for a representative test case, such as the evaluation of the RVLT UAM reference concept vehicles for a set of potential mission requirements (e.g., range, payload, atmospherics, noise requirements), and various objectives (e.g., passenger throughput, economic value, sustainability metrics).

State of the Art and Critical Gaps:

There are more than 800 UAM vehicle concepts in varying stages of development. No preferred type of aircraft has emerged, meaning that a generalized framework is required to provide flexibility, and that some means of comparing available options for vehicle solutions to a given problem is needed. At present, there are tools such as OpenMDAO, which manage continuous-variable trades in highly dimensional design space but do not have an outer-loop tool for managing multiple disconnected parts of the design space in a simultaneous design study. There is also a need for a tool to help manage the description of an instance of an aircraft across disciplines and through permutations and excursions and versions; at present, there are tools such as Common Parametric Aircraft Configuration Schema (CPACS) [Ref. 7], which provide much of this functionality but with a very heavyweight design paradigm. The preferred solution for data exchange is something that is flexible, limits the amount of discipline-tool logic that needs to be implemented in the tool for data exchange, and allows most of the initial setup and maintenance of discipline models to be performed in the discipline tools themselves.

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 objectives, and the Directorate Strategic Implementation Plan's Strategic Thrust 4: Safe, Quiet, and Affordable Vertical Lift Air Vehicles.

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. Silva, C., Johnson, W., "Practical Conceptual Design of Quieter Urban VTOL Aircraft," Presented at the Vertical Flight Society’s 77th Annual Forum & Technology Display, Virtual, May 10–14, 2021.
4. Gray, J. S., J. T. Hwang, J. R. R. A. Martins, K. T. Moore, and B. A. Naylor, “OpenMDAO: An Open-Source Framework for Multidisciplinary Design, Analysis, and Optimization,” Structural and Multidisciplinary Optimization, 2019.
5. Ruh, M. L., Sarojini, D., Fletcher, A., Asher, I., and Hwang, J. T., "Large-scale Multidisciplinary Design Optimization of the NASA Lift-plus-Cruise Concept using a Novel Aircraft Design Framework," VFS Autonomous VTOL Technical Meeting, Mesa, AZ, January 24-26, 2023.
6. Meyn, L., "Rotorcraft Optimization Tools: Incorporating Rotorcraft Design Codes into Multi-Disciplinary Design, Analysis, and Optimization," AHS Technical Meeting on Aeromechanics Design for Vertical Lift, Holiday Inn at Fisherman's Wharf, San Francisco, CA, January 16-18, 2018. Software may be requested via: https://software.nasa.gov/software/ARC-18184-1
7. Alder, M., E. Moerland, J. Jepsen and B. Nagel. Recent Advances in Establishing a Common Language for Aircraft Design with CPACS. Aerospace Europe Conference 2020, Bordeaux, France, 2020.

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

Related Subtopic Pointers: T11.06
Lead Center: MSFC
Participating Center(s): ARC, GSFC, JPL, JSC, LaRC

Subtopic Introduction:

The term “space weather” refers broadly to variations in the particle and radiation environment in the solar system caused by variable solar conditions. In particular, changes in solar features (e.g., sunspots, filaments) can generate eruptive events (e.g., solar flares, coronal mass ejections) that may possibly result in hazards to spacecraft, astronauts, and even ground-based technologies and infrastructure (e.g., power grids, pipelines). Space weather events can also disrupt communications, navigation, and electric power subsystems. Because of the importance of these technologies to our national interest in the digital age, NASA’s Heliophysics Division invests in activities intended to improve our understanding of space weather phenomena and to enable novel monitoring, prediction, and mitigation capabilities.

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

Scope Description:

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 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.
The role of NASA under the PROSWIFT Act includes providing increased understanding of the fundamental physics of the Sun-Earth system through space-based observations and modeling and through monitoring of space weather for NASA's space missions. NASA’s work includes the development of operational and commercial space-weather capabilities that will ultimately safeguard the lives of astronauts, the function of spacecraft, the success of spacefaring missions, and national assets on the ground and in space, which will enable 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. Both human and robotic missions are susceptible to the radiation effects caused by space weather in near-Earth, cis-lunar, and interplanetary space; thus, solutions to predict and 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. Although 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. This work is especially compelling when it draws upon educational opportunities available to many research institutions, such as space-weather schools and analysis bootcamps. 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 is 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 empower innovative projects by using 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 National Oceanic and Atmospheric Administration (NOAA) or Department of Defense (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. This area provides an essential jumping-on point for research institutions, small university programs, and individual researchers who are beginning to build a space-weather research program. 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).

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.

(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 it into a specific activity listed within the NSWSAP and the PROSWIFT Act.

Expected TRL or TRL Range at completion of the Project: 3 to 7

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 (i.e., 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:

- Our understanding of the fundamental processes involved in space-weather phenomena is incomplete, and it is likely that we will require data that we do not know are required.
- Many of the data sets currently being acquired are intended for research use and are either not available or not validated for real-time space-weather analysis.
- We do not currently measure ionospheric, magnetospheric, or heliospheric conditions throughout the full range of their respective locations.
- Mechanisms do not yet exist to enable a broad range of the community to participate in the improvement of operational models. Substantial barriers may exist for entry into the space-weather field for small research institutions.
- The research environment advances understanding rather than the improvement of operational products. A substantial “valley of death” exists in which the results of space-weather research do not always include associated advances in operational capabilities.

Severe space-weather events are a recurring threat to the national interest, including critical power and communications infrastructure, space-based assets, and the missions of astronauts and spacecraft. Extreme space-weather events can cause substantial harm to national security and economic vitality. Continued preparations for space-weather events are a crucial aspect of American resilience that bolsters the national security and facilitates continued U.S. leadership in space ventures. A robust space-weather program is essential for the success of NASA missions.

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 assembled under 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. The NASA Space Weather Program competes ideas and products, leverages existing agency capabilities, collaborates with other agencies, and fosters partnership with user communities. NASA's 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 that enable advancements in forecasting and nowcasting. Progress in this field creates more accurate characterization and predictions of space weather 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:

1. Public Law 116-181—Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act: https://www.congress.gov/116/plaws/publ181/PLAW-116publ181.pdf
   The PROSWIFT Act, signed into law October 21, 2020, establishes the policy of the United States to protect its citizens from the effects of space weather on in-space resources and ground-based infrastructure by supporting space-weather research to include forecasts and predictions. Using a strategy of interagency collaboration, within and outside the Federal Government to include international partners, the PROSWIFT Act seeks to ameliorate social and financial impacts of space-weather events to society.
2. Executive Order 13744—Coordinating Efforts to Prepare the Nation for Space Weather Events: https://www.federalregister.gov/documents/2016/10/18/2016-25290/coordinating-efforts-to-prepare-the-nation-for-space-weather-events
   This Executive Order describes the policy of the United States with respect to preparations for space-weather events so that economic loss and human hardship will be minimized.

3. SWORM: https://www.sworm.gov/
   The SWORM working group is a Federal interagency coordinating body organized under the Space Weather, Security, and Hazards (SWSH) subcommittee. The SWSH is a part of the NSTC Committee on Homeland and National Security, assembled under the OSTP. The SWORM coordinates Federal Government departments and Agencies to meet the goals and objectives specified in the National Space Weather Strategy and Action Plan released in March 2019.
4. National Space Weather Strategy and Action Plan: https://trumpwhitehouse.archives.gov/wp-content/uploads/2019/03/National-Space-Weather-Strategy-and-Action-Plan-2019.pdf
   The White House Executive OSTP released the NSWSAP on March 26th, 2019, during the National Space Council meeting in Huntsville, AL. This strategy and action plan is an update to the original NSWSAP, released in October 2015.
5. Space Weather Phase 1 Benchmarks: https://www.sworm.gov/publications/2018/Space-Weather-Phase-1-Benchmarks-Report.pdf
   Created by the SWORM subcommittee, te benchmarks describe a space-weather event's ability to affect the United States, provide input for creating engineering standards, develop risk assessments and estimates, establish thresholds for action, develop mitigation procedures, and enhance planning for response and recovery.
6. Space Weather Research-to-Operations and Operations-to-Research Framework: https://www.whitehouse.gov/wp-content/uploads/2022/03/03-2022-Space-Weather-R2O2R-Framework.pdf
   Created by the SWORM subcommittee in March 2022, this document identifies mechanisms for sustaining and transitioning models and observational capabilities from research to operation.
7. An Executive Order (EO) on Coordinating National Resilience to Electromagnetic Pulses (EMPs): https://www.federalregister.gov/documents/2019/03/29/2019-06325/coordinating-national-resilience-to-electromagnetic-pulses
   Released by the White House on March 26, 2019, this 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.
8. Space Weather Science and Observation Gap Analysis: https://space.jhuapl.edu/stories/space-weather-science-and-observation-gap-analysis
   Compiled by the Applied Physics Laboratory (APL) and released April 2021, this report was the result of analysis for the Space Weather Science Application Program (SWxSA) within NASA's Heliophysics Division 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.
9. Exploration Systems Development Mission Directorate (ESDMD): https://www.nasa.gov/exploration-systems-development-mission-directorate/
   This website defines and manages systems development for programs critical to NASA's Artemis program and planning for NASA's Moon to Mars exploration approach in an integrated manner.
10. Space Operations Mission Directorate (SOMD): https://www.nasa.gov/directorates/space-operations/
    This NASA organization 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 LEO, including commercial launch services to the International Space Station.

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

Related Subtopic Pointers: T11.06
Lead Center: ARC
Participating Center(s): GSFC, LaRC

Subtopic Introduction:

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 to10 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 (ML) that will 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 Research Center and the Scientific Computing project at Goddard Space Flight Center. 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. Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

Scope Title: Scope No: 1 Exascale Computing

Scope Description:

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 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.
- Reduce the cost of providing a given level of supercomputing performance for NASA applications such as FUN3D with help from AI and ML.
- 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.
- Use AI/ML for code translations, such as Fortran to C and for predicting code performance and/or optimization.

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 HEC projects: the High-End Computing Capability project at Ames Research Center and the Scientific Computing project at Goddard Space Flight Center. 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
- Research
- Analysis

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.
- Encouragement to develop new application areas like AI and ML.

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.

3. The year 2023 is the first year for this subtopic, and Phase I proposals are yet to produce any results; therefore, this subtopic should be continued in year 2024 to get Phase II opportunities.

