NASA SBIR 2022 Phase I Solicitation

Science

S11.01 Lidar Remote-Sensing Technologies

Lead Center: JPL

Participating Center(s): GSFC

Scope Title

Lidar Remote-Sensing Technologies

Scope Description

NASA recognizes the potential of lidar technology to meet many of its science objectives by providing new capabilities or offering enhancements over current measurements of atmospheric, geophysical, and topographic parameters from ground, airborne, and space-based platforms. To meet NASA’s requirements for remote sensing from space, advances are needed in state-of-the-art lidar technology with an emphasis on compactness, efficiency, reliability, lifetime, and high performance. Innovative lidar subsystem and component technologies that directly address the measurement of atmospheric constituents and surface features of the Earth, Mars, the Moon, and other planetary bodies will be considered under this subtopic. Compact, high-efficiency lidar instruments for deployment on unconventional platforms, such as unmanned aerial vehicles, SmallSats, and CubeSats are also considered and encouraged. Proposals must show relevance to the development of lidar instruments that can be used for NASA science-focused measurements or to support current technology programs. Meeting science needs leads to four primary instrument types:

- Backscatter: Measures beam reflection from aerosols and clouds to retrieve the optical and microphysical properties of suspended particulates.
- Laser spectral absorption: Measures laser absorption by trace gases from atmospheric or surface backscatter and volatiles on surfaces of airless planetary bodies at multiple laser wavelengths to retrieve concentration of gas within measurement volume.
- Ranging: Measures the return beam’s time of flight to retrieve distance.
- Doppler: Measures wavelength changes in the return beam to retrieve relative velocity.

Expected TRL or TRL Range at completion of the Project

3 to 6

Primary Technology Taxonomy
Level 1
TX 08 Sensors and Instruments

Level 2
TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II

- Prototype
- Hardware
- Software

Desired Deliverables Description

Phase I research should demonstrate technical feasibility and show a path toward a Phase II prototype unit. A typical Phase I deliverable could be a technical report demonstrating the feasibility of the technology and a design that is to be built under a Phase II program. In some instances where a small subsystem is under investigation, a prototype deliverable under the Phase I is acceptable.

Phase II prototypes should be capable of laboratory demonstration and preferably suitable for operation in the field from a ground-based station, an aircraft platform, or any science platform amply defended by the proposer. Higher fidelity Phase II prototypes that are fielded in harsh environments such as aircraft often require follow-on programs such as Phase III SBIR to evaluate and optimize performance in relevant environment.

As seen in the section below on “State of the Art and Critical Gaps,” desired deliverables are oriented toward subsystem or system-level lidar technology solutions, as opposed to a stand-alone component. That is, desired technologies should be toward a lidar system, rather than a component such as a laser or photodetector of unspecified applicability to a measurement goal.

State of the Art and Critical Gaps

- Transformative technologies and architectures are sought to vastly reduce the cost, size, and complexity of lidar instruments from a system perspective. Advances are sought for high-efficiency high-pulse energy (>>1 mJ) and high power (>>1 W) transmitters for operation on a wide range of compact (SmallSat, CubeSat, or Unmanned Aerial Vehicle size) packages. Reduction in the complexity of laser architectures is sought, while still meeting performance metrics for the measured geophysical observable. Hybrid diode/fiber/crystal architectures are sought as affordable sensor solutions to help reduce complexity and sensitivity to environmental effects (vibration, thermal variations, and pressure variations). Laser thermal management often poses an engineering challenge that drives lidar systems to deploy on large and costly platforms. Hence, novel thermal management systems for laser, optical, and electronic subsystems are sought to increase efficiency, decrease physical footprint, and transition laser systems to more compact platforms. New materials concepts could be of interest for the reduction of weight for lidar-specific telescopes, optical benches, and subcomponents. Integrated subsystems combining laser, optical, fiber, and/or photodetector components are of interest for reducing the size, weight, and power of lidar instruments.
- Compact, efficient, and rugged narrow-linewidth pulsed lasers operating between ultraviolet and infrared wavelengths suitable for lidar are sought. Specific wavelengths are of interest to match absorption lines or atmospheric transmission are: 290 to 320 nm (ozone absorption), 450 to 490 nm (ocean sensing), 532 nm (aerosols), 820 nm (water vapor line), 935 nm (water vapor line), 1064 nm (aerosols), 1550 nm (Doppler
wind), 1645 to 1650 nm (high pulse energy (>10 mJ) for methane line, Doppler wind, and orbital debris tracking), 2050 nm (Doppler wind), 3000 to 4000 nm (hydrocarbon lines and ice measurement), and 6000 nm (non-terrestrial ice and water measurement). Architectures involving new developments in high-efficiency diode laser, quantum cascade laser, and fiber laser technologies are especially encouraged. For pulsed lasers two different regimes of repetition rate and pulse energies are desired: from 1 to 10 kHz with pulse energy greater than 1 mJ and from 20 to 100 Hz with pulse energy greater than 100 mJ. For laser spectral absorption applications, such as differential absorption lidar, a single frequency (pulse transform limited) and frequency-agile source is required to tune >100 pm on a shot-by-shot basis while maintaining high spectral purity of >1,000:1. Laser sources of wavelength at or around 780 nm are not sought this year. Laser sources for lidar measurements of carbon dioxide are not sought this year.

- Novel approaches and components for lidar receivers are sought, matching one or more of the wavelengths listed in the bullet above. Such receiver technology could include integrated optical/photonic circuitry, freeform telescopes and/or active optics, frequency-agile ultra-narrow-band solar blocking filters for water vapor differential absorption lidar (DIAL) (<10 pm FWHM (full width at half maximum), >80% transmission and phase locked to the transmit wavelength), and phased-array or electro-optical beam scanners for large (>10 cm) apertures (especially those preserving transmission of circular polarization). Integrated receivers for Doppler wind measurement at 1550, 1650, or 2050 nm wavelength are sought for coherent heterodyne detection at bandwidths of 1 GHz or higher, combining local oscillator laser, photodetector, and/or fiber mixing. Development of telescopes should be submitted to a different subtopic (S12.03), unless the design is specifically a lidar component, such as a telescope integrated with other optics. Receivers for direct-detection wind lidar are not sought this year.
- New three-dimensional (3D) mapping and hazard detection lidar with compact and high-efficiency diode and fiber lasers to measure range and surface reflectance of planets or asteroids from >100 km altitude during mapping to <1 m during landing or sample collection, within size, weight, and power to fit into a CubeSat or smaller. New lidar technologies are sought that allow system reconfiguration in orbit, single-photon sensitivities and single beam for long-distance measurement, and variable dynamic range and multiple beams for near-range measurements. High-speed 2D scanners are also sought for single-beam lidars that enable wide scan angles with high repeatability and accuracy.

**Relevance / Science Traceability**

The proposed subtopic addresses missions, programs, and projects identified by the Science Mission Directorate (SMD), including:

- Atmospheric water vapor: Profiling of tropospheric water vapor supports studies in weather and dynamics, radiation budget, clouds, and aerosol processes.
- Aerosols: Profiling of atmospheric aerosols and how aerosols relate to clouds and precipitation.
- Atmospheric winds: Profiling of wind fields to support studies in weather and atmospheric dynamics on Earth and atmospheric structure of planets.
- Topography: Altimetry to support studies of vegetation and the cryosphere of Earth, as well as the surface of planets and solar system bodies.
- Greenhouse gases: Column measurements of atmospheric gases, such as methane, that affect climate variability.
- Hydrocarbons: Measurements of planetary atmospheres.
- Gases related to air quality: Sensing of tropospheric ozone, nitrogen dioxide, or formaldehyde to support NASA projects in atmospheric chemistry and health effects.
- Automated landing, hazard avoidance, and docking: Technologies to aid spacecraft and lander maneuvering and safe operations.

**References**

- NASA missions are aligned with the National Research Council's decadal surveys, with the latest survey on earth science published in 2018 under the title “Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space”: [http://sites.nationalacademies.org/DEPS/esas2017/index.htm](http://sites.nationalacademies.org/DEPS/esas2017/index.htm)
S11.02 Technologies for Active Microwave Remote Sensing

Lead Center: JPL

Participating Center(s): GSFC

Scope Title

High-Efficiency Solid-State Power Amplifiers

Scope Description

This subtopic supports technologies to aid NASA in its active microwave sensing missions. Specifically, we are seeking L- and/or S-band solid-state power amplifiers (SSPAs) to achieve a power-added efficiency (PAE) of >50% for 1 kW peak transmit power, through the use of efficient multidevice power combining techniques or other efficiency improvements. There is also a need for high-efficiency ultra-high-frequency (335 to 535 MHz) monolithic microwave integrated circuit (MMIC) power amplifiers, with saturated output power greater than 20 W, high efficiency of >70%, and gain flatness of 1 dB over the band.

Solid-state amplifiers that meet high efficiency (>50% PAE) requirements and have small form factors would be suitable for SmallSats, support single-satellite missions (such as RainCube), and enable future swarm techniques. No such devices at these high frequencies, high powers, and efficiencies are currently available. We expect a power amplifier with TRL 2 to 4 at the completion of the project.

Expected TRL or TRL Range at completion of the Project

2 to 4

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description
Phase I: Provide research and analysis to advance scope concept as a final report.

Phase II: Design and simulation of 1-kW S-/L-band amplifiers with >50% PAE, with prototype.

State of the Art and Critical Gaps

Advances in Surface Deformation and Change are strongly desired for Earth remote sensing, for land use, natural hazards, and disaster response. NASA-ISRO Synthetic Aperture Radar (NISAR) is a Flagship-class mission, but only able to revisit locations on ~weekly basis, whereas future constellation concepts, using SmallSats would decrease revisit time to less than 1 day, which is game changing for studying earthquake precursors and 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.