Relevance / Science Traceability:

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

References:

1. "NASA High-End Computing Program User Needs Assessment 2020," https://hec.nasa.gov/workshop20/HEC_Needs_Assessment_2020.pdf
2. 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
3. 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
4. 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)

Related Subtopic Pointers: T11.06
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) topics. These advancements are of interest across SMD and nearly all of the rest of NASA, including the Space Operations and Exploration Systems Development Mission Directorates (SOMD and ESDMD, respectively). Although there is a vast range of possible topics, this year the emphasis is on interoperability. This includes "generic" Interoperability challenges such as model and simulation fidelities, time scales, precision, uncertainty representation, etc. As in previous years, we seek innovative proposals to address some of the fundamental M&S challenges. For example, the problem of pragmatic use of variable fidelity is still an open problem. The current state of the art (SOA) still basically involves creation of ever-growing models, with periodic attempts to create reduced-order or surrogate models. We can do better.

In addition, this year there is also an emphasis on more specific M&S interoperability challenges associated with the emergence of model-based or digital transformations. 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 are exposing some of the challenges in doing this kind of operability extension across disciplines, domains, life cycle phases, and Project/Center customizations. Solutions to these challenges are desired. Ideally, the solutions are scalable and meet the needs of a variety of users/use cases.

Scope Title: Scope1: Campaign and System Modeling and Simulation

Scope Description

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. Provide conceptual phase models and tools that allow design teams to easily develop, populate, and visualize very broad, multidimensional trade spaces; also, develop 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. Develop 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.

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 because of 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 United States. 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:

1. INCOSE: "Systems Engineering Vision 2035," https://www.incose.org/about-systems-engineering/se-vision-2035
2. NASA: "LUVOIR: Large Ultraviolet Optical Infrared Surveyor," https://asd.gsfc.nasa.gov/luvoir/
3. NASA: "Origins Space Telescope," https://asd.gsfc.nasa.gov/firs/
4. NASA: "Habitable Exoplanet Observatory (HabEx)," https://www.jpl.nasa.gov/habex/
5. NASA: "The Lynx Mission Concept," https://wwwastro.msfc.nasa.gov/lynx/
6. NASA: "LISA: Laser Interferometer Space Antenna," https://lisa.gsfc.nasa.gov/
7. NASA: "Nancy Grace Roman Space Telescope," https://roman.gsfc.nasa.gov/
8. NASA: "Mars Exploration: Missions," https://mars.nasa.gov/programmissions/
9. NASA: "Jet Propulsion Laboratory Missions," https://www.jpl.nasa.gov/missions/
10. "NASA Science," https://science.nasa.gov
11. NASA: "Artemis," https://www.nasa.gov/specials/artemis/
12. 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 MBx, 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 projects 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 and NASA-industry collaboration and datacentric information exchange. Ideally, the proposed solutions should leverage standard industry tools where

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 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, 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.
- To be able 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 the models.

Note that this scope area focus is on digital transformation and is a special case of the broader Campaign and System Modeling and Simulation scope.

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 interests to integrate engineering and science activities across the program/project lifecycle. The solution can investigate processes, data products, and translation between the lifecycle gates. The goal is to support streamlining of engineering or science business processes, achieve 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 include:

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; 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 an deeply integrated approach to tooling and data exchange across NASA and all of its partners.

References:

1. INCOSE: "Systems Engineering Vision 2035," https://www.incose.org/about-systems-engineering/se-vision-2035
2. "NASA Science," https://science.nasa.gov
3. NASA: "Artemis," https://www.nasa.gov/specials/artemis/
4. NASA: "Mars Sample Return Mission," https://mars.nasa.gov/msr/
5. NASA: "Mars Exploration: Missions," https://mars.nasa.gov/programmissions/
6. NASA: "Jet Propulsion Laboratory Missions," https://www.jpl.nasa.gov/missions/

S17.04 Application of Artificial Intelligence for Science Modeling and Instrumentation (SBIR)

Related Subtopic Pointers: T11.06
Lead Center: GSFC
Participating Center(s): ARC, JPL, LaRC

Subtopic Introduction:

NASA, NOAA (National Oceanic and Atmospheric Administration) , and other Federal agencies maintain extensive Earth and Space observation networks and are continuously developing the next generation of 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 forecasting systems. NASA is looking for proposals to introduce and use trained surrogate models to accelerate and improve the efficiency, accuracy, and timeliness of atmospheric and heliophysics model forecast products, driven by remote sensing and in situ data sources. With an emphasis on short-term predictability for the risk of localized extreme events, the results of this work will lead to better and quicker forecasts of future states and an understanding of risk for localized extreme atmospheric weather and space weather events resulting in earlier warnings, which will save lives, reduce property damage, and enhance resiliency of critical national infrastructure.

Scope Title: Accelerating NASA Science and Engineering Through the Application of Artificial Intelligence to Data Assimilation

Scope Description:

The current high-resolution, physics-based weather and heliophysics models require significant amounts of computational capacity and wall-clock time to generate even short-term forecasts. As an alternative, NASA is looking to apply artificial intelligence (AI), machine learning (ML), and deep learning (DL) methods to generate surrogate models that can significantly speed up short-term predictions, while maintaining a high degree of accuracy and skill. NASA is not looking to replace its physics-based models, but rather have a trained surrogate model with a high degree of accuracy that accelerates forecasts at equal to or higher spatiotemporal resolution than the original model.

Approaches to this may consider a full model or focus on specific model components (such as the following for weather models: dynamics, moist physics, chemistry, etc.) that can be substituted into the physics-based approach, including, but not limited to, computer vision, pattern recognition, feature extraction, super resolution, gap filling, and more.

Proposals MUST specify and be in alignment with existing and/or future NASA/NOAA programs and models, such as the Goddard Earth Observing System (GEOS) from the Global Modeling and Assimilation Office (GMAO) or the Community Coordinated Modeling Center (CCMC). 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 trained model components 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, including a final report, any software developed, training sets, etc.
- Phase II will expand on this proof of concept to a full prototype with a very similar set of deliverables, including a final report, software, training sets, etc.

State of the Art and Critical Gaps:

NASA, along with other Federal Agencies and commercial and foreign research organizations performing science and engineering, are making large strides in the use of AI technologies (which includes 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 Earth's physical system to improve short-term predictability and risk assessments.

In addition, emerging computational platforms now provide significant improvements in computing capabilities to enable AI/ML 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): Surrogate models for increased computational performance and more accurate short-term, seasonal-to-subseasonal, and retrospective forecasts.
- Goddard Institute for Space Studies (GISS): Surrogate models for increased computational performance and more accurate decadal and retrospective 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.
- NASA Community Coordinated Modeling Center (CCMC): Building the next-generation space science and space weather models.
- NASA Solar Dynamics Observatory (SDO) Science.

References:

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2. NASA, Heliophysics 2024 Decadal Survey, 2023. https://science.nasa.gov/heliophysics/2024_decadal_survey
3. NASA, Most Recent Decadal Surveys, 2023. https://science.nasa.gov/about-us/science-strategy/decadal-surveys
4. NASA, Global Modeling and Assimilation Office, 2023. https://gmao.gsfc.nasa.gov/
5. NASA, Goddard Institute for Space Studies, 2023. https://www.giss.nasa.gov/
6. NASA, Earth Science data, 2023. https://earthdata.nasa.gov/
7. NASA, Center for Climate Simulation, 2023. https://www.nccs.nasa.gov/
8. NASA, High-End Computing Program. https://www.hec.nasa.gov/
9. NASA, Community Coordinated Modeling Center. https://ccmc.gsfc.nasa.gov/
10. NASA, Solar Dynamics Observatory (SDO) Science. https://sdo.gsfc.nasa.gov/mission/science.php
11. NOAA, Public Law 115–25, Weather Research and Forecasting Innovation Act of 2017.
12. The White House, Memorandum M-19-25: Fiscal Year 2021 Administration Research and Development Budget Priorities, 2019.

In addition, proposers are encouraged to search the NASA Technical Report Server (NTRS) for additional information to help guide potential solutions:

1. https://ntrs.nasa.gov/

TX12: Materials, Structures, Mechanical Systems, and Manufacturing

This area covers technologies for developing new materials with improved or combined properties, structures that use materials to meet system performance requirements, and innovative manufacturing processes.

H5.01 Lunar Surface 50 kW-Class Solar Array Structures (SBIR)

Related Subtopic Pointers: T12.01, T12.09
Lead Center: LaRC
Participating Center(s): GRC

Subtopic Introduction:

NASA intends to land near the lunar south pole (at south latitudes ranging from 85° to 90°) in 2026 in the Artemis III mission, and then to establish a sustainable long-term presence by 2028.

Scope Title: Lunar Surface 50-kW-Class Solar Array Structures

Scope Description:

NASA intends to land near the lunar south pole (at south latitudes ranging from 85° to 90°) in 2026 in the Artemis III mission, and then to establish a sustainable long-term presence by 2028. At exactly the lunar south pole (90° S), the Sun's 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 “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 five times. Increasing the unit solar array size from first-generation 10 kW to second-generation ~50 kW is a logical course of action as power needs increase for new infrastructure such as ISRU or the Foundation Surface Habitat, which can require >>10 kW of power. This 5x size increase 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 [Ref. 5] as the “Adaptable Solar Array Systems” Technology Gap, which requires new and/or novel performance or function that has not been demonstrated (solutions to this gap type are generally TRL 1-4); this gap type aligns with the New Technology TRL 1-4 definition within the NASA Technology Readiness Assessment Report (2016). Additionally, NASA’s No. 1 Lunar Infrastructure Goal (LI-1) is to “Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.” [Ref. 6]

Solar array 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 at least 10 m above the surface to reduce shadowing from local terrain are required [Ref. 7]. 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 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.
- Minimum of 10-m height above the surface to reduce shadowing from 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 less than 0.5° of vertical.
- Retractable over hardware temperature range of -60 °C to +60 °C 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.
- Analysis and testing of dust effects and dust mitigation methods.
- 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 ppm/°C).
- Integration of novel structural health monitoring (SHM) technologies.
- Validated modeling, analysis, and simulation techniques.
- Modular and adaptable solar array concepts for multiple lunar surface use cases.
- Multipurpose, external robotic actuators instead of traditional single-purpose actuators [Ref. 8, Appendix A].
- 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.
- Completely new solar array material processing and handling approaches such as ISRU-created materials.

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: 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
- 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:

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.

These 50-kW-class solar arrays are listed in NASA’s HEOMD-405 Integrated Exploration Capabilities Gap List as the “Adaptable Solar Array Systems” Technology Gap, which requires new and/or novel performance or function that has not been demonstrated (solutions to this gap type are generally TRL 1-4); this gap type aligns with the New Technology TRL 1-4 definition within the NASA Technology Readiness Assessment Report (2016). Additionally, NASA’s No. 1 Lunar Infrastructure Goal (LI-1) is to “Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.”

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. 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.

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3. NASA Space Tech News, “Three Companies to Help NASA Advance Solar Array Technology for Moon,” August 23, 2022, https://www.nasa.gov/press-release/three-companies-to-help-nasa-advance-solar-array-technology-for-moon
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 Exploration Systems Development Technical Integration Office, HEOMD-405 Version 3, “FY 2023 Integrated Exploration Capabilities Gap List,” February 22, 2023.
6. NASA Moon-to-Mars Objectives document, September 2022, https://www.nasa.gov/sites/default/files/atoms/files/m2m-objectives-exec-summary.pdf
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H5.05 Inflatable Softgoods for Next Generation Habitation Systems (SBIR)

Related Subtopic Pointers: T12.01, T12.09
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 for exploration habitation scenarios (lunar surface, Mars transit) and commercial low-Earth orbit (LEO) applications, to which the research under this subtopic could be directly applied. These inflatable structures consist of many softgoods layers that provide a hermetic seal to the internal atmosphere (bladder), a structural restraint layer that carries the pressure load (typically high-strength synthetic webbing or cord made of materials such as Vectran or Kevlar, with strengths of up to 20,000 lbs/in width), and a series of outer protective layers designed to protect the bladder and restraint layer from impact damage and the space environment. This subtopic specifically addresses nondestructive structural health monitoring (SHM) of the restraint layer through the integration of sensing capabilities.

Scope Title: Structural Health Monitoring for Inflatable Softgoods Restraint Layer

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. Given the protective layers above the restraint layer, its primary degradation over time is via creep. Accurate measurement of strain is therefore of primary interest to track any significant changes across the components of the restraint layer and help predict the level of degradation or 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 wired sensors, including adhesive foil strain gages, fiber optics, accelerometers, and acoustic sensors, all have potential drawbacks to integration with a softgoods restraint layer. These include difficulty in bonding to a high-strength synthetic material like Vectran, added steps in manufacturing of the restraint layer materials, creation of hard point(s) on the material, and ingress/egress of wired connections that could both lead to a local failure or degrade performance, and robustness/durability of the sensor/wiring to packing/fold cycles and the space environment. Alternatively, wireless sensors must be able to operate independently of handheld interrogation devices due to constricted access internally and externally, and be operable between interior and exterior layers of the multilayer inflatable shell that may be metallized (i.e., layers of aluminized MLI on the exterior or foil-lined bladder(s) on the inside), in addition to other possible sources of interference from the habitat. There is a current technology gap for a proven sensor system that can integrate into or onto the structural restraint layer nondestructively and be feasibly integrated into the manufacturing flow of the overall inflatable article when including an array of possibly several hundred sensors. The proposed work should seek to demonstrate not only a sensor but the approach and methodology to integrating the sensors and interrogation hardware with an inflatable structure. This may include direct integration into or onto the restraint layer where substantial consideration must be given to the ingress/egress of any wiring and connectors, and how the sensor and/or control electronics are attached and located. It may also include sensors/interrogators in close proximity to the restraint layer, but the method of incorporation, and validation of a robust and repeatable strain measurement would have to be proven. 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 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 (e.g., there may only be 0.1% change over a year).
- The proposed sensor must be able to measure strain in a discrete restraint layer component such as a webbing or cord that could be as narrow as 0.5 to 1 in. in width.
- Additional sensing capabilities (impact, temperature, etc.) are of secondary importance under this call, and should not be the focus, but can be highlighted as a possible future augmentation of the same sensor system proposed.

Sensor System Softgoods Integration Focus:

- There should be a strong focus on the method and vetting of integration of any sensor system with the 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 or layer(s), and integration, attachment and ingress/egress of any wiring or control hardware needed).
- The proposal should address how the strength/behavior of the softgoods materials with integrated sensor(s) will be quantified, including required test facilities and materials. Note typical materials used in the restraint layer have strengths of 15,000 to 20,000 lb/in. in width.
- The complexity and additional work added to integrate and operate the sensor system should also be considered and addressed for its impact on the fabrication process of the inflatable structure and any additional work required on the mission to set up, operate, or read data from the system. The desire is to have a system with broad applicability to different inflatable architectures that may use varying combinations, sizes, and layouts of webbing, cordage and/or fabric.

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 (could be in a prelaunch folded configuration for several months)
- 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 restraint layer where the sensors are needed has multiple softgoods layers in front and behind it as part of a multilayer system (see cutaway image: https://commons.wikimedia.org/wiki/File:TransHab_shell_cutaway.jpg) Thus, the structural restraint layer is not accessible or observable during the mission, and the layer is in close contact with the layers around it.
- Preference is for an integrated sensing system that can be interrogated as a whole versus handheld or single sensor interrogation systems due to access, crew time, and monitoring of the habitat while uncrewed.
- One or more additional layers could be added to the stack-up of layers next to or in contact with the restraint layer, to carry the power/wiring/interrogation components. Wireless sensing or sensors could be either directly attached to the restraint layer or be placed in a separate carrier layer in close contact with the restraint layer. This additional layer(s) should minimize thickness and intrusion on the other layers, and any hardware needed should be evaluated for possible location inside the habitat versus attached to the softgoods layers.
- The outer layers typically have multilayer insulation (MLI), which incorporates thin metallic depositions. The inner bladder may also have metallic foil integrated to decrease permeability. If wireless sensing equipment is to be used, 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 listed, integration of at least one sensor into/onto a single cord/webbing component (if a direct attachment is used), and preliminary breadboard testing with its interrogator would be expected under Phase I on an applicable high-strength softgoods component(s) as a proof of concept. Integration into an assembled 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 with a sensor integrated on a single applicable high-strength softgoods component(s) (webbing or cord).
Phase II:
Integration of multiple sensors into an assembled inflatable softgoods structure or higher fidelity subcomponent test(s) to validate the feasibility of the approach with multiple sensors and how it would be scaled to a full-scale crewed inflatable structure, including prototype interrogation hardware and software to read pertinent data from the sensor array.

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 multilayered 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:

Development of inflatable softgoods is relevant to exploration habitats (lunar surface, Mars transit) as well as commercial low-Earth orbit habitat development. NextSTEP Appendix A; Habitation Systems 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 (Commercial LEO Destinations) is focused on the development of commercial space stations in low-Earth orbit. The work under this subtopic could serve to complement ongoing development work under these programs and increase the potential for infusion of inflatable softgoods into future habitation concepts by reducing risks associated with understanding, tracking, and predicting material behavior. 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.

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H8.01 In Space Production Applications (InSPA) Flight Development and Demonstrations on ISS (SBIR)

Related Subtopic Pointers: T12.01, T12.09
Lead Center: ARC
Participating Center(s): JSC, LaRC, MSFC

Subtopic Introduction:

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.

Scope Title: Use of the ISS to Foster Commercialization of LEO Space

Scope Description:

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 2.5 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/international-space-station/space-station-research-and-technology/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:

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2. Space Station Research & Technology at: Space Station Research Explorer on NASA.gov
3. Center for the Advancement of Science In Space, Inc. at: https://www.issnationallab.org and In-Space Production Applications (issnationallab.org). Both links are external.

S12.02 Precision Deployable Optical Structures and Metrology (SBIR)

Related Subtopic Pointers: T12.01, T12.09
Lead Center: JPL
Participating Center(s): GSFC

Subtopic Introduction:

Space telescopes continue to require larger apertures for the primary mirror systems, but also require precision components for the entirety of the optical chain. This subtopic aims to increase the number of options available to achieve large apertures, ultrastable systems, or other novel deployable space structures not achievable with current technologies.

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 Habitable Worlds Observatory calls for a 6-m-class aperture. Future cryogenic missions demand 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 5- 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. We are seeking technology for a range of missions from CubeSats to Pioneers to Explorers to Flagships. 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 Habitable Worlds Observatory (HWO) will drive telescope/instrument stability requirements to new levels. The mission concepts responsive to the 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 HWO mission concept. Ultrastable optomechanical systems were listed as a "critical" technology gap with an "urgent" priority in the LUVOIR STDT (Large UV/Optical/IR Surveyor Science and Technology Definition Team) Final Report for the Astro2020 Decadal Survey and continue to be highly applicable to HWO.

References:

1. Habitable Worlds Observatory: https://cor.gsfc.nasa.gov/studies/habitable-worlds/hwo.php
2. Large UV/Optical/IR Surveyor (LUVOIR): https://asd.gsfc.nasa.gov/luvoir/
3. Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/
4. Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/
5. Exoplanets: https://exoplanets.nasa.gov/what-is-an-exoplanet/technology/

6. NASA in-Space Assembled Telescope (iSAT) Study: https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/
7. NASA Astrophysics: https://science.nasa.gov/astrophysics
8. Astrophysics Technology Development archive: https://www.astrostrategictech.us/
9. 2022 Astrophysics Biennial Technology report: https://apd440.gsfc.nasa.gov/technology.html. (This includes the list of prioritized Astrophysics technology gaps: https://apd440.gsfc.nasa.gov/tech_gap_priorities.html)

Z4.07 Advanced Materials and Manufacturing for In-Space Operations (SBIR)

Related Subtopic Pointers: T12.01, T12.09
Lead Center: LaRC
Participating Center(s): GRC, MSFC

Subtopic Introduction:
This subtopic addresses technology gaps to enable sustainable operations in the lunar surface environment. Specifically, it seeks proposals to enable (a) in-situ resource utilization (ISRU) to build infrastructure on the Moon, (b) operations on the surface that require cryogenic liquid transfer, and (c) laser systems that can operate in-space and on extraterrestrial surfaces and are capable of being used in manufacturing and recycling operations.

Scope Title: ISRU-Based Structural Elements for the Assembly of Lunar Infrastructure

Scope Description:

As humanity returns to the lunar surface for sustained exploration, there is an emphasis on building infrastructure elements produced from lunar regolith [1-6]. Conversion of the raw resources produced by ISRU extraction into useful components requires manufacturing processes and equipment 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. Manufacturing methods are needed to produce components for the construction of lunar infrastructure from these elements as well as from other materials that may be available in smaller quantities.