Relevance / Science Traceability

Surface Deformation and Change science is a continuing Decadal Survey topic, and follow-ons to the science desired for NISAR mission are already in planning. Cloud, water, and precipitation measurements increase capability of measurements to smaller particles and enable much more compact instruments.

References


Scope Title

Deployable Antenna Technologies

Scope Description

Low-frequency deployable antennas for Earth and planetary radar sounders: antennas capable of being hosted by SmallSat/CubeSat platforms are required for missions to icy worlds, large/small body interiors (i.e., comets, asteroids), and for Earth at center frequencies from 5 to 100 MHz, with fractional bandwidths >=10%. Dual-frequency solutions or even tri-frequency solutions are desired; for example, an approximately 5- to 6-MHz band, with an approximately 85- to 95-MHz band. Designs need to be temperature tolerant; that is, not changing performance parameters drastically over flight temperature ranges of ~100 °C.

High-frequency (V-band) deployable antennas for SmallSats and CubeSats: Small-format, deployable antennas are desired (for 65 to 70 GHz) with an aperture size of ~1 m² that when stowed, fit into form factors suitable for SmallSats—with a desire for similar on the more-challenging CubeSat format. Concepts that remove, reduce, or control creases/seams in the resulting surface, on the order of a fraction of a wavelength at 70 GHz, are highly desired.

Expected TRL or TRL Range at completion of the Project

2 to 4

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments
Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype

Desired Deliverables Description

For both antenna types (low and high frequency) a paper design is desired for Phase I, and a prototype for Phase II. Concepts and prototypes for targeted advances in deployment technologies are welcome and do not need to address every need for mission-ready hardware.

State of the Art and Critical Gaps

Low-frequency antennas, per physics, are large, and so are deployable, even for large spacecraft. For Small/CubeSats the challenges are to get enough of an antenna aperture with the proper length to achieve relatively high bandwidths. No such 10% fractional antenna exists for the Small/CubeSat form factors.

High-frequency antennas can often be hosted without deployment, but a ~1-m\(^2\)-diameter antenna on a Small/CubeSat is required to be deployable. A specific challenge for high-frequency deployable antennas is to deploy the aperture with enough accuracy such that the imperfections (i.e., residual folds, support ribs, etc.) are flat enough for antenna performance.

Relevance / Science Traceability

Low-frequency-band antennas are of great interest to subsurface studies, such as those completed by MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) and SHARAD (Shallow Radar) for Mars and planned for Europa by the REASON (Radar for Europa Assessment and Sounding: Ocean to Near-surface) on the Europa Clipper. Studying the subsurfaces of other icy worlds is of great interest to planetary science, as is tomography of small bodies such as comets and asteroids. Because of the impact of the ionosphere, low frequency sounding of Earth is very challenging from space, but there is great interest in solutions to make this a reality. Lastly, such low-frequency bands are also of interest to radio astronomy, such as that being done for OLFAR, [9].

V-band deployable antennas are mission enabling for pressure sounding from space.

References

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

- REASON: [https://www.jpl.nasa.gov/missions/europa-clipper/][10]
- MARSIS: [https://mars.nasa.gov/express/mission/sc_science_marsis01.html][11]

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


Scope Title

Steerable Aperture Technologies
Scope Description

Technologies enabling low-mass steerable technologies, especially for L- or S-bands—including, but not limited to—antenna or radiofrequency (RF) electronics, enabling steering: cross track +/-7° and along track +/-15°. This would enable a complete antenna system with a mass density of 10 kg/m² (or less) with a minimum aperture of 12 m².

Examples of different electronics solutions include completely integrated transmit/receive (TR) modules, with all control features for steering included; or alternatively, an ultra-compact TR module controller, which can control N modules, thus allowing reduction in size and complexity of the TR modules themselves.

Expected TRL or TRL Range at completion of the Project

2 to 4

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype

Desired Deliverables Description

Phase I: A paper study with analysis.

Phase II: Prototype of subcomponent.

State of the Art and Critical Gaps

No technology currently exists for such low mass density for steerable arrays.

Relevance / Science Traceability

Surface Deformation and Change science is a key Earth Science Decadal Survey topic.

References


Scope Title

Low-Power W-Band Transceiver
**Scope Description**

Require a low-power compact W-band (monolithic integrated circuit or application-specific integrated circuit (ASIC) preferred) transceiver with up/down converters with excellent cancellers to use the same antenna for transmit and receive. Application is in space landing radar altimetry and velocimetry. Wide-temperature-tolerant technologies are encouraged to reduce thermal control mass, either through designs insensitive to temperature changes or active compensation through feedback. Electronics must be tolerant to a high-radiation environment through design (rather than excessive shielding). In the early phases of this work, radiation tolerance must be considered in the semiconductor/materials choices, but it is not necessary to demonstrate radiation tolerance until later. For ocean worlds around Jupiter, bounding (worst-case) radiation rates are expected to be at less than 50 rad(Si)/sec—with minimal shielding—during the period of performance (landing or altimeter flyby), but overall total dose is expected to be in the hundreds of krad total ionizing dose (TID). Most cases will be less extreme in radiation.

**Expected TRL or TRL Range at completion of the Project**

2 to 4

**Primary Technology Taxonomy**

**Level 1**

TX 08 Sensors and Instruments

**Level 2**

TX 08.X Other Sensors and Instruments

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype

**Desired Deliverables Description**

Phase I: Paper study/design.

Phase II: Prototype.

**State of the Art and Critical Gaps**

Low-power-consumption transceivers for W-band are critical for studies of atmospheric science, pressure sounding, and atmospheric composition for both Earth and planetary science. Such transceivers currently do not exist.

**Relevance / Science Traceability**

- ACE (Advanced Composition Explorer): [https://solarsystem.nasa.gov/missions/ace/in-depth/][13]
- Planetary Terminal Descent and Landing Radar Final Report: [https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19710011019.pdf][14]

**References**

Missions for atmospheric science and altimetry applications:
S11.03 Technologies for Passive Microwave Remote Sensing

Lead Center: JPL

Participating Center(s): JPL

Scope Title

Components or Methods to Improve the Sensitivity, Calibration, or Resolution of Microwave/Millimeter-Wave Radiometers

Scope Description

NASA requires novel solutions to challenges of developing stable, sensitive, and high-resolution radiometers and spectrometers operating from microwave frequencies to 1 THz. Novel technologies are requested to address challenges in the current state of the art of passive microwave remote sensing. Technologies could improve the sensitivity, calibration, or resolution of remote-sensing systems or reduce the size, weight, and power (SWaP). Companies are invited to provide unique solutions to problems in this area. Possible technologies could include:

- Low-noise receivers at frequencies up to 1 THz.
- Solutions to reduce system 1/f noise over time periods greater than 1 sec.
- Internal calibration systems or methods to improve calibration repeatability over time periods greater than days or weeks.

Expected TRL or TRL Range at completion of the Project

3 to 5

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II

- Prototype
- Research
- Analysis
- Software

Desired Deliverables Description
Research, analysis, software, or hardware prototyping of novel components or methods to improve the performance of passive microwave remote sensing.

- Depending on the complexity of the proposed work, Phase I deliverables may include a prototype system or a study.
- Phase II deliverables should include a prototype component or system with test data verifying functionality.

State of the Art and Critical Gaps

Depending on frequency, current passive microwave remote-sensing instrumentation is limited in sensitivity (as through system noise, 1/f noise, or calibration uncertainty), resolution, or in SWaP. Critical gaps depend on specific frequency and application.

Relevance / Science Traceability

Critical need: Creative solutions to improve the performance of future Earth-observing, planetary, and astrophysics missions. The wide range of frequencies in this scope are used for numerous science measurements such as Earth science temperature profiling, ice cloud remote sensing, and planetary molecular species detection.

References


Scope Title

Advanced Digital Electronic or Photonic Systems Technology for Microwave Remote Sensing

Scope Description

Technology critical to increasing the utility of microwave remote sensing based on photonic (or other novel analog) systems, application-specific integrated circuits (ASICs), and field programmable gate arrays (FPGAs) are showing great promise. This topic solicits proposals for such systems or subsystems to process microwave signals for passive remote-sensing applications for spectrometry or total power radiometry. Example applications include:

- Photonic (or other analog) systems for spectrometers, beam-forming arrays, correlation arrays, oscillators, noise sources, and other active or passive microwave instruments having size, weight, and power (SWaP) or performance advantages over digital technology.
- ASIC-based solutions for digital beam forming creating one or more beams to replace mechanically scanned antennas.
- Digitizers for spectrometry starting at 20 Gsps, 20 GHz bandwidth, 4 or more-bit resolution, and simple interface to a FPGA.
- ASIC implementations of polyphase spectrometer digital signal processing with ~1 W/GHz; 10-GHz-bandwidth polarimetric spectrometer with 1,024 channels; and radiation-hardened and minimized power dissipation.

All systems or subsystems should also focus on low-power, radiation-tolerant broad-band microwave spectrometers for NASA applications. Proposals should compare predicted performance and SWaP to conventional radiofrequency and digital-processing methods.

NOTE: Proposers for specific photonic integrated circuit (PIC) technology should instead see related STTR subtopic T8.07.

Expected TRL or TRL Range at completion of the Project

3 to 5
Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description

Demonstration of novel subsystem or system to enable increased capability in passive microwave remote-sensing instruments. Photonic systems specifically are low-TRL emerging technologies, so offerors are encouraged to identify and propose designs where photonic technology would be most beneficial. For electronic solutions, low-power spectrometer (or other application in the Scope Description) for an ASIC or other component that can be incorporated into multiple NASA microwave remote-sensing instruments.