In this solicitation, proposals are invited for approaches that utilize aluminum (Al), iron (Fe), or other less-refined alloys (slag) derived from ISRU processes to produce structural angles, rods, or tubes in the lunar south pole region. The manufacturing of ISRU-based truss elements will be of importance to sustainable construction of lunar surface infrastructure for Artemis missions and initial commercial activities. Typical requirements for structural truss elements of interest include:

- Truss member cross sections in order of preference (range of dimensions chosen to show scale-up to future configurations):
    - Tube: diameter of 10 mm and 40 mm with thickness of 1.5 mm and 2.0 mm
    - Angle: flange length of 10 mm and 40 mm; flange thickness of 2.0 mm and 8.0 mm
    - Square rod: 10 mm, 15 mm, 20 mm square
- Truss member length: 0.5 m, 2.0 m

- Quantity: minimum = 100, goal = 500 (to show repeatability and scale-up potential of the process)

Proposals to the current solicitation can assume that ISRU-derived materials are available in molten form at purity levels ranging from less-refined alloys (slag) to 99% pure metal. The selection of a particular material for the truss element manufacturing must take into account a demonstrated or projected ability to support tensile and bending loads in the lunar environment and include justification for its proposed manufacturability and performance. Of particular interest is the use of aluminum material, which is expected to be on hand for use in power infrastructure and distribution systems (aluminum power cables). Thus, truss manufacturing processes using aluminum are of high interest, including 1xxx series aluminum and 6xxx series aluminum alloy.

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

- Joining approach is of high interest and importance and should be described in detail. The joining of the proposed truss elements can be achieved using adhesive, mechanical, or welding approaches. Approach should be justified.
- Description of equipment required for efficient manufacturing, including the dimensions, mass, power requirements, production rates, operating environments, thermal management requirements, and any other required support.
- Equipment and manufacturing systems that account for limited availability of resources, such as coolant, and maintenance logistics on the Moon that may be needed for the production of the structural elements. Provide consumption rates of any consumables.
- Preliminary proof-of-concept experiments for feasibility of the proposed material systems, processing methods, joining, and equipment.
- Proposals must indicate expected mechanical properties (stiffness, strength), straightness, and finish of the truss elements that are required and achievable to ensure performance of the elements as well as their subsequent joining and other operations. Include plan for characterizing these properties and range of variability.

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 the production of selected structural elements on the lunar surface given the available resources. The concept will include a detailed design and description of the equipment that would be required and how that equipment succeeds in operating in the lunar environment. Preliminary proof-of-concept system components and the production of precursor truss elements are highly desirable at this stage. Demonstrated or projected strength properties such as flexural, tensile, and compressive strengths must be provided.

Phase II would develop and demonstrate a pilot-scale system for the production of selected structural elements from the list provided in the scope. This would include designing and building of production equipment and the processing of commercially available material that is similar to the materials expected to be available on the Moon, either in raw form or from other processes. Scale-up of production, system reliability, and maintenance and repair considerations are of great interest.

State of the Art and Critical Gaps:

Sustainable long-term exploration of the Moon is going to be dependent on the utilization of resources that can be found on the Moon. While there are various efforts looking at the excavation of those resources, there are currently gaps in understanding the detailed process requirements for turning various material feedstocks that may be available on the Moon into useful products. These efforts require understanding of the material properties through the process cycle and how these properties would be impacted with the processes conducted 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 by 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 Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.
    - LI-4 Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy.
- 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: Cold-Tolerant Interface Seals for Lunar Operations

Scope Description:

As humanity returns to the lunar surface for sustained exploration [1], there is a need for technologies that enable survival in the extreme lunar environment. In particular, surface system technologies will be required to support extended operations. NASA has listed capabilities required to accomplish the goals of deep space human exploration at the Moon, Mars, and beyond [2]. Among the recurring tenets is the design of systems for maintainability and reuse to support long-term operations independent of Earth. This subtopic seeks to address the need for interface seals to enable surface transfers at cold temperatures. Proposals are invited for approaches that utilize a variety of sealing materials, including elastomeric, polymeric, metallic and hybrid material solutions.

Of primary interest are concepts that enable sustained operations involving cryogenic transfer. Performance goals for the technology solutions sought are the following:

- Lifetime: >10 mate/demate cycles in cold, dusty environment.
- Temperature range: 300 to 90 K (evolvable down to 20 K).
- Pressure range: ~14 to 100 psi.
- Seal integrity: Equal to or better than state of the art (SOA).
- Environmental robustness:
    - Seal integrity achievable in a dusty environment (no lubricants).
    - Tolerant to vacuum, ultraviolet (UV) radiation, atomic oxygen, and ionizing radiation.

Examples of use cases include, but are not limited to:

- LOX (90 K) internal, transferred in sunlight (>300 K).
- LOX (90 K) internal, transferred in shadow near poles (35 K).
- Water (~275 K) internal, transferred in sunlight (>300 K).
- Water (~275 K) internal, transferred in shadow near poles (35 K).

The need is for a material with the ability to cycle between the thermal extremes and still endure multiple compressions (mate/demate cycles) without experiencing permanent deformations.

Ideas that may be of interest include, but are not limited to, approaches to extend the low-temperature usability of polymeric and metallic materials using innovative mechanisms to extend operational capability. Existing techniques or emerging concepts are of interest. Examples include, but are not limited to:

- Incorporation of dynamic bonds [3], facile mechanochemical cycloreversion of polymer cross-linkers [4], and other innovative mechanisms for extending retention of compressibility across multiple cycles.
- Exploitation of smart materials approaches such as shape memory for different classes of materials [5].
- Metals with high elastic strain limits.
- Concepts for metallic/hybrid seals that include, but are not limited to, C-seals, E-seals, spring-energized seals, and metal bellows mechanical seals [6].

Proposal elements should include:

- Material design concepts that will be evaluated.
- Fundamental characterization suite to obtain evidence of feasibility as materials for the required performance.
- Preliminary proof-of-concept experiments for feasibility of the proposed material systems tested at low temperatures.

Proposals must account for the scalability of concepts for fabrication of prototype seals.

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
- Prototype

Desired Deliverables Description:

Phase I will provide concepts for demonstration of the material performance under the required operating conditions and preliminary experimental data indicating the viability of the proposed solution.
Phase II will explore fabrication methods to produce prototype seals and test them under simulated operation.

State of the Art and Critical Gaps:

Ground-based cryogenic transfer seals:

- Lifetime: 1 mate/demate cycle (softgoods permanently deform upon sealing).
- Temperature range: ~530 to 60 K.
- Pressure range: Up to ~1,200 psig.

- Seal integrity: ASTM F-37 sealability ~0.009 mL/h.
- Environmental robustness: Seals are precision-cleaned and kept bagged until installation.
- No active particulate mitigation employed during mate.

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 by commercial companies and international partners. Sustained operations involving cryogenic transfer will be critical for these missions.

Development of interface seals to enable surface transfers at cold temperatures would support Capability Touch Points that include Cryogenic Fluid Management, In-Situ Resource Utilization (ISRU), and Advanced Habitation Systems. This work would also support the STMD Strategic Thrust "Live: Sustainable Living and Working Farther from Earth."

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 07/13/2023].
2. Moon to Mars Objectives: https://www.nasa.gov/sites/default/files/atoms/files/m2m-objectives-exec-summary.pdf [accessed 07/13/23].
3. Chakma, P. and Konkolewicz, D., Dynamic Covalent Bonds in Polymeric Materials, Angewandte Chemie, 58(29), 2019, pp. 9682-9695.
4. Wang, S., et al., Facile Mechanochemical Cycloreversion of Polymer Cross-Linkers Enhances Tear Resistance, Science, 380(6651), 2023, pp. 1248-1252.
5. Goldade, V., Shil'ko, S. and Neverov, A., Smart Materials Taxonomy, CRC Press, 2015.
6. Muller, H. K., Nau, B. S., Fluid Sealing Technology, New York: Marcel Dekker, 1998.

Scope Title: Space-Based Laser Technology for In-Space and Extraterrestrial Surface Manufacturing Operations

Scope Description:

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, to enable colonization, and to make possible the exploitation of in situ resources. Manufacturing and materials processing in those locations are subject to variable gravity, vacuum or reduced pressure, large temperature variations compared to terrestrial processing conditions, radiation, and atomic oxygen. Currently, there are no readily available lasers for manufacturing designed to operate in these environments; thus, critical manufacturing processes and experiments needed to develop these processes cannot be performed. Examples of critical manufacturing processes include welding, cutting, cleaning, forming, additive manufacturing, and machining (such as drilling/milling). High-power lasers of appropriate wavelength and focus to cut, clean, weld, heat treat, and otherwise process common space alloys, including primarily aluminum alloys followed by SS, Ti, and refractory metals, are required. Proposal elements of interest include, but are not limited to:

- Subsystem design and test for vacuum environments (specify vacuum level).
- Subsystem design and test for space thermal environments (specify).
- Subsystem design and test for radiation environments (specify).
- Evaluation of any effects of reduced-gravity and microgravity on systems (0g, 0.17g, and 0.38g).
- A design or prototype of a physical system that could be used to demonstrate materials processes 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).
- High-power lasers of appropriate wavelength and focus to cut, clean, weld, heat treat, and otherwise process common space alloys, including primarily aluminum alloys followed by SS, Ti, and refractory metals.

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:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I will provide concepts of a test article and test subsystems in a vacuum environment.
The concept for a testbed will include definition of the equipment that would be required, and a description of protections and controls required to succeed in operating in the environment of space, lunar surface, or Martian surface.

Phase II would result in full system build and test in relevant environments to have a flight-ready, space-based laser for space, lunar surface, and 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. A space-capable laser-based manufacturing system that allows experiments can advance many gaps, including lunar surface manufacturing and outfitting with metals, polymers, and composites; ISRU-derived materials for feedstocks (e.g., Al, Si), lunar and Martian; model-based technologies for materials, structures, and manufacturing; and on-demand manufacturing of metals, electronic components, recycling, and reuse.

Relevance / Science Traceability:

This topic has relevance to the following thrusts and outcomes:

- Explore: Develop technologies supporting emerging space industries, including Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft Technologies.
- Live: Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities.

Exploration goals will require the use of recycled orbital debris, lunar and Martian resources to minimize the transport of materials and components from Earth, and the use of joining in-space to enable structures on scaled, much larger than launch vehicle payload fairings. 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 integrated computational materials engineering (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:

1. 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
2. NASA SLS-SPEC-159 Rev. G. Cross-Program Design Specification for Natural Environments (DSNE), NASA 2019. https://ntrs.nasa.gov/api/citations/20200000867/downloads/20200000867.pdf

TX13: Ground, Test, and Surface Systems

This area covers technologies for preparing, assembling, validating, executing, supporting, and maintaining aeronautics and space activities and operations, on Earth and on other planetary surfaces.