- Depending on the complexity of the proposed work, Phase I deliverables may include a prototype system or a study.
- Phase II deliverables should include a prototype component or system with test data verifying functionality.

State of the Art and Critical Gaps

- Photonic systems for microwave remote sensing are an emerging technology not used in current NASA microwave missions, but they may enable significant increases in bandwidth or reduction in SWaP. Again, state-of-the-art digital electronic solutions typically consume many watts of power.
- Digital beamforming: most digital beamforming applications have focused on either specific narrowband approach for commercial communications or military radars. NASA needs solutions that consume low power and operate over wide bandwidths.
- Digitizers: High-speed digitizers exist but have poorly designed output interfaces. Specifically designed ASICs could reduce this power by a factor of 10 but pose challenges in design and radiation tolerance. A low-power solution could be used in a wide range of NASA remote-sensing applications.
- Spectrometers: The state of the art is currently the use of conventional microwave electronics for frequency conversion and filtering for spectrometers. Wideband spectrometers still generally require over 10 W. Current FPGA-based spectrometers require ~10 W/GHz and are not flight qualifiable.

Relevance / Science Traceability

Photonic systems may enable significantly increased bandwidth of Earth-viewing, astrophysics, and planetary science missions. This may allow for increased bandwidth or resolution receivers, with applications such as hyperspectral radiometry.

Broadband spectrometers are required for Earth-observing, planetary, and astrophysics missions. The rapid increase in speed and reduction in power per gigahertz in the digital realm of digital spectrometer capability is directly applicable to planetary science and enables radio-frequency interference (RFI) mitigation for Earth science.
References


Scope Title

Deployable Antenna Apertures at Frequencies up to Millimeter Wave

Scope Description

Deployable antenna apertures are required for a wide range of NASA passive remote-sensing applications from SmallSat platforms. Current deployable antenna technology is extremely limited above Ka-band. NASA requires low-loss deployable antenna apertures at frequencies up to 200 GHz or beyond. Deployed aperture diameters of 0.5 m or larger are desired, but proposers are invited to propose concepts for smaller apertures at higher frequencies.

NASA also requires low-loss broad-band deployable or compact antenna feeds with bandwidths of two octaves. Frequencies of interest start at 500 MHz. Loss should be as low as possible (less than 1%). The possibility of thermal control is desired to improve system calibration stability.

Expected TRL or TRL Range at completion of the Project

3 to 5

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II

- Analysis
- Prototype
- Hardware

Desired Deliverables Description

Phase I deliverables should consist of analysis and potential prototyping of key enabling technologies.

Phase II deliverables should include a deployable antenna prototype.
State of the Art and Critical Gaps

Current low-loss deployable antennas are limited to Ka-band. Deployable apertures at higher frequencies are required for a wide range of applications, as aperture size is currently an instrument size, weight, and power (SWaP) driver for many applications up to 200 GHz.

Relevance / Science Traceability

Antennas at these frequencies are used for a wide range of passive and active microwave remote sensing, including measurements of water vapor and temperature.

References

- Passive remote sensing such as performed by the Global Precipitation Mission (GPM) Microwave Imager (GMI): https://gpm.nasa.gov/missions/GPM/GMI [17]

S11.04 Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter

Lead Center: JPL

Participating Center(s): ARC, GSFC, LaRC

Scope Title:

Sensor and Detector Technologies for Visible, Infrared (IR), Far-IR, and Submillimeter

Scope Description:

NASA is seeking new technologies or improvements to existing technologies to meet the detector needs of future missions, as described in the most recent decadal surveys (links are external):


Please note:

1. Technologies for visible detectors are not being solicited this year.
2. Technologies for lidar detectors are not being solicited this year.
3. For FY 2022 emphasis will be placed on Earth-Science-related technologies (infrared (IR) and far-IR detectors and technologies).
Low-power and low-cost readout integrated electronics:

- Photodiode arrays: In-pixel digital readout integrated circuit (DROIC) for high-dynamic-range IR imaging and spectral imaging (10 to 60 Hz operation) focal plane arrays to circumvent the limitations in charge well capacity, by using in-pixel digital counters that can provide orders-of-magnitude larger effective well depth, thereby affording longer integration times.

- Microwave kinetic inductance detector/transition-edge sensor (MKID/TES) detectors: A radiation-tolerant, digital readout system is needed for the readout of low-temperature detectors such as MKIDs or other detector types that use microwave-frequency-domain multiplexing techniques. Each readout channel of the system should be capable of generating a set of at least 1,500 carrier tones in a bandwidth of at least 1 GHz with 14-bit precision and 1-kHz frequency placement resolution. The returning-frequency multiplexed signals from the detector array will be digitized with at least 12-bit resolution. A channelizer will then perform a down-conversion at each carrier frequency with a configurable decimation factor and maximum individual subchannel bandwidth of at least 50 Hz. The power consumption of a system consisting of multiple readout channels should be at most 20 mW per subchannel or 30 W per 1-GHz readout channel. That requirement would most likely indicate the use of a radio-frequency (RF) system on a chip (SoC) or application-specific integrated circuit (ASIC) with combined digitizer and channelizer functionality.

- Bolometric arrays: Low-power, low-noise, cryogenic multiplexed readout for large-format two-dimensional (2D) bolometer arrays with 1,000 or more pixels, operating at 65 to 350 mK. We require a superconducting readout capable of reading 2 TES per pixel within a 1 mm² 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, CH₄, N₂O) 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, MgB₂, or multilayered engineered superconductors with tunable critical temperature) or engineered semiconductor materials, especially 2D electron gas (2DEG) and quantum wells (QW).

- Array receivers: Development of a robust wafer-level packaging/integration technology that will allow high-frequency-capable interconnects and allow two dissimilar substrates (i.e., silicon and GaAs) to be aligned and mechanically "welded" together. Specially develop ball grid and/or through-silicon via (TSV) technology that can support submillimeter-wave (frequency above 300 GHz) arrays. Compact and efficient systems for array receiver calibration and control are also needed.

- Receiver components: Development of advanced terahertz receiver components is desired. Such components include:
  - Novel concepts for room-temperature-operated receivers for Earth science with competitive noise performance (goal of 5 times the quantum limit in the 500 to 1,200 GHz range).
  - Local oscillators capable of spectral coverage 2 to 5 THz, output power up to >2 mW, frequency agility with >1 GHz near chosen terahertz frequency, and continuous phase-locking ability over the terahertz-tunable range with <100-kHz line width. Both solid-state (low-parasitic Schottky diodes) as well as quantum cascade lasers (for f > 2 THz).
  - Components and devices such as mixers, isolators, and orthomode transducers, working in the terahertz range, that enable future heterodyne array receivers.
  - Novel receiver architectures such as single-sideband heterodyne terahertz receivers and high-precision measurement accuracy for multiple lines.
  - ASIC-based SoC solutions are needed for heterodyne receiver backends. ASICs capable of binning >6 GHz intermediate frequency bandwidth into 0.1- to 0.5-MHz channels with low power dissipation (<0.5 W) would be needed for array receivers.
  - Novel quasi-optical devices for terahertz beam multiplexing for a large (16+) number of pixels with
>20% bandwidth.
- Low-power, low-noise intermediate-frequency (IF) amplifiers that can be used for array receivers. Both cryogenic as well as room temperature operated.
- Novel concepts for terahertz preamplifiers from 300 GHz to 5 THz.

Expected TRL or TRL Range at completion of the Project:

2 to 4

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype

Desired Deliverables Description:

For Phase I activities the deliverables are nominally feasibility studies, detailed design, or determination of the trade space and detailed optimization of the design, as described in a final report. In some circumstances simple prototype models for the hardware can be demonstrated and tested.

For Phase II studies a working prototype that can be tested at one of the NASA centers is highly desirable.

State of the Art and Critical Gaps:

Efficient multipixel readout electronics are needed both for room-temperature operation as well as cryogenic temperatures. We can produce millions-of-pixel detector arrays at IR wavelengths up to about 14 µm, only because there are ROICs available on the market. Without these, high-density, large-format IR arrays such as quantum well IR photodetectors, HgCdTe, and strained-layer superlattices would not exist. The Moore's Law corollary for pixel count describes the number of pixels for the digital camera industry as growing in an exponential manner over the past several decades, and the trend is continuing. The future of long-wave detectors is moving toward tens of thousands of pixels and beyond. Readout circuits capable of addressing their needs do not exist, and without them the astronomical community will not be able to keep up with the needs of the future. These technology needs must be addressed now, or we are at risk of being unable to meet the science requirements of the future:

- Commercially available ROICs typically have well depths of less than 10 million electrons.
- 6- to 9-bit, ROACH-2 board solutions with 2,000 bands, <10 kHz bandwidth in each are state of the art (SOA).
- IR detector systems are needed for Earth imaging based on the recently released Earth Decadal Survey.
- Direct detectors with $D \sim 10^9$ 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 $D \sim 10^{12}$ cm-rtHz/W. Broadband (>15%) heterodyne detectors that can provide sensitivities of 5× to 10× the quantum limit in the submillimeter-wave range while operating at 30 to 77 K are an improvement in the SOA because of the higher operating temperature.
- Detector array detection efficiency <20% at 532 nm (including fill factor and probability of detection) for low-after-pulsing, low-dead-time designs is SOA.
- Far-IR bolometric heterodyne detectors are limited to 3-dB gain bandwidth of around 3 GHz. Novel superconducting material such as MgB$_2$ can provide significant enhancement of up to 9 GHz IF bandwidth.
Cryogenic low-noise amplifiers (LNAs) in the 4 to 8 GHz bandwidth with thermal stability are needed for focal plane arrays, Origins Space Telescope (OST) instruments, Origins Survey Spectrometers (OSSs), MKIDs, far-IR imagers and polarimeters (FIPs), Heterodyne Instrument on OST (HERO), and the Lynx Telescope. DC power dissipation should be only a few milliwatts.

Another frequency range of interest for LNAs is 0.5 to 8.5 GHz. This is useful for HERO. Other NASA systems in the Space Geodesy Project (SGP) would be interested in bandwidths up to 2 to 14 GHz.

15 to 20 dB gain and <5 K noise over the 4 to 8 GHz bandwidth has been demonstrated.

Currently, all space-borne heterodyne receivers are single pixel. Novel architectures are needed for ~100-pixel arrays at 1.9 THz.

The current SOA readout circuit is capable of reading 1 TES per pixel in a 1-mm² area. 2D arrays developed by NIST have been a boon for current NASA programs. However, NIST has declined to continue to produce 2D circuits or to develop one capable of a 2-TES-per-pixel readout. This work is extremely important to NASA’s filled, kilopixel bolometer array program.

2D cryogenic readout circuits are analogous to semiconductor ROICs operating at much higher temperatures. We can produce detector arrays of millions-of-pixels at IR wavelengths up to about 14 µm, only because there are ROICs available on the market. Without these, high-density, large-format IR arrays such as quantum well infrared photodiode, HgCdTe, and strained-layer superlattices would not exist.

Relevance / Science Traceability:

- Future short-, mid-, and long-wave IR Earth science and planetary science missions all require detectors that are sensitive and broadband with low power requirements.
- Future astrophysics instruments require cryogenic detectors that are supersensitive and broadband and provide imaging capability (multipixel).
- Aerosol spaceborne lidar as identified by the 2017 decadal survey to reduce uncertainty about climate forcing in aerosol-cloud interactions and ocean ecosystem carbon dioxide uptake. Additional applications in planetary surface mapping, vegetation, and trace-gas lidar.
- Earth radiation budget measurement per 2007 decadal survey Clouds and Earth’s Radiant Energy System (CERES) Tier-1 designation to maintain the continuous radiation budget measurement for climate modeling and better understand radiative forcings.
- Astrophysical missions such as OST will need IR and far-IR detector and related technologies.
- LANDSAT Thermal InfraRed Sensor (TIRS), Climate Absolute Radiance and Refractivity Observatory (CLARREO), BOREal Ecosystem Atmosphere Study (BOREAS), Methane Trace Gas Sounder, or other IR Earth-observing missions.
- Current science missions utilizing 2D, large-format cryogenic readout circuits:
  - HAWC + (High Resolution Airborne Wideband Camera Upgrade) for SOFIA (Stratospheric Observatory for Infrared Astronomy) future missions
  - PIPER (Primordial Inflation Polarization Experiment), balloon-borne.
  - PICO (Probe of Inflation and Cosmic Origins), a probe-class cosmic microwave background mission concept.

References:


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**S11.05 Suborbital Instruments and Sensor Systems for Earth Science Measurements**

Lead Center: JPL

Participating Center(s): ARC, GSFC, JPL

**Scope Title**

Sensors and Sensor Systems Targeting Trace Gases

**Scope Description**

Earth science measurements from space are considerably enhanced by observations from generally much less costly suborbital instruments and sensor systems. These instruments and sensors support NASA’s Earth Science Division science, calibration/validation and environmental monitoring activities by providing ancillary data for satellite calibration and validation; algorithm development/refinement; and finer-scale process studies. NASA seeks measurement capabilities that support current satellite and model validation, advancement of surface-based remote-sensing networks, and targeted Airborne Science Program and ship-based field campaign activities as discussed in the ROSES solicitation. Data from such sensors also inform process studies to improve our scientific understanding of the Earth system. In-situ sensor systems (air-, land-, and water-based) can comprise stand-alone instrument and data packages; instrument systems configured for integration on ship-based (or alternate surface-based platform) and in-water deployments, NASA’s Airborne Science aircraft fleet or commercial providers, uncrewed aircraft systems (UAS), balloons, and ground networks; or end-to-end solutions providing needed data products from mated sensor and airborne/surface/subsurface platforms. An important goal is to create sustainable measurement capabilities to support NASA’s Earth Science objectives, with infusion of new technologies and
systems into current/future NASA research programs. Instrument prototypes as a deliverable in Phase II proposals and/or field demonstrations are highly encouraged.

Complete instrument systems are generally desired, including features such as remote/unattended operation and data acquisition, and minimum size, weight, and power consumption. All proposals must summarize the current state of the art and demonstrate how the proposed sensor or sensor system represents a significant improvement over the state of the art.

Specific desired sensors or subsystems include:

- Small, lightweight, turn-key trace in situ gas measurement sensors with 1 to 10 Hz time response that are suitable for small aircraft, UAV, or balloon deployment and capable of detecting:
  - NOx, NOy, CH2O, O3, benzene, toluene at <5% uncertainty.
  - CO, CH4, OCS, N2O at <1% uncertainty.
  - SO2 at <100 parts per trillion by volume (pptv) uncertainty.

  where these uncertainties apply to measurements made on airborne platforms under flight conditions (variable ambient pressure and temperature).

- Small, turn-key spectrometer-based Sun photometer sensors capable of detecting NO2, CH2O, and O3, at <5% uncertainty. These sensors must be capable of long-term measurements to support NASA ground networks. Improved performance Sun and sky viewing spectrometer subsystems that increase measurement accuracy and stability and simplify instrument calibration of Sun photometers may be considered. Potential improvements are wavelength stability (<100 pm/°C) and reduced stray light (<10⁻⁴).

- Real-time, 0.1 to 1 Hz gas-phase radioisotopic (especially radiocarbon) measurements suitable for distinguishing emissions sources and for deployment on aircraft or UAVs.

- Airborne-capable bulk or film retroreflector subsystems that advance NASA open-path trace-gas measurements (similar to the widely used NASA LaRC Diode Laser Hygrometer). Operational at wavelengths between 2 and 12 µm, or some subset of wavelengths within that range, with low return light cone divergence (<2°).

- Low-volume (<0.1 L) multipass cell spectrometer subsystems that advance NASA extractive trace-gas measurements. Operational at wavelengths 2 to 5 µm or greater with pathlengths of 50+ meters.

- Aircraft static-air-temperature sensor measurements to better than 0.1 °C accuracy under upper troposphere-lower stratosphere conditions.

- In situ spectrometer instruments for measuring atmospheric trace gases (ozone, NO2, IO) from fixed platforms, ships, and small autonomous surface vessels. The instrument requirements are: Low-power operation modes; portability; autonomous operation: active, fast, and precise pointing for targeting Sun or Moon while gathering data; absolute radiometric calibration conservation, user-friendly field tools for the validation of the optical characterization of the system such as radiometric and spectral calibration and field of view (FOV); very low straylight and low electrical noise with capability to monitor and account for the electrical noise; wide dynamic range with capabilities of measuring low and high light intensities with the same optics (Sun, Moon, sky, and reflective surfaces); broad UV-vis-IR (ultraviolet-visible-infrared) spectral range with 0.6 nm spectral resolution for trace gases; capability of operating on fixed and moving ocean platforms; and auxiliary environmental sensors (site temperature, humidity, and pressure).

- Innovative, high-value sensors directly targeting a stated NASA need (including aerosols, clouds, and ocean) may also be considered. Proposals responding to this specific bullet are strongly encouraged to identify at least one relevant NASA subject matter expert.
Expected TRL or TRL Range at completion of the Project

4 to 7

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II

- Prototype
- Hardware
- Software

Desired Deliverables Description

The ideal Phase I proposal would demonstrate a clear idea of the problem to be solved, potential solutions to this problem, and an appreciation for potential risks or stumbling blocks that might jeopardize the success of the Phase I and II projects. The ideal Phase I effort would then address and hopefully overcome any major challenges to (1) demonstrate feasibility of the proposed solution and (2) clear the way for the Phase II effort. These accomplishments would be detailed in the Phase I final report and serve as the foundation for a Phase II proposal.

The ideal Phase II effort would build, characterize, and deliver a prototype instrument to NASA including necessary hardware and operating software. The prototype would be fully functional, but the packaging may be more utilitarian (i.e., less polished) than a commercial model.

State of the Art and Critical Gaps

The subtopic is and remains highly relevant to NASA Science Mission Directorate (SMD) and Earth Science research programs, in particular the Earth Science Atmospheric Composition, Climate Variability & Change, and Carbon Cycle and Ecosystems focus areas. Suborbital in situ and remote sensors inform NASA ground, ship, and airborne science campaigns led by these programs and provide important validation of the current and next generation of satellite-based sensors (e.g., PACE, OCO-2, TEMPO, GLIMR, SBG, A-CCP; see links in References). The solicited measurements will be highly relevant to current and future NASA campaigns with objectives and observing strategies similar to past campaigns (e.g., ACTIVATE, NAAMES, EXPORTS, CAMP2EX, FIREX-AQ, KORUS-AQ, and DISCOVER-AQ; see links in References).

Relevance / Science Traceability

The subtopic is and remains highly relevant to NASA SMD and Earth Science research programs, in particular the Earth Science Atmospheric Composition, Weather and Atmospheric Dynamics, Climate Variability & Change,
Carbon Cycle and Ecosystems, and Earth Surface and Interior focus areas. In situ and ground-based sensors inform NASA ship and airborne science campaigns led by these programs and provide important validation of the current and next generation of satellite-based sensors (e.g., PACE, OCO-2, TEMPO, GLIMR, SBG, A-CCP; see links in References). The solicited measurements will be highly relevant future NASA campaigns with objectives and observing strategies similar to past campaigns (e.g., NAAMES, EXPORTS, CAMP2EX, FIREX-AQ, KORUS-AQ, DISCOVER-AQ; see links in References). The need horizon of the subtopic sensors and sensors systems is both near-term (<5 yr) and midterm (5 to 10 yr).