A1.08 Aeronautics Ground Test and Measurement Technologies: Diagnostic Systems for High-Speed Flows and Combustion (SBIR)

Related Subtopic Pointers: T13.01
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 the 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 Measurement 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. Technologies that can be applied to NASA's portfolio of large-scale ground test facilities are of primary interest.

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), in both combusting and noncombusting flows. 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 are also of interest. Measurement systems should be both reliable and robust and preferably 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 flow fields so that frequency spectra of the measured phenomena can be obtained is a secondary benefit but not required.

The highest priority will be given to compact/miniaturized systems that could be installed inside a wind tunnel test article and/or systems capable of measuring temperature, water vapor concentrations, and velocity at the nozzle exit of large hypersonic tunnels, such as the 8-ft High Temperature Tunnel at NASA LaRC.

- For embeddable miniaturized measurement systems, external power, fiber optic, and/or data signal connections can be used. 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.
- Measurement diagnostics for the nozzle exit of large hypersonic tunnels will be used to quantify facility performance and to determine test article inflow conditions. Such flow fields may contain water droplets; therefore, any diagnostic proposed for this environment must be insensitive to water droplets. Measurements of the nozzle-exit flow field are desired at high repetition rates (tens of kilohertz) and should be able to operate continuously or repeatedly for several minutes' duration to obtain an appropriate amount of data to improve statistical error and provide detailed information about the time-varying nature of these flow fields.

Expected TRL or TRL Range at completion of the Project: 4 to 7

Primary Technology Taxonomy:

- Level 1: TX 13 Ground, Test, and Surface Systems
- Level 2: TX 13.X Other Ground, Test, and Surface Systems

Desired Deliverables of Phase I and Phase II:

- Hardware

- Prototype
- Research
- Analysis
- Software

Desired Deliverables Description:

Phase I: Research shall include proof of concept of proposed idea. The proposer must provide the design for the comprehensive system that would be developed in Phase II, including detailed analysis of the expected performance (consideration for beam steering, spatial resolution, time response, accuracy, precision, etc.) A benchtop demonstration of the prototype in a company's lab is strongly encouraged.

Phase II: Production and delivery of a turnkey system with sufficient documentation for NASA researchers to install and operate the measurement system in NASA's facilities. NASA may choose, at its discretion, to visit the contractor's site prior to hardware delivery to observe system setup and operation (including software). Any computer equipment or electronic systems included in the system must comply with the government's 889 Certification requirements. If the measurement system hardware is very expensive, a Phase IIE/III funding may be required, but some less expensive technologies should be able to deliver a full-scale demonstration system in Phase II.

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.

There are also very limited technologies for measuring nozzle exit conditions in hypersonic facilities. Some systems exist, but there have been very limited applications. A technology that can measure nozzle exit conditions could also be used for engine inlet and outflow conditions. A promising technology was developed to study aircraft engine outflow plumes using Air Force SBIR project support. This included using an array of laser beams to perform absorption spectroscopy at the exit of a J-85 jet engine. Temperature and water vapor concentration was measured over an area of ~1 m × 1 m. A gap in this technology is that the gas velocity, a highly desirable parameter, was not measured. More consideration would be given to an approach that provides a full reconstruction of the velocity, temperature, and water content across the entire face of the 8-ft tunnel exit diameter. Another gap that is needed by the facility managers and customers at some of the larger combustion heated hypersonic facilities at NASA is the ability to measure water vapor droplet size and concentration (water droplets are an undesirable consequence of combustion heating and can affect engine performance). The proposed instrument need not meet all of these requirements but should show a viable path towards the desired spatially resolved facility characterization detailed above.

Relevance / Science Traceability:

The target application of this technology is at NASA’s large-scale test facilities: the National Transonic Facility (NTF) and Transonic Dynamics Tunnel (TDT) at Langley Research Center, the 8×6 Supersonic Wind Tunnel and the 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. The ARMD/AETC-owned 8-ft High Temperature Tunnel at NASA Langley also benefits from this technology, particularly if designed to measure nozzle exit conditions. The technology also has other applications, such as to measure inflow or outflow for engines being tested at NASA Glenn.

References:

ARMD Strategic Implementation Plan: https://www.nasa.gov/wp-content/uploads/2021/04/sip-2023-final-508.pdf

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Scope Title: Nonintrusive Soot Measurements for Altitude Combustion Facilities

Scope Description:

Recent studies have determined that contrails emitted from aircraft have a significantly higher warming impact on the planet than the CO_2 emissions from burning fuel. They do so by trapping heat that would otherwise be released into space. The contrails are generated by the condensation and freezing of water vapor in the atmosphere on the soot particles emitted as a by-product of burning aviation fuel. Therefore, nonintrusive soot diagnostics are needed to measure particle size and concentration in combusting flows at high-altitude conditions. The measurement system must be compatible with the optical access available in high-altitude combustion facilities, where the by-products from a combustor are delivered via a transition pipe to a simulated cooled high-altitude environment. Measurements of the soot particles as they exhaust from a 0.5- to 1-in.-diameter nozzle into a 24-in.-diameter by 72-in.-long altitude chamber after traveling approximately 36 in. from the combustion zone via a 1-in. heated transition pipe are desired. The measurement volume shall be located within the nozzle exit region where the hot combustion products have not yet mixed with the cold ambient air, resulting in ice particle formation. The measurement volume may be up to 0.5 cubic in. Optical access consists of windows along the axial flow direction distributed circumferentially every 90 degrees. One set of opposing windows are fixed 60-in. by 4-in. Starphire glass windows spanning the chamber length. The other set of opposing windows are a linear series of 2-in.-diameter window ports that extend along the chamber length, with spacing of 3.75 in. between each window. (See Refs. 3 and 4 for more details of the Particulate Aerosol Laboratory (PAL) facility at NASA GRC.) The glass in these windows can be any type of glass desired. The current windows are UV Fused Silica. Laser illumination can enter and exit through one pair of windows and scattered light collected from the perpendicular windows or above/below the plane of the laser. The measurement system must be rugged; however, the components should be mounted externally to the chamber and will only experience ambient room conditions. Measurements shall be point, planar, or volumetric measurements, producing a statistically valid sample in less than 1 min. The measurement systems should be capable of sensing particulates from 5 nm to 100 nm and concentrations from 10^3 particles/cm^3 to 10^6 particles/cm^3. Sample rates of 1 Hz or better are preferred. Measurement systems should be validated against accepted standards (thermocouples, calibration flames, particle sizing instruments, 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.

The use of these measurement system/techniques in atmospheric nucleation chambers is critical for studying emissions and contrails at upper atmospheric conditions. The target application is at the nozzle exit in the altitude chamber of the PAL at NASA GRC.

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:

- Research
- Analysis
- 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 integration into the optical access ports available in the PAL facility.

Desired deliverables for Phase II would be prototype hardware that has been validated through test (ground-based or flight), and traceable metrics for hardware calibration and characterization. The prototype system will be configured to operate on/through the window ports of the PAL facility chamber, of which the specific design and dimensions will be provided by NASA at the time of Phase II award. The prototype hardware should be delivered ready to install and use in the PAL facility with set-up and operational instructions. NASA may choose, at its discretion, to visit the contractor’s site prior to hardware delivery to observe system setup and operation (including software). Any computer equipment or electronic systems included in the system must comply with the government’s 889 Certification requirements.

State of the Art and Critical Gaps:

The NASA Glenn Research Center Particulate Aerosol Laboratory (PAL) is a ground test facility for studying emissions and contrails at upper atmospheric conditions. The facility consists of a small-scale combustor that generates hot combustion gases and soot nanoparticles, which flow through a transition pipe into a jet nozzle that exhausts into the altitude chamber. Thermodynamic conditions experienced in flight are matched in the altitude chamber, allowing the study of ice particle formation of simulated aircraft engine exhaust plumes. A nonintrusive optical diagnostic technique based on Mie scattering provides ice particle size and number density. A suite of commercial extractive particle measurement instruments provides soot number density, size, and black carbon mass distributions. The soot characterization measurements obtained from the extractive techniques are not completely reliable and only practical in the transition pipe and combustion zone due to icing of the extraction probe and difficulty in extracting samples from a low-pressure, low temperature environment. The goal of the proposed work would be to supply a nonintrusive soot characterization system that can be mounted externally to the altitude chamber and provide measurements with a 12-in. standoff distance via available window ports.

Depending on the ultimate system design and configuration, measurement approaches that could ultimately be made into a compact format for use in actual flight testing would be given more consideration.

Relevance / Science Traceability:

The scope of this activity ties directly to ARMD’s Sustainable Aviation objective of achieving the U.S. climate goal of net-zero greenhouse gas emissions from the aviation sector by 2050. NASA is leading federal agencies and industry to accelerate the development of sustainable technologies, which includes the use of high-blend sustainable aviation fuels. Contrail formation is postulated to be a more significant environmental impact factor on the temperature of the planet than pollution by-products (CO_2) of the aviation industry. Advanced diagnostics are required to improve our understanding of the soot formation process and the proper characterization of new fuel formulations on soot formation.

References:

1. https://www.nasa.gov/wp-content/uploads/2021/04/sip-2023-final-508.pdf
2. https://www.nasa.gov/aeroresearch/sustainable-aviation
3. https://acp.copernicus.org/articles/13/10049/2013/
4. https://ntrs.nasa.gov/api/citations/20120001788/downloads/20120001788.pdf

TX14: Thermal Management Systems

This area covers technologies for acquiring, transporting, and rejecting heat, as well as insulating and controlling the flow of heat to maintain temperatures within specified limits.

S16.05 Thermal Control Systems (SBIR)

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

Subtopic Introduction:
NASA is searching for innovative thermal control technologies that enable lunar science and support solar system exploration. The thermal control systems subtopic has three scopes:

1. Coatings for Extreme Environments for Thermal Radiators and Complex Surfaces
2. Thermal Technologies for Lunar Science
3. Artificial Intelligence for Spacecraft Thermal Control Systems

Upon successful development, these technologies will empower NASA’s robots and astronauts to conduct unprecedented lunar exploration, enabling them to accomplish a greater scope of scientific research than ever before.