Relevant Programs and Program Officers include:

- NASA ESD Ocean Biology and Biogeochemistry Program (Laura Lorenzoni, HQ Program Manager).
- NASA ESD Tropospheric Composition Program (Barry Lefer, HQ Program Manager).
- NASA ESD Radiation Sciences Program (Hal Maring, HQ Program Manager).
- NASA ESD Weather and Atmospheric Dynamics Program (Amber Emory, HQ Program Manager).
- NASA ESD Earth Surface and Interior Program (Ben Phillips and Kevin Reath, HQ Program Managers).
- NASA ESD Airborne Science Program (Bruce Tagg, HQ Program Manager).

References

Relevant current and past satellite missions and field campaigns include:

- Decadal Survey Recommended ACCP Mission (now named Atmos) focusing on aerosols, clouds, convection, and precipitation: https://science.nasa.gov/earth-science/decadal-surveys [29]
- CAMP2Ex airborne field campaign focusing on tropical meteorology and aerosol science: https://espo.nasa.gov/camp2ex [31]
- 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/ [32]
- GLIMR Satellite Mission focusing on geostationary observations of coastal waters and ocean productivity, land-to-sea carbon fluxes, and harmful algal blooms along the U.S. coast and other regions of interest off South America and the Caribbean Sea: https://www.nasa.gov/press-release/nasa-targets-coastal-ecosystems-with-new-space-sensor [33]
- 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 [34]
- DISCOVER-AQ airborne and ground-based campaign targeting pollution and air quality in four areas of the United States: https://discover-aq.larc.nasa.gov/ [35]
- NAAMES Earth Venture Suborbital field campaign targeting the North Atlantic phytoplankton bloom cycle and impacts on atmospheric aerosols, trace gases, and clouds: https://naames.larc.nasa.gov [36]
- AToM airborne field campaign mapping the global distribution of aerosols and trace gases from pole to pole: https://espo.nasa.gov/atom/content/ATom [37]
- PACE Satellite Mission, scheduled to launch in 2022, that focuses on observations of ocean biology, aerosols, and clouds: https://pace.gsfc.nasa.gov/ [38]
- EXPORTS field campaign targeting the export and fate of upper ocean net primary production using satellite observations and surface-based measurements: https://oceaneXports.org [39]
- Decadal Survey Planetary Boundary Layer (PBL) Incubation Study: https://science.nasa.gov/earth-science/decadal-pbl [41]
- Decadal Survey Surface Topography and Vegetation (STV) Incubation Study: https://science.nasa.gov/earth-science/decadal-stv [42]
The NASA Earth Science (http://science.nasa.gov/earth-science/) and Applied Sciences (http://appliedsciences.nasa.gov/) programs seek innovative and unique approaches to increase the utilization and extend the benefit of Earth Science research data to better meet societal needs. The focus of this subtopic is to develop digital tools for non-expert end users who are not scientists. These users need analytical tools to make decisions in the context of climate change, specifically related to wildfire mitigation and water management. Tools must be intuitive, and results must be reliable and not subject to misinterpretation. Innovative solutions could range from simple, intuitive mobile applications to dashboard tools that integrate NASA science data with domain-specific contextual data, to sophisticated decision-support software that merges deep analysis with powerful prediction capabilities to provide insights and the ability to explore "what-if" scenarios.

This subtopic develops core capabilities that can be integrated to build remote-sensing-driven decision support tools (DSTs) customized to the requirements of different users in varied fields who are grappling with current and anticipated impacts from wildfires and inadequacy of fresh water. Proven development and commercialization strategies should be used to meet these objectives. The goal of this solicitation is to directly link what is being done at NASA with the end-user community to support decision making. Responsive proposals must include a clear identification of tools that will be used and a clear end-user or business application to which the tools, systems, and so forth are intended to support. Proposals should explain how the proposed capabilities will address an end-user need, business opportunity, or gap area in decision support capabilities. Proposals should also outline existing capabilities, including software, models, and data that are already implemented at NASA or through related NASA activities, and describe how the proposed activities may leverage, complement, or expand from the existing infrastructure. Proposals should discuss the level of computing resources required for their methods as well as the plan to ensure availability of the resources needed.

**Expected TRL or TRL Range at completion of the Project**

3 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 11 Software, Modeling, Simulation, and Information Processing

**Level 2**

TX 11.X Other Software, Modeling, Simulation, and Information Processing

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Software

**Desired Deliverables Description**
Research proposed to this subtopic should demonstrate technical feasibility during Phase I, and in partnership with commercial customers (to include other Federal Agencies and state and local governments), show a path toward a Phase II prototype demonstration with significant communication with commercial stakeholders to increase the potential for nongovernmental market penetration.

State of the Art and Critical Gaps

Currently, creating DSTs that effectively utilize remote-sensing data requires significant efforts by experts in multiple domains. NASA Earth science data, while accessible, is massive in breadth and scope—a true “Big Data” problem. However, the formatting of the data is not easily accessed or readily usable beyond remote sensing experts and the research community, suggesting that application by commercial users is even more challenging. Although the data have commercial use, they are underutilized because of accessibility and translation issues. This creates a barrier to the widespread use of Earth observations by state and local governments, businesses, and the public. This subtopic aims to democratize the creation of Earth-science-driven DSTs related to fire mitigation and freshwater management and encourage DST development that significantly increases the return on investment for Earth science missions.

Relevance / Science Traceability

NASA Mandate 51 USC Section 60506: ensure the availability and widest possible use of accurate and current data on global warming; also, use practical benefits for society as an important measure of success.

From the 2018 Earth Science Decadal Survey: "While some discoveries are grounded entirely on observations from space, many more depend on combining information from a range of sources, including field campaigns, laboratory experiments, computer modeling, and theoretical studies...Science based on integrating information from several approaches can lead to products where the insights from the whole are much greater than the sum of the parts..."

References

Proposed decision support tools should leverage NASA’s rich Earth science data:

- Earth data: [https://earthdata.nasa.gov/](https://earthdata.nasa.gov/) [45]

S12.01 Exoplanet Detection and Characterization Technologies

Lead Center: GSFC

Participating Center(s): GSFC

Scope Title

Control of Scattered Starlight with Coronagraphs

Scope Description

This scope addresses the unique problem of imaging and spectroscopic characterization of faint astrophysical objects that are located within the obscuring glare of much brighter stellar sources. Examples include planetary systems beyond our own, the detailed inner structure of galaxies with very bright nuclei, binary star formation, and stellar evolution. Contrast ratios of one million to ten billion over an angular spatial scale of 0.05 to 1.5 arcsec are typical of these objects. Achieving a very low background requires control of both scattered and diffracted light. The
failure to control either amplitude or phase fluctuations in the optical train severely reduces the effectiveness of starlight cancellation schemes.

This innovative research focuses on advances in coronagraphic instruments that operate at visible and near-infrared wavelengths. The ultimate application of these instruments is to operate in space as part of a future observatory mission concept such as the Habitable Exoplanet Observatory (HabEx) and Large Ultraviolet Optical Infrared Surveyor (LUVOIR). Measurement techniques include imaging, photometry, spectroscopy, and polarimetry. There is interest in component development and innovative instrument design, as well as in the fabrication of subsystem devices that include, but are not limited to, the following areas:

Starlight diffraction control and characterization technologies:

- Diffraction control masks for coronographs and scaled starshade experiments, which includes transmissive scalar, polarization-dependent, spatial apodizing, and hybrid metal/dielectric masks, including those with extremely low reflectivity regions that allow them to be used in reflection.
- Systems to measure spatial optical density, phase inhomogeneity, scattering, spectral dispersion, thermal variations, and to otherwise estimate the accuracy of high-dynamic range apodizing masks.
- Methods to distinguish the coherent and incoherent scatter in a broadband speckle field.

Wavefront control technologies:

- Small-stroke, high-precision, deformable mirrors scalable to 10,000 or more actuators (both to further the state of the art towards flight-like hardware and to explore novel concepts). Multiple deformable mirror technologies in various phases of development and processes are encouraged to ultimately improve the state of the art in deformable mirror technology. Process improvements are needed to improve repeatability, yield, power consumption, connectivity, stability, and performance precision of current devices.
- High-precision, stable, deformable mirrors whose nominal surface can carry optical prescriptions for dual use as imaging optics such as off-axis parabolas and apodizing elements. Like 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
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

See SPIE conference papers and articles published in the Journal of Astronomical Telescopes and Instrumentation on high contrast coronagraphy, segmented coronagraph design and analysis, and starshades.

- Exoplanet Exploration Program: https://exoplanets.nasa.gov/exep/ [48]
  - Specifically, the technology pages and those addressing coronagraphs: https://exoplanets.nasa.gov/exep/technology/technology-overview/ [49]
  - The 5-year technology development plan: https://exoplanets.nasa.gov/internal_resources/446/ [50]
- Goddard Space Flight Center: https://www.nasa.gov/goddard [51]

Scope Title

Control of Scattered Light with Starshades

Scope Description

As with coronagraphs, this scope addresses the unique problem of imaging and spectroscopic characterization of faint astrophysical objects that are located within the obscuring glare of much brighter stellar sources. Examples include planetary systems beyond our own, the detailed inner structure of galaxies with very bright nuclei, binary star formation, and stellar evolution. Contrast ratios of one million to ten billion over an angular spatial scale of 0.05 to 1.5 arcsec are typical of these objects. Achieving a very low background requires control of both scattered and diffracted light. The starshade’s shape is designed to control the diffraction of starlight and form a deep shadow around the distant telescope. In this way, high contrast is achieved with a diffraction-limited telescope that does not require an internal high-precision wavefront control system. Sources of scatter include sunlight glinting on the sharp edges of the starshade, and multiple reflections between petal surfaces and edge assemblies. Earthshine on the telescope-facing surfaces must also be considered.

The research focuses on:

- Low-scatter, low-reflectivity, sharp, flexible razor-sharp edges for control of solar scatter at the perimeter of the starshade.
Large-area (hundreds of square meters) anti-reflection and thermal-control coatings for flexible optical shield surfaces that are robust to cleaning and handling for starshade optical surfaces.

Particulate contamination mitigation measures, including (but not limited to) dust-resistant coatings, vacuum-ultraviolet-eroding coatings, and on-orbit cleaning technologies.

**Expected TRL or TRL Range at completion of the Project**

2 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 08 Sensors and Instruments

**Level 2**

TX 08.2 Observatories

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Hardware

**Desired Deliverables Description**

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 flight-like geometries. Model validation of perturbation sensitivities have also been demonstrated for contrast levels of $10^{-9}$. A full-scale 10-m disk including the optical shield has been constructed, deployed, and shown to meet flight deployment requirements. Half-scale petals have been constructed and tested, validating the required thermal stability. Formation flying sensitivity has been demonstrated in the laboratory and through modeling to levels required for flight. Critical gaps relevant to this call include the fabrication of sharp optical edges and optical edge assemblies as well as methods to mitigate both particulate and molecular contamination of the edges and the telescope-facing surfaces.

**Relevance / Science Traceability**

These technologies are directly applicable to mission concept studies such as Habitable Exoplanet Observatory (HabEx), Large Ultraviolet Optical Infrared Surveyor (LUVOIR), starshade missions, and any space telescopes that could potentially be used for exoplanet imaging and characterization.

**References**

Technology development reports, concept videos, and prototype deployment videos:

[https://exoplanets.nasa.gov/exep/technology/starshade/](https://exoplanets.nasa.gov/exep/technology/starshade/) [52]
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
Phase II will emphasize hardware/software development with delivery of specific hardware or software products for NASA, targeting demonstration operations at a ground-based telescope in coordination with the lead NASA center. Phase II deliverables include a working prototype or engineering model of the proposed product/platform or software along with documentation of development, capabilities, and measurements (showing specific improvement metrics); and tools as necessary. Proposed prototypes shall demonstrate a path towards a flight-capable platform. Opportunities and plans should also be identified and summarized for potential commercialization or NASA infusion.

State of the Art and Critical Gaps

High-resolving-power spectrographs (R ~ 150,000) with simultaneous ultraviolet (UV), visible, and near-infrared (NIR) coverage and exquisite long-term stability are required for PRV studies. Classical bulk optic spectrographs traditionally used for PRV science impose architectural constraints because of their large mass and limited optical flexibility. Integrated photonic spectrographs are wafer-thin devices that could reduce instrument volume by up to 3 orders of magnitude. Spectrometers that are fiber fed, with high illumination stability, excellent wavelength calibration, and precise temperature and pressure control represent the immediate future of precision RV measurements.

Traditional RV spectrographs would benefit from improvements in grating technology. Diffraction-limited PRV spectrographs require echelle gratings with low wavefront error and high efficiency—both of which are very challenging to achieve. Echelle spectrographs are designed to operate at high angle of incidence and very high diffraction order; thus, the grating must have very accurate groove placement (for low wavefront error) and very flat groove facets (for high efficiency). For decades, echelle gratings have been fabricated by diamond ruling, but it is difficult to achieve the level of performance required for PRV instruments. Newer grating fabrication techniques using lithographic methods to form the grooves may be a promising approach. As spectrograph stability imposes limits on how precisely RV can be measured, spectral references play a critical role in characterizing and ensuring this precision. Only laser frequency combs (LFCs) and line-referenced Fabry-Pérot etalons are capable of providing the broad spectral coverage and long-term stability needed for extreme PRV detection of exoplanets. Although both frequency combs and etalons can deliver high-precision spectrograph calibration, the former requires relatively complex hardware in the visible portion of the spectrum.

Commercial fiber laser astrocombs covering 450 to 1400 nm at 25 GHz line spacing and <3 dB intensity variations over the entire bandwidth are available for ground-based astronomical spectrographs. However, the cost for these systems is often so prohibitive that recent RV spectrograph projects either do not use a LFC or include it only as a future upgrade. Alternatively, astrocombs produced by electro-optic modulation (EOM) of a laser source have been demonstrated in the NIR. EOM combs produce modes spaced at a radiofrequency (RF) modulation frequency, typically 10 to 30, and they avoid the line-filtering step required by commercial mode-locked fiber laser combs. The comb frequency can be stabilized by referencing the laser pump source to a molecular absorption feature or another frequency comb. Where octave spanning EOM combs are available, f-2f self-referencing provides the greatest stability. EOM combs must be spectrally broadened to provide the bandwidth necessary for PRV applications. This is accomplished through pulse amplification followed by injection into highly nonlinear fiber or nonlinear optical waveguides.

Power consumption of the frequency comb calibration system will be a significant driver of mission cost for space based PRV systems and motivates the development of a comb system that operates with less than 20 W of spacecraft power. Thus, for flight applications, it is highly desirable to develop frequency comb technology with low power consumption: ~10 to 30 GHz mode spacing; compact size; broad (octave spanning) spectral grasp across both the visible and NIR; low phase noise; stability traceable to the International System of Units definition of the second; and importantly, long life.

The intrinsic illumination stability of the spectrometer also sets a fundamental measurement floor. As the image of the star varies at the entrance to the spectrometer because of atmospheric effects and telescope guiding errors, so too does the recorded stellar spectrum, leading to a spurious RV offset. Current seeing-limited PRV instruments use multimode optical fibers, which provide some degree of azimuthal image scrambling, to efficiently deliver stellar light from the telescope focal plane to the spectrometer input. Novel-core-geometry fibers, in concert with dedicated optical double-scramblers, are often used to further homogenize and stabilize the telescope illumination pattern in both the image and pupil planes. However, these systems still demonstrate measurable sensitivity to incident illumination variations from the telescope and atmosphere. Furthermore, as spectral resolution requirements
increase, the commensurate increase in instrument size becomes impractical. Thus, the community has turned to implementing image and pupil slicers to reformat the near or far fields of light entering the spectrometer by preferentially redistributing starlight exiting the fiber to maintain high spectral resolution, efficiency, and compact spectrometer size.

Relevance / Science Traceability

The NASA Strategic Plan (2018) and Space Mission Directorate Science Plan (2014) both call for discovery and characterization of habitable Earth analogs and the search for biosignatures on those worlds. These goals were endorsed and amplified upon in the recent National Academy of Science (NAS) Exoplanet Report, which emphasized that a knowledge of the orbits and masses is essential to the complete and correct characterization of potentially habitable worlds. PRV measurements are needed to follow up on the transiting worlds discovered by Kepler, K2, and Transiting Exoplanet Survey Satellite (TESS). The interpretation of the transit spectra that the James Webb Space Telescope (JWST) will obtain will depend on knowledge of a planet’s surface gravity, which comes from its radius (from the transit data) and its mass (from PRV measurements or, in some cases, transit timing variations). Without knowledge of a planet’s mass, the interpretation of its spectrum is subject to many ambiguities.

These ambiguities will only be exacerbated for the direct-imaging missions such as the proposed Habitable Exoplanet Observatory (HabEx) and Large Ultraviolet Optical Infrared Surveyor (LUVOIR) flagships, which will obtain spectra of Earth analogs around a few tens to hundreds of stars. Even if a radius can be inferred from the planet’s brightness and an estimate of its albedo, the lack of a dynamical mass precludes any knowledge of the planet’s density, bulk composition, and surface gravity, which are needed to determine, for example, absolute gas column densities. Moreover, a fully characterized orbit is challenging to determine from just a few direct images and may even be confused in the presence of multiple planets. Is a planet in a highly eccentric orbit habitable or not? Only dynamic (PRV) measurements can provide such information. Thus, highly precise and highly stable PRV measurements are absolutely critical to the complete characterization of habitable worlds.

The NAS report also noted that measurements from space might be a final option if the problem of telluric contamination cannot be solved. The Earth’s atmosphere will limit precise radial velocity measurements to ~10 cm/sec at wavelengths longer than ~700 nm and greater than 30 cm/sec at wavelengths >900 nm, making it challenging to mitigate the effects of stellar activity without a measurement of the color dependence due to stellar activity in the PRV time series. A space-based PRV mission, such as has been suggested in the NASA EarthFinder mission concept study, may be necessary. If so, the low-SWaP technologies developed under this SBIR program could help enable space-based implementations of the PRV method.

References

Precision radial velocity:

- 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/NNEExplore/EPRV/ [56]

Photonic lanterns:

Astrocombs:


Nonlinear waveguides:


Spectral flattening:


S12.02 Precision Deployable Optical Structures and Metrology

Lead Center: GSFC

Participating Center(s): GSFC

**Scope Title:**

Precision Optical Metering Structures and Instruments

**Scope Description:**

Future space astronomy missions from ultraviolet to millimeter wavelengths will push the state of the art in current optomechanical technologies. Size, dimensional stability, temperature, risk, manufacturability, and cost are important factors, separately and in combination. The Large Ultraviolet Optical Infrared Surveyor (LUVOIR) calls for deployed apertures as large as 15 m in diameter; the Origins Space Telescope (OST), for operational temperatures as low as 4 K; and LUVOIR and the Habitable Exoplanet Observatory (HabEx), for exquisite optical quality. Methods to construct large telescopes in space are also under development. Additionally, sunshields for thermal control and starshades for exoplanet imaging require deployment schemes to achieve 30- to 70-m-class space structures.