Scope Title: Coatings for Extreme Environments for Thermal Radiators and Complex Surfaces

Scope Description:

Thermal coatings are an integral part of a space mission and are essential to the survivability of the spacecraft and instrument. Radiator surface coatings with desired emissivity and absorptivity provide a passive means for instrument temperature control. A growing number of uses for these coatings include radiator surfaces with complex geometries and topographies. Existing stable, dissipative radiator coating systems are challenging to apply onto these complex geometry systems, and new formulations are desired to provide improved optical performance with added durability and manufacturability with less sensitivity to thickness control requirements. Radiator coatings are desired to maintain optical stability in extreme temperature exposures as well as long-duration, intense ultraviolet (UV) and solar wind exposures for near-solar missions. Additionally, with NASA's new initiative to return to the Moon, a new coating technology that will keep surfaces clean with minimized solar absorptance or infrared (IR) emittance impacts is needed. These dust-mitigating coating systems and cleaning techniques may employ active tilt/maneuvering systems such as rotating surfaces to aid in dust removal. It is desired that the processing time for coated hardware, because of strict humidity and temperature-controlled application and cure conditions, be reduced. Examples of technologies include, but are not limited to, the following:

- Highly stable, dissipative white coatings in intense, long-duration UV and solar wind environments.
- Operator-sprayed coatings that have high structural/adhesive tolerance to coating thickness variation while in widely varying thermal cycling vacuum environments for application to complex hardware where thickness control is challenging or impractical.
- Stable, dissipative coatings with accelerated, elevated cure schedules and those independent of humidity control for use with aluminum or carbon composite substrates.
- Coating systems with dust-mitigating and cleaning properties for lunar and Martian environments.

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

Primary Technology Taxonomy:

- Level 1: TX 14 Thermal Management Systems
- Level 2: TX 14.3 Thermal Protection Components and Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I Deliverables:

- Successful development of coating formulations that lead to the desired dust mitigation.
- Deliverable of coupon.
- Samples of the hardware for further testing at NASA facilities.
- Final report.

Phase II Deliverables:

- Results of performance characterization tests.
- Results of stability test of the coating formulations and their mechanical durability test under the influence of simulated space and lunar environmental conditions.
- Test coupon.
- Final report.

State of the Art and Critical Gaps:

There are limited options for durable, stable thermal control coatings that are dust shedding in charging environments. Current state-of-the-art, sprayable radiation-stable coatings are able to fully coat complex, irregular surfaces only with significant effort and expertise, but these coatings are porous and can become imbedded with dust and particulates. Additionally, these coatings lack the stability of other historic nondissipative systems and are sensitive to structural stability issues with vacuum thermal cycling when their thickness is outside a narrow range. Currently, no single thermal control material appears to provide stability and durability and meet optical property requirements for sustained durations in extreme environments on complex substrates.

Relevance / Science Traceability:

Many SMD missions will greatly benefit from an improved, durable thermal coating system for extreme environments. Every mission that does not have a flat radiator surface and cannot afford the 4-week processing time and required time to develop techniques for application to complex substrates will benefit. These projects will include large flagship-scale projects to SmallSat and CubeSat systems and any lunar-related project and projects involved with robotic science rovers and landers.

References:

1. References for dust mitigation coatings such as lotus thermal coatings: https://ntrs.nasa.gov/search.jsp?R=20150020486
2. References in Subtopic Z13.01, Active and Passive Dust Mitigation Surfaces.

Scope Title: Thermal Technologies for Lunar Science

Scope Description:

The lunar environment poses significant challenges to small (less than a half meter in each direction) and low-power (~100 W or less) payloads, rovers, and landers required for lunar science. The lunar day/night cycle is approximately 1 Earth month. During that time, surface temperatures on the lunar surface can reach 400 K at local solar noon or drop to below 100 K during the lunar night—and even colder in permanently shadowed regions. These hot and cold conditions can last several Earth days, because of the slow rotation of the Moon, or permanently in shadowed craters. Lunar dust deposited on heat-rejection surfaces and coatings will increase the heat absorbed from the Sun, thus reducing the effectiveness of radiators for heat rejection. The lunar gravity, which is 1/6th of the Earth's, will limit the ability of typical low-power heat transport devices, but the gravity field may provide advantages that could be utilized. Higher heat dissipation capacity and large systems should be addressed in Z2.01. This call seeks to solicit innovative proposals to enable lunar science in the difficult lunar environment. The

Farside Seismic Suite (FSS) represents a typical-size instrument for lunar science (Refs. 3 and 4). Examples technologies include, but are not limited to, the following:

- Advanced two-phase passive and active thermal control systems (TCSs) as well as single-phase active loops that may be turned off. Novel heat transfer fluids for these TCSs that are more efficient, nontoxic and freeze resistant.
- Zero- or low-power nonconsumable/regenerative heat generation sources.
- High-thermal-capacitance thermal storage. New phase-change materials with the latent heat greater than 500 kJ/kg, metal-to-mass ratio of 1:1, densities less than 700 kg/m^3, and melting temperatures from 0 to +330 K. Materials should be easily handled, nontoxic, chemically compatible, not corrosive or explosive, and reliably reproducible. Furthermore, new types of thermal energy storage are also desired.
- Advanced thermal insulation for application in Moon, Mars, and Venus environments.
- Variable heat rejection (>10:1 turndown ratio) and passive switching with high turndown ratios (e.g., >400:1). Furthermore, small form factors are also desired.
- High-performance thermal interface materials (TIMs) for thermal coupling to vibrating components.
- Advanced thermostats and alternative passive technologies operating below 210 K.

Technologies should show substantial increase over the state of the art. Technology proposals should address power usage in day and night/shadow, mass, heat transport when turned on, heat leak when turned off, temperature drops through the system, heat storage/release amount, sensitivity to lunar topography and orientation, and so forth.

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

Primary Technology Taxonomy:

- Level 1: TX 14 Thermal Management Systems
- Level 2: TX 14.X Other Thermal Management Systems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

- Conceptual design (Phase I).
- Physics-based analysis or model (Phase I).
- Proof-of-concept hardware (Phase I).
- Proof-of-concept hardware tested against simulated loads in proposed environments (Phase II).
- Final report (Phase I, Phase II).

State of the Art and Critical Gaps:

Missions like Surveyor and Lunokhod hibernated during the night or reduced operational power near noon, in attempts to survive single or multiple lunar cycles. ALSEPs (Apollo Lunar Surface Experiments

Packages) were deployed on several Apollo missions and had select experiments that operated for many lunar cycles. However, both Lunokhod and ALSEP benefited from radioisotope heat and power sources, which are either too expensive or not likely to be available for near-term future lunar science experiments. In fact, most modern lunar surface mission planning is based on solar power and batteries and typically avoids the challenges associated with surviving the full lunar cycle or shadowed regions. Because interest in lunar science and the development of abilities to deliver payloads to the lunar surface is resurgent, the capability to operate through the entire lunar environment is critical. In the absence of perpetual power supplies like radioisotope thermoelectric generators (RTGs), thermal management approaches to accommodate the lunar extremes, extended day/night cycles, and shadowed regions are seen as enabling.

Relevance / Science Traceability:

SMD lunar surface science investigations will employ small, low-power payloads that will require advanced thermal control approaches and techniques to survive and operate for extended duration through extreme thermal environments on the lunar surface.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. The delivery timeline for the CLPS can be found at this link: https://www.nasa.gov/commercial-lunar-payload-services-overview. Flight opportunities are expected to continue well into the future. It is also expected that larger and more complex payloads will be accommodated going forward. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References:

1. NASA's Exploration Campaign: Back to the Moon and on to Mars: https://science.nasa.gov/earth/moon/nasas-exploration-campaign-back-to-the-moon-and-on-to-mars/
2. NASA Prepares for Performing New Science on the Moon: https://www.jpl.nasa.gov/news/news.php?release=2007-068
3. The Farside Seismic Suite: https://www.jpl.nasa.gov/missions/the-farside-seismic-suite
4. Panning, M.P. et. al., “FARSIDE SEISMIC SUITE (FSS): SURVIVING THE LUNAR NIGHT AND DELIVERING THE FIRST SEISMIC DATA FROM THE FARSIDE OF THE MOON,” 53rd Lunar and Planetary Science Conference (2022): https://www.hou.usra.edu/meetings/lpsc2022/pdf/1576.pdf
5. NASA History Division, The Surveyor Program: https://history.nasa.gov/TM-3487/ch2-1.htm
6. USRA Lunar and Planetary Institute, The Surveyor Program: https://www.lpi.usra.edu/lunar/missions/surveyor/
7. Moon Facts: https://science.nasa.gov/moon/facts/
8. Apollo Lunar Roving Vehicle Documentation: https://www.hq.nasa.gov/alsj/alsj-LRVdocs.html
9. Apollo Experience Report: Thermal Design of Apollo Lunar Surface Experiments Package: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720013192.pdf
10. Garrison, M.B. and Nguyen, D.H., "Thermal Considerations for Designing the Next Lunar Lander," *AIP Conf. Proc.* 880, pp. 35–42 (2007): https://aip.scitation.org/doi/10.1063/1.2437438

Scope Title: Artificial Intelligence for Spacecraft Thermal Control Systems

Scope Description:

A traditional modeling process of spacecraft thermal control systems (TCSs) involves many critical steps that are time consuming. In addition, it has limited flexibility in accommodating changes to requirements and growing complexity of the TCSs. The current NASA programs such as Artemis, Commercial Lunar Payload Services (CLPS), and Mars Sample Return mission are facing new challenges that require a more effective way to address them. This call seeks to solicit innovative proposals to utilize artificial intelligence (AI), generative design, and machine learning techniques for design optimizations of spacecraft TCSs.

Examples of specific approaches to be developed for spacecraft TCSs include, but are not limited to, the following:

- Shape recognition and image segmentation with convolutional neural networks (CNNs) for a more efficient generation of thermal model geometries.
- Development of algorithms for employing support vector machines (SVMs) to improve prediction of multilayer insulation (MLI) properties.
- Physics-informed neural networks (PINNs) for high-fidelity modeling of TCSs.
- Utilizing autoencoders or other unsupervised learning approaches to generate detailed thermal models from condensed representations.
- Development of genetic algorithms (GAs) to assist design evolution and maturity level.
- Advancement of language models for transferring knowledge and automating report generation.
- Generative design (GD) for TCS mass and performance optimization.
- AI-defined surrogate models for TCS design optimization and accelerating complex simulations.