This subtopic addresses the need to mature technologies that can be used to fabricate 10- to 20-m-class, lightweight, ambient, or cryogenic flight-qualified observatory systems and subsystems (telescopes, sunshields, starshades). Proposals to fabricate demonstration components and subsystems with direct scalability to flight systems through validated models will be given preference. The target launch volume and expected disturbances,
along with the estimate of system performance, should be included in the discussion. Novel metrology solutions to
establish and maintain optical alignment will also be accepted.

Technologies including, but not limited to, the following areas are of particular interest:

Precision structures/materials:

- Low coefficient of thermal expansion/coefficient of moisture expansion (CTE/CME) materials/structures to
  enable highly dimensionally stable optics, optical benches, and metering structures.
- Materials/structures to enable deep-cryogenic (down to 4 K) operation.
- Novel athermalization methods to join materials/structures with differing mechanical/thermal properties.
- Lightweight materials/structures to enable high-mass-efficiency structures.
- Precision joints/latches to enable submicron-level repeatability.
- Mechanical connections providing microdynamic stability suitable for robotic assembly.

Deployable technologies:

- Precision deployable modules for assembly of optical telescopes (e.g., innovative active or passive
  deployable primary or secondary support structures).
- Hybrid deployable/assembled architectures, packaging, and deployment designs for large sunshields and
  external occulters (20- to 50-m class).
- Packaging techniques to enable more efficient deployable structures.

Metrology:

- Techniques to verify dimensional stability requirements at subnanometer-level precision (10 to 100 pm).
- Techniques to monitor and maintain telescope optical alignment for on-ground and in-orbit operation.

A successful proposal shows a path toward a Phase II delivery of demonstration hardware scalable to 5-m
diameter for ground test characterization. Proposals should show an understanding of one or more relevant
science needs and present a feasible plan to fully develop the relevant subsystem technologies and transition them
into a future NASA program(s).

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

**Primary Technology Taxonomy:**

**Level 1:**

TX 12 Materials, Structures, Mechanical Systems, and Manufacturing

**Level 2:**

TX 12.2 Structures

**Desired Deliverables of Phase I and Phase II:**

- Research
- Analysis
- Prototype
- Hardware

**Desired Deliverables Description:**
For Phase I, a successful deliverable would include a demonstration of the functionality and/or performance of a system/subsystem with model predictions to explain observed behavior as well as make predictions on future designs.

For Phase II this should be demonstrated on units that can be scaled to future flight sizes.

State of the Art and Critical Gaps:

The James Webb Space Telescope represents the state of the art in large deployable telescopes. The Roman Space Telescope (RST) coronagraph instrument (CGI) will drive telescope/instrument stability requirements to new levels. The mission concepts in the upcoming Astro2020 decadal survey will push technological requirements even further in the areas of deployment, size, stability, lightweighting, and operational temperature. Each of these mission studies have identified technology gaps related to their respective mission requirements.

Relevance / Science Traceability:

These technologies are directly applicable to the RST CGI and the HabEx, LUVOIR, and OST mission concepts. Ultra-stable opto-mechanical systems are listed as a "critical" technology gap with an "urgent" priority in the LUVOIR STDT Final Report for the Astro2020 Decadal Survey.

References:

5. NASA in-Space Assembled Telescope (iSAT) Study: [https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/](https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/) [66]

S12.03 Advanced Optical Systems and Fabrication/Testing/Control Technologies for Extended-Ultraviolet/Optical and Infrared Telescope

Lead Center: GSFC

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

Scope Title

INTRODUCTION

Scope Description

Accomplishing NASA’s high-priority science at all levels (flagship, probe, Medium-Class Explorers (MIDEX), Small Explorers (SMEX), rocket, and balloon) requires low-cost, ultra-stable, normal-incidence mirror systems with low mass-to-collecting-area ratios. Here, a mirror system is defined as the mirror substrate, supporting structure, and associated actuation and thermal management systems. After performance (diffraction limit, stability, collecting area), the most important metric for an advanced optical system is affordability or areal cost (cost per square meter of collecting aperture), followed by mass.

This subtopic has multiple scopes. Each scope has its own sponsoring NASA center and is important to that Center. Centers will review proposals submitted to their Scope and manage any awarded contracts.

Scopes are defined based on specific applications, technology gap needs, or operating wavelength regime. Each scope has its own defined performance metrics.
Proposals must show an understanding of one or more relevant science needs and present a feasible plan to develop the proposed technology for infusion into a NASA program: suborbital rocket or balloon, competed SMEX or MIDEX, or Decadal-class mission. Successful proposals will demonstrate an ability to manufacture, test, and control ultra-low-cost optical systems that can meet science performance requirements and mission requirements (including processing and infrastructure issues). Material behavior, process control, active and/or passive optical performance, and mounting/deploying issues should be resolved and demonstrated.

Expected TRL or TRL Range at completion of the Project

3 to 5

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II

- Research
- Prototype
- Hardware

Desired Deliverables Description

- An ideal Phase I deliverable would be a precision optical system of at least 0.25 m; a relevant subcomponent of a system; a prototype demonstration of a fabrication, test, or control technology leading to a successful Phase II delivery; or a reviewed preliminary design and manufacturing plan that demonstrates feasibility. Although detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.
- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 m or a relevant subcomponent (with a TRL in the 4 to 5 range) or working fabrication, test, or control system. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase II would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly that can be integrated into the potential mission as well as demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analyses).

State of the Art and Critical Gaps

Current normal-incidence space mirrors cost $4 million to $6 million per square meter of optical surface area. This research effort seeks to improve the performance of advanced precision optical components while reducing their cost by 5× to 50×, to between $100K/m² and $1M/m².

Relevance / Science Traceability

This subtopic primarily supports potential Astrophysics Division missions. It has made optical systems in the past for potential balloon experiments. Future potential Decadal missions include Laser Interferometer Space Antenna (LISA), Habitable Exoplanet Observatory (HabEx), Large UV/Optical/Near-IR Surveyor (LUVOIR), and the Origins
Space Telescope (OST).

References


Scope Title

Telescopes for Balloon Missions

Scope Description

Astronomy from a stratospheric balloon platform offers numerous advantages. At typical balloon cruise altitudes (100,000 to 130,000 ft.), 99%+ of the atmosphere is below the balloon, and the attenuation due to the remaining atmosphere is small. This is particularly important in the near-ultraviolet (NUV) bands and in the infrared (IR) bands near 2.7 and 4.25 µm. The lack of atmosphere nearly eliminates scintillation and allows the resolution potential of relatively large optics to be realized, and the small amount of atmosphere reduces scattered light and allows observations of brighter objects, even during daylight hours.

Potential balloon science missions are either in the extreme UV (EUV), UV/optical (UVO), or in the infrared/far-infrared (IR/FIR):

- EUV missions require optical components with surface slopes of <0.1 µrad.
- UVO science missions require 1-m-class telescopes diffraction limited at 500 nm.
- IR science missions require 2-m-class telescopes diffraction limited at 5 µm.
- FIR missions require 2-m-class (or larger) telescopes diffraction limited at 50 µm.

In all cases, telescopes must be able to maintain diffraction-limited performance for elevation angles ranging from 10° to 65° over a temperature range of 220 to 280 K.

Also, the telescopes need to have a total mass of less than 300 kg and be able to survive a 10g shock (on landing) without damage.

For packaging reasons, the primary mirror assembly must have a radius of curvature 3 m (nominal) and a mass <150 kg.

Expected TRL or TRL Range at completion of the Project

3 to 5

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II
Desired Deliverables Description

- Phase I will produce a preliminary design and report including initial design requirements such as wavefront error budget, mass allocation budget, structural stiffness requirements, etc., as well as trade studies performed and an analysis that compares the design to the expected performance over the specified operating range. Development challenges shall be identified during Phase I, including trade studies and challenges to be addressed during Phase II with subsystem proof-of-concept demonstration hardware.
- If Phase II can only produce a subscale component, then it should also produce a detailed final design, including final requirements (wavefront error budget, mass allocation, etc.) and a performance assessment over the specified operating range.

State of the Art and Critical Gaps

Current SOA (state-of-the-art) UVO mirrors made from Zerodur\(^{(R)}\) or Ultra-Low Expansion Glass, ULE\(^{(R)}\), for example, require lightweighting to meet balloon mass limitations and cannot meet diffraction-limited performance over the wide temperature range because of the coefficient of thermal expansion limitations. Current SOA IR mirrors are typically made from aluminum and the diffraction-limited performance is limited by gravity sag change as a function of elevation angle.

Relevance / Science Traceability

“Vision and Voyages for Planetary Science in the Decade 2013-2022”:

- Page 22, last paragraph of NASA Telescope Facilities within the Summary Section:
  "...Balloon- and rocket-borne telescopes offer a cost-effective means of studying planetary bodies at wavelengths inaccessible from the ground. Because of their modest costs and development times, they also provide training opportunities for would-be developers of future spacecraft instruments. Although NASA's Science Mission Directorate regularly flies balloon missions into the stratosphere, there are few funding opportunities to take advantage of this resource for planetary science because typical planetary grants are too small to support these missions. A funding line to promote further use of these suborbital observing platforms for planetary observations would complement and reduce the load on the already oversubscribed planetary astronomy program..."

- Page 203, 5th paragraph of section titled "Earth and Space-Based Telescopes":
  "...Significant planetary work can be done from balloon-based missions flying higher than 45,000 ft. This altitude provides access to electromagnetic radiation that would otherwise be absorbed by Earth’s atmosphere and permits high-spatial-resolution imaging unaffected by atmospheric turbulence. These facilities offer a combination of cost, flexibility, risk tolerance, and support for innovative solutions that is ideal for the pursuit of certain scientific opportunities, the development of new instrumentation, and infrastructure support. Given the rarity of giant-planet missions, these types of observing platforms (high-altitude telescopes on balloons and sounding rockets) can be used to fill an important data gap..."