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

Primary Technology Taxonomy:

- Level 1: TX 14 Thermal Management Systems
- Level 2: TX 14.2 Thermal Control Components and Systems

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- 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:

Thermal design and modeling have made significant advancements in recent years, reaching a state-of-the-art level in many aspects. Advanced computational tools, such as finite element analysis (FEA) and computational fluid dynamics (CFD), have allowed for more accurate prediction and optimization of thermal behavior in spacecraft TCSs. The integration of machine learning techniques has shown promise in automating thermal design processes and enhancing model accuracy. However, despite these advancements there are critical gaps that still need to be addressed. One major challenge is the lack of comprehensive thermal models that capture complex interactions between different components and thermal phenomena. Additionally, incorporating real-world variability and uncertainty into thermal models remains a challenge. Moreover, the limited availability of high-quality thermal data for model validation further hampers progress. Bridging these critical gaps will require further research and innovation to develop more robust and reliable thermal design and modeling techniques that can cater to NASA needs and applications.

Relevance / Science Traceability:

NASA SMD spacecraft and missions that could benefit include:

- Lunar science
- Mars exploration
- SmallSats/CubeSats
- Rovers and surface mobility
- Future science missions

References:

1. Pyne, T., “From Manual to Automated: Optimizing Spacecraft Thermal Engineering Processes with AI,” Proceedings of Spacecraft Thermal Control Workshop (2023).
2. NASA Turns to AI to Design Mission Hardware (2023): https://www.nasa.gov/feature/goddard/2023/nasa-turns-to-ai-to-design-mission-hardware

Z10.01: Cryogenic Fluid Management (SBIR)

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

Subtopic Introduction:

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).

Scope Title: Cryogenic Fluid Management (CFM)

Scope Description:

This subtopic seeks technologies related to the following:

- Subgrid computational fluid dynamics (CFD) model of the film condensation process for 1g and low-g (lunar or Martian) to be implemented into commercial industry-standard CFD codes. The subgrid model should capture the formation and growth of the liquid layer as well as its movement along a wall boundary. The film subgrid model should be coupled to a volume-of-fluid (VOF) scheme that is used to model bulk vapor and liquid phases. The film subgrid model and VOF scheme should be coupled so that the film can interact (join) with the bulk liquid phase and interact (evaporate/condense) with the bulk vapor phase where mass and energy are conserved. The condensation subgrid model should be validated against experimental data (with a target accuracy of 25%), with a preference for condensation data without a noncondensable. Emphasis should be placed on cryogenic fluid data, but noncryogenic data is acceptable. Phase I should be focused on simplified geometries (vertical plates/walls), and Phase II should be focused on complicated geometries (full propellant cylindrical). The subgrid model and implementation scheme should be the final deliverable. Condensation data and model-anchoring with liquid oxygen is highly desirable.
- Development of heat flux sensors capable of measuring heat fluxes between 5 and 0.1 W/m2 for cryogenic applications. The sensors should have a target uncertainty of 2% full scale or less at temperatures as high as 300 K and at least as low as 77 K with a goal of 20 K. Proposers should target a demonstration of sensor operability in the 77-K temperature range in Phase I, with a full demonstration of calibration and uncertainty in Phase II. Deliverable for Phase II should be the calibrated heat flux sensor.
- Liquid hydrogen pumps for high-pressure-ratio applications. Two classes of pumps are envisioned: Class 1 are tank- mounted, electrically powered booster pumps with close-coupled motor, and Class 2 are 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 LH2 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 LH2 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 at least 0.6 kg/s. The high-pressure pumps will receive subcooled LH2 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, size envelope, and life evaluation 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:

1. Johnson, W. et al. "Demonstration of Multilayer Insulation, Vapor Cooling of Structure, and Mass Gauging for Large Scale Upper Stages: Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER) Final Report." https://ntrs.nasa.gov/citations/20205008233
2. Hartwig, J.W., et al. “Test Data Analysis of the Vented Chill, No-Vent Fill Liquid Nitrogen CRYOTE-2 Experiments.” International Journal of Heat and Mass Transfer 167, 120781. 2021.

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, Transport, and Rejection

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, dust, 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.
- Heat rejection turndown, including variable emissivity radiator coatings.
- Self-healing coolant tubes for MMOD-impact resilience.
- Fiber optic sensors for active thermal control systems.
    - An integrated fiber optic sensor that combines a single pressure sensor and a single temperature sensor into one fitting for use in a pumped fluid loop to minimize mass and the number of potential leak paths.
    - A stretch goal is to incorporate full two-fault tolerance (three of each sensor) into a single fiber optic sensor.
    - An additional stretch goal is to incorporate sensing for real-time chemical analysis of the thermal control fluid.

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.

Scope Title: High-Temperature Heat Acquisition, Transport, and Rejection

Scope Description:

NASA is seeking the development of thermal transport systems for space applications that require efficient management of large amounts of thermal energy from a reactor (e.g., a nuclear reactor) through a power conversion system and transport to a waste heat radiator. NASA desires a high-temperature energy transfer system capable of processing 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. NASA desires lightweight high-temperature radiators achieving <6 kg/m^2 with coatings that demonstrate a hemispherical infrared (IR) emissivity above 0.90 at temperatures approaching 900 K. The coating system should have stable optical and structural properties through temperature cycling between 100 K to 1,000 K and prolonged exposure at 900 K through the expected 15-year mission life in ultraviolet (UV) radiation and solar wind. The coating system should have charge-dissipative characteristics with a surface resistivity below $1x10^9$ ohm/cm^2 over the operational temperature of the mission. 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, pumped fluid loops, heat exchangers, lightweight high-temperature space radiators, and stable radiator optical coatings. Special consideration should be given to interfaces (at the reactor, power conversion system, or radiator) 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. Additionally, the large heat loads associated with nuclear power and propulsion systems require radiators that are a significant fraction of the total mass of the system, so lightweight high-temperature radiators are needed to enable such systems.

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.
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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.

TX15: Flight Vehicle Systems

This area covers technologies for aerosciences and flight mechanics. Aerosciences is the prediction of vehicle and component atmospheric flight performance and flow qualities to enable robust and efficient flight vehicle development, achieving performance requirements while ix minimizing environmental impacts. Flight mechanics provides the analysis, prediction, measurement, and test of vehicle dynamics, trajectories, and performance.

A1.10 Structural Sensors for Health Monitoring of Hypersonic Vehicles (SBIR)

Related Subtopic Pointers: T15.04
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., high thermal, vibrational, and acoustic environments). The long-term goal for the application of this technology would be on an operational, reusable hypersonic aircraft (with nonablative thermal protection systems). 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 to real-time trajectory modification and flight planning in order to improve vehicle/system reliability. Although 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. Instrumentation and SHM systems are of interest for both nonablating airframe and propulsion structural systems.

At the completion of Phase II and a $1M 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. The resulting sensor technologies and data methodologies will increase efficacy of data on near-term flight tests. Furthermore, the Phase II resulting technology could bring NASA one step closer to the goal of an effective neural network of sensors, despite harsh environments, that will improve safety and advance flight resource utility.

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 limits the ability to assess the flight vehicle's readiness for a following flight quickly, and (4) it reduces 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 nonablative structures and materials operating in extreme environments, with application to both airframe and propulsion structural 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's 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 both real-time SHM and 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 a 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 hertz to hundreds of kilohertz.

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

TX16: Air Traffic Management and Range Tracking Systems

This area covers safety and automation technologies that include far reaching concepts and technologies for future planning and operations and ones that safely extend the capabilities and range of uses for air transportation and commercial space integration.

A3.01 Advanced Air Traffic Management for Traditional Aviation Missions (SBIR)

Lead Center: ARC
Participating Center(s): LaRC

Subtopic Introduction:

Innovation is needed to spur the development of effective new air traffic management techniques, tools, and technologies that will improve the efficiency, scalability, and environmental compatibility of "traditional" civil aviation missions in the national airspace system, that is, transporting people and goods hundreds or thousands of miles across the country or around the world. Although the missions are traditional, this subtopic recognizes that the means for such may be conventional, innovative, or revolutionary. Going forward, traditional aviation missions may be fulfilled by a collaboration of conventional and autonomous agents and vehicles. Thus, the technologies and concepts proposed under this subtopic are expected to be highly innovative and yet still poised to advance an established industry that is a major driver of the U.S. economy. Although NASA also sponsors research into non-traditional, emerging aviation missions such as emergency response and very short-haul transport of people or small packages, this subtopic recognizes the critical role of traditional aviation missions to established, major stakeholders such as the FAA, airlines, airline industry service providers, and, most importantly, the traveling public.

Scope Title: Advanced Air Traffic Management for Traditional Aviation Missions

Scope Description:

NASA has a decades-long record of delivering advanced technologies to the Federal Aviation Administration (FAA) to improve the efficiency of operations in the National Airspace System (NAS) and is working on developing capabilities to make NAS operations more efficient, sustainable, and scalable. The FAA has developed a vision for modernizing operations, supporting infrastructure, and integrated safety management to accommodate greater diversity and a higher number of operations within the NAS through the introduction of new, extensible traffic management services while simultaneously bringing improvements to traditional Air Traffic Services. This vision is called "Info-Centric NAS."

NASA continues to work closely with the FAA and the larger aviation community to develop a vision and research roadmap for the future of aviation over the next 25 years and beyond—a concept called "Sky for All" that 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, scalability, and environmental compatibility of "traditional" civil aviation missions in the NAS, that is, transporting people and goods hundreds or thousands of miles across the country or around the world.

Proposals may 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.
- Tools and methods to facilitate teaming and collaboration between human operators and the autonomous agents/technologies needed to realize a more scalable airspace system (i.e., human-autonomy teaming). Objectives:
  - Improve the effectiveness or efficiency with which human operators work with increasingly autonomous airspace systems.
  - Leverage the benefits of human operator expertise and participation in the airspace system.
  - Address challenges associated with integrating new technologies in the airspace environment that involve human participation/decision making.
- Digital services and technologies to facilitate an integrated airspace for crewed, remotely crewed, or highly autonomous aircraft. Examples include:
  - Services for an integrated information environment that facilitates the exchange of real-time operational information.
  - Automated algorithms that can handle complex separation assurance practices.
  - Trajectory management methods that equitably mitigate weather hazards and constrained airspace resources while optimizing for cost, schedule, and/or environmental considerations using ground-, cockpit-, and/or cloud-based systems.

- Advanced tools or methods that improve the predictability of airspace operations, thereby accelerating 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 airspace structure using conventional (or similar) procedures.

Proposals that focus exclusively on one or more of the following types of operations will not be considered, as they are outside the scope of this subtopic:

- Small UAS operations (e.g., UAS Traffic Management, also known as UTM).
- Advanced air mobility (AAM) operations.
- Electric vertical-takeoff-and-landing (eVTOL) aircraft operations.
- Class E airspace operations.
- 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:

NASA’s intent is to select proposals that have the potential to move a critical technology and concepts beyond Phase II SBIR funding and transition it to Phase III, where NASA’s aeronautics programs, another government agency, or a commercial entity in the aeronautics sector can fund further maturation as needed, leading to actual usage in future airspace operations. The Phase I outcome should establish the scientific, technical, and commercial feasibility of the proposed innovation in fulfillment of NASA objectives and broader aviation community needs. Phase I should demonstrate advancement of a specific technology or techniques, supported by analytical and experimental studies that are documented in a final report. Phase II efforts could yield: (1) models supported with experimental data, (2) software related to a model that was developed, (3) a material system or prototype tool, or (4) modeling tools for incorporation in software, etc. that can be infused into a NASA project or lead to commercialization of the technology. Consequently, Phase II efforts are strengthened when they include a partnership with a potential end-user of the technology.

Phase I award recipients must be thinking about commercialization and which organizations will be able to use the technology following a Phase II effort. It is necessary to take that into account, rather than just focusing on developing technology without putting a strong effort into developing a commercial partner or setting the effort up for continued funding by teaming with an organization post-Phase II.

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.), human-autonomy teaming, providing comprehensive strategic scheduling and traffic management technologies, and enabling concepts that will scale up to accommodate increased demand and complexity of operations.

Relevance / Science Traceability:

The Airspace Operations and Safety Program (AOSP) works with the FAA, industry, and academic partners to conceive and develop Next Generation Air Transportation System (NextGen) technologies to further improve the safety of current and future aircraft.

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:

1. NASA Airspace Operations and Safety Program website: https://www.nasa.gov/aeroresearch/programs/aosp
2. FAA's "Info-Centric NAS" Vision: https://www.faa.gov/about/office_org/headquarters_offices/ang/icn
3. NASA's "Sky for All" website: https://nari.arc.nasa.gov/skyforall/
4. NASA’s “Sustainable Flight National Partnership” website: https://www.nasa.gov/directorates/armd/sfnp/

A3.02 Advanced Air Traffic Management for Nontraditional Airspace Missions and Aerial Wildfire Response (SBIR)

Lead Center: ARC
Participating Center(s): LaRC

Subtopic Introduction:

NASA's Aeronautics Research Mission Directorate (ARMD) has made significant contributions 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 that will support "nontraditional" aviation missions, specifically (1) advanced air mobility (AAM) applications for commerce and mobility and (2) wildfire response applications for public safety and environmental stewardship. NASA’s research to enable such missions to be safely and fully integrated into the airspace leverages capabilities of a service-based architecture inspired by 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 missions, ranging from urban air taxi to local cargo delivery and public-good missions, such as emergency response operations.

Innovation is needed to spur the development of effective new air traffic management concepts, tools, and technologies that will support the advent and scalability of AAM and wildfire response operations. Although NASA also sponsors research pertaining to traditional, longer-haul air transportation missions involving the movement of people and goods over hundreds or thousands of miles, the current subtopic's application to nontraditional airspace missions is highly relevant to NASA's aeronautics research mission, its nontraditional stakeholders (e.g., third-party service suppliers, public safety and government entities, and nontraditional operators, etc.) and the public at large.

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 aviation missions. 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.
- Tools and methods to bridge the gap between current-day operations and future AAM operations by facilitating teaming and collaboration between human operators and the autonomous agents/technologies needed for AAM operations to scale (i.e., human-autonomy teaming). Objectives include:
    - Improve the effectiveness or efficiency with which human operators work with increasingly autonomous airspace systems.
    - Leverage the benefits of human operator expertise and participation in the airspace system.
    - Address challenges associated with integrating new technologies in the airspace environment that involve human participation/decision making.
- 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 AAM operations with legacy operations in low-altitude airspace and 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).

Future service-based architectures also require resiliency to cyberattacks to ensure safe and robust operations that maintain expected levels of safety and security. 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:

NASA's intent is to select proposals that have the potential to move a critical technology and concepts beyond Phase II SBIR funding and transition it to Phase III, where NASA's aeronautics programs, another Government agency, or a commercial entity in the aeronautics sector can fund further maturation as needed, leading to actual usage in future airspace operations. The Phase I outcome should establish the scientific, technical, and commercial feasibility of the proposed innovation in fulfillment of NASA objectives and broader aviation community needs. Phase I should demonstrate advancement of a specific technology or techniques, supported by analytical and experimental studies that are documented in a final report. Phase II efforts could yield: (1) models supported with experimental data, (2) software related to a model that was developed, (3) a material system or prototype tool, or (4) modeling tools for incorporation in software, etc. that can be infused into a NASA project or lead to commercialization of the technology. Consequently, Phase II efforts are strengthened when they include a partnership with a potential end-user of the technology. Phase I award recipients must be thinking about commercialization and which organizations will be able to use the technology following a Phase II effort. It is necessary to take that into account, rather than just focusing on developing technology without putting a strong effort into developing a commercial partner or setting the effort up for continued funding by teaming with an organization post-Phase II.

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.
- Facilitating productive human-autonomy teaming.
- 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 aviation missions (e.g., space traffic management, automated air cargo, traffic management for small UAS (e.g., 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

1. https://www.nasa.gov/aeroresearch/programs/aosp
2. https://www.nasa.gov/directorates/armd/armd-strategic-implementation-plan/

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 better predict, mitigate, and manage wildland fires.

NASA's history of contributions to wildfire and other disaster management efforts includes remote sensing, instrumentation, mapping, data fusion, and prediction. More recently, 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 a 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 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:

- Existing airspace management techniques are manual and cannot accommodate new aircraft types suitable for wildfire response operations (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 firefighting 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 multi-mission 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., non-connected 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.

Proposers wanting to focus on **applications of autonomy or enablers for autonomy to operate a vehicle** in a wildfire- or disaster-response mission should submit their proposal to Subtopic A2.02: Enabling Aircraft Autonomy, under the scope "Autonomy for disaster response."

By contrast, proposers wanting to focus on **services or technologies to coordinate airborne operations across a wildfire area** should submit their proposal to the current subtopic scope.

Proposals focused on the following will be rejected for this subtopic:

- Technologies that help autonomous or piloted flight in areas with degraded visibility
- Technologies that enable single-pilot multi-ship operations
- Technologies that support unmanned logistic operations such as moving supplies to a different area
- Technologies that support wildfire suppression and management missions

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:

NASA's intent is to select proposals that have the potential to move a critical technology and concepts beyond Phase II SBIR funding and transition it to Phase III, where NASA's aeronautics programs, another Government agency, or a commercial entity in the aeronautics sector can fund further maturation as needed, leading to actual usage in future airspace operations. The Phase I outcome should establish the scientific, technical, and commercial feasibility of the proposed innovation in fulfillment of NASA objectives and broader aviation community needs. Phase I should demonstrate advancement of a specific technology or techniques, supported by analytical and experimental studies that are documented in a final report. Phase II efforts could yield: (1) models supported with experimental data, (2) software related to a model that was developed, (3) a material system or prototype tool, or (4) modeling tools for incorporation in software, etc. that can be infused into a NASA project or lead to commercialization of the technology. Consequently, Phase II efforts are strengthened when they include a partnership with a potential end-user of the technology. Phase I award recipients must be thinking about commercialization and which organizations will be able to use the technology following a Phase II effort. It is necessary to take that into account, rather than just focusing on developing technology without putting a strong effort into developing a commercial partner or setting the effort up for continued funding by teaming with an organization post-Phase II.

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:

1. https://www.nasa.gov/aeroresearch/programs/aosp
2. https://www.nasa.gov/directorates/armd/armd-strategic-implementation-plan/

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 the 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 in order to 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 with technologies that 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:

1. 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 with technologies that 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:

1. 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 with technologies that 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:

1. https://www.nasa.gov/aeroresearch/programs/aosp

TX17: Guidance, Navigation, and Control (GN&C)

This area covers the unique GN&C system technologies that enable new missions; reduce cost, schedule, mass or power while maintaining or improving GN&C performance; improve system safety and longevity; or reduce environmental impact of aerospace vehicle operations.

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 GNC technologies in support of future science and exploration mission requirements. This subtopic covers mission-enabling technologies that have significant SWaP-CP improvements over the state-of-the-art 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.

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 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 International Space Station (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:

1. 2020 NASA Technology Taxonomy: https://go.nasa.gov/3hGhFJf
2. 2017 NASA Strategic Technology Investment Plan: https://www.nasa.gov/wp-content/uploads/2015/06/2017-8-1_stip_final-508ed.pdf

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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 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 SOA, is a critical enabling technology for CubeSat-based Earth observations that normally would require a spinning antenna (e.g., ocean winds).

Relevance / Science Traceability:

Requirement: The star tracker should have the ability to provide 0.05° or better pointing angle accuracy (in roll, pitch, and yaw) while the CubeSat is spinning up to 20 rpm in low Earth orbit (300 to 1,000 km altitude).
Relevant CubeSats are anticipated to be oriented such that the Earth-observing antenna is pointing off-nadir by up to 40° to 50°. This provides a sufficient Earth-incidence angle to enable retrieval of ocean surface winds and other horizontally resolved atmospheric measurables (e.g., precipitation). For this science application, the star tracker is providing ~1-km geolocation accuracy for such measurements.

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

References:

1. Erlank, A.O. and Steyn, W.H.: "Arcminute attitude estimation for CubeSats with a novel nano star tracker," *IFAC Proceedings Volumes*, 47(3), pp. 9679-9684, 2014; https://doi.org/10.3182/20140824-6-ZA-1003.00267
2. 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.
3. Walton, M.P. and Long, D.G.: "Architectures for Earth-observing CubeSat scatterometers," *CubeSats and NanoSats for Remote Sensing II,* Vol. 10769, 1076904, International Society for Optics and Photonics, 2018; https://doi.org/10.1117/12.2321696
4. Walton, P. and Long, D.: "Space of solutions to ocean surface wind measurement using scatterometer constellations," Journal of Applied Remote Sensing, 13(3), 032506, 2019; https://doi.org/10.1117/1.JRS.13.032506

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 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 environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in a relevant environment.	A high-fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high-fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and	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	Documented test performance demonstrating agreement with analytical predictions.

		platform (ground, airborne, or space).	removed. Limited documentation available.	
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 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 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 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/otps/2020-nasa-technology-taxonomy/).

The current SBIR subtopics are aligned to the Technology Taxonomy.

Appendix C: List of NASA SBIR Phase I Clauses, Regulations and Certifications

Introduction

Offerors who submit a 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 proposal package.

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