Potential advocates include planetary scientists at Goddard Space Flight Center (GSFC), Johns Hopkins Applied Physics Laboratory (APL), Southwest Research Institute (SWRI), and other sites.

References

- For additional discussion of the advantages of observations from stratosphere platforms, refer to:
- For additional information about scientific balloons, refer to: [https://www.csbf.nasa.gov/docs.html](https://www.csbf.nasa.gov/docs.html) [70]
Scope Title

Optical Components and Telescopes for Large Ultraviolet/Optical/Near-IR Telescopes

Scope Description

Potential ultraviolet/optical (UVO) space missions require telescopes with apertures ranging from 1 to 8 m monolithic or 3 to 16 m segmented with better than 500 nm diffraction-limited performance or 40 nm rms transmitted wavefront (achieved either passively or via active control). Optical components need to have <5 nm rms surface figures. Additionally, a potential exoplanet mission, using an internal coronagraph, requires total telescope wavefront stability on order of 10 pm rms per 10 min. This stability specification places severe constraints on the dynamic mechanical and thermal performance of a 4-m or larger telescope. Potential enabling technologies include active thermal control systems, ultrastable mirror support structures, athermal telescope structures, athermal mirror struts, ultrastable joints with low coefficients of thermal expansion (CTE), and vibration compensation. Analysis indicates that the first mode for structure and optical components needs to be in the range of 60 to 500 Hz. Also, operating temperatures should range from 250 to 300 K.

Mirror areal density depends upon available launch vehicle capacities to Sun-Earth L2 (i.e., 15 kg/m$^2$ for a 5-m-fairing Evolved Expendable Launch Vehicle (EELV) versus 150 kg/m$^2$ for a 10-m-fairing Space Launch System (SLS)). Regarding areal cost, a good goal is to keep the total cost of the primary mirror at or below $100M. Thus, an 8-m-class mirror (with 50 m$^2$ of collecting area) should have an areal cost of less than $2M/m^2$. Also, a 16-m-class mirror (with 200 m$^2$ of collecting area) should have an areal cost of less than $0.5M/m^2$.

Key technologies to enable such a mirror include new and improved:

- Mirror substrate materials and/or architectural designs.
- Processes to rapidly fabricate and test UVO-quality mirrors.
- Mirror support structures, joints, and mechanisms that are athermal or have 0 CTE at the desired scale.
- Mirror support structures, joints, and mechanisms that are ultrastable at the desired scale.
- Mirror support structures with low mass that can survive launch at the desired scale.
- Mechanisms and sensors to align segmented mirrors to <1 nm rms precisions.
- Thermal control (<1 mK) to reduce wavefront stability to <10 pm rms per 10 min.
- Dynamic isolation (>140 dB) to reduce wavefront stability to <10 pm rms per 10 min.

Also needed is the ability to fully characterize surface errors and predict optical performance via integrated optomechanical modeling.

Potential solutions for substrate material/architecture include but are not limited to: ultra-uniform low-CTE glasses, silicon carbide, nanolaminates, or carbon-fiber-reinforced polymer. Potential solutions for mirror support structure material/architecture include, but are not limited to additive manufacturing, nature-inspired architectures, nanoparticle composites, carbon fiber, graphite composite, and ceramic or SiC materials. Potential solutions for new fabrication processes include, but are not limited to additive manufacturing, direct precision machining, rapid optical fabrication, roller embossing at optical tolerances, slumping, or replication technologies to manufacture 1- to 2-m- (or larger) precision quality components. Potential solutions for achieving the 10-pm wavefront stability include, but are not limited to: metrology, passive control, and active control for optical alignment and mirror phasing; active vibration isolation; metrology; and passive and active thermal control.

Expected TRL or TRL Range at completion of the Project

2 to 5

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments
Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Hardware
- Software
- Prototype

Desired Deliverables Description

- An ideal Phase I deliverable would be a precision optical system of at least 0.25 m; a relevant subcomponent of a system; a prototype demonstration of a fabrication, test, or control technology leading to a successful Phase II delivery; or a reviewed preliminary design and manufacturing plan that demonstrates feasibility. While detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.

- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 m or relevant subcomponent (with a TRL in the 4 to 5 range) or a working fabrication, test, or control system. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase II would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly that can be integrated into the potential mission as well as demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analyses).

State of the Art and Critical Gaps

The precision fabrication of large mirrors is a daunting task. The fabrication process needs to be scaled from the state-of-the-art (SOA) Hubble mirror at 2.4 m both in precision and dimensions of the mirrors.

Relevance / Science Traceability

This Subtopic Scope supports potential Astrophysics Division missions. Previously, optical systems have been made for balloon experiments. Future potential Decadal missions include Laser Interferometer Space Antenna (LISA), Habitable Exoplanet Observatory (HabEx), Large UV/Optical/Near-IR Surveyor (LUVOIR), and the Origins Space Telescope (OST).

References

The HabEx and LUVOIR space telescope studies are developing concepts for UVOIR space telescopes for exo-Earth discovery and characterization, exoplanet science, general astrophysics, and solar system astronomy.

- The HabEx Interim Report: https://www.jpl.nasa.gov/habex/ [63]
Scope Description

Topic #1: LISA Epoxy Study

Many applications for space-based optical metrology systems require structures with low coefficient of thermal expansion (CTE) to maintain precision alignment and extremely stable optical pathlength. Gravitational wave observatories such as LISA (Laser Interferometer Space Antenna) rely on single-material telescopes to maintain alignment and pathlength stability by constructing the telescopes out of glass such as ULE® or low CTE materials such as Zerodur® or ClearCeram®. For manufacturability, these telescopes must be made in pieces that are assembled to make a complete telescope.

For many years the bonding technique of choice has been hydroxide catalysis bonding, originally developed for the Gravity Probe B mission, but used more recently for the optical bench in the LISA Pathfinder mission. This bonding technique easily supports the small 20-mm steering mirrors and optics on an optical bench, but it does not so easily support the expected launch loads of a telescope structure.

Proposals are solicited to develop high-strength, high-glass-transition-temperature, low-viscosity adhesives that can be cured near room temperature and maintain full performance with low cure shrinkage. The near-room-temperature cure is necessary to avoid damaging low-CTE ceramics such as Zerodur®. The adhesive should cure rapidly so that it can be used during alignment of a telescope without requiring extremely stable alignment support equipment over long durations of time. A cure process that involves an initial ultraviolet (UV) exposure to set the adhesive rapidly and then is followed by a thermal cure at only slightly elevated above room temperature might be one way to accomplish this.

Specific metrics:

- Shear strength: >4,000 psi (28 MPa) at 25 °C.
- Tensile strength: >6,300 psi (45 MPa) at 25 °C.
- Glass transition onset temperature: >60 °C with near-room-temperature cure.
- Low viscosity: ~12 Poise (1.2 PaS).
- Pot life: >60 min.
- Low outgassing.

Topic #2: Ultrastable Structures

Telescope stability is enabling for missions at all wavelengths (UV, optical, infrared (IR) and far-IR). It is particularly enabling for coronagraph and interferometric instruments. The stiffer an optical component and structure is, the more stable the resulting telescope will be. Historically, high-stiffness low-mass mirrors and structures have been achieved using low-density materials (such as beryllium or SiC) or extreme lightweighting of glass mirrors. Currently, this subtopic is investing in additively manufactured mirrors. In all previous cases, however, the fabricated mirrors used "classical" geometric architectural forms. Biologically inspired architectures might yield mirrors and telescope structures with lower mass and higher stiffness. Biologically inspired architectures might enable the design of structures that more efficiently distribute load and control modal responses.

Expected TRL or TRL Range at completion of the Project

2 to 3

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.2 Observatories
Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description

For Topic #1:

- Phase I deliverable would be a process, tested in a relevant TRL-6 environment, whose performance metrics are better than hydroxide catalysis bonding of Zerodur\textsuperscript{(R)}, as demonstrated on test coupons.
- Phase 2 deliverable would be a data package of: (a) additional testing of coupons with sufficient quantity to provide greater than 99\% statistical confidence of performance, (b) testing of flight-traceable component bonds in a relevant environment, and (c) characterization of longitudinal performance.

For Topic #2:

- An ideal Phase I deliverable would be a precision optical system of at least 0.15 m or a relevant subcomponent of a system whose stiffness or modal properties can be modeled and verified by test.
- An ideal Phase II project would further advance the technology by producing a flight-qualifiable optical system greater than 0.5 m or a relevant subcomponent (with a TRL in the 4 to 5 range).
- Phase I and Phase II system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials.

State of the Art and Critical Gaps

Historically, high-stiffness low-mass mirrors and structures have been achieved using low-density materials such as beryllium or extreme lightweighting of glass mirrors. Previously, this subtopic has invested in alternative materials such as SiC and graphite fiber composites. Currently, this subtopic is investing in additive manufacturing technologies. In all previous cases, however, the fabricated mirrors used "classical" geometric architectural forms.

Relevance / Science Traceability

Mirror technology is enabling for all potential Science Mission Directorate (SMD) science. Currently, this scope does not require traceability to any specific science mission. However, it may demonstrate the feasibility of this technology for IR or far-IR performance.

References

NASA X-ray and Cryogenic Facility: https://optics.msfc.nasa.gov/tech-2/ [71]
components "in flight."

Given that deterministic optical fabrication is relatively mature, technology advances are solicited that primarily reduce cost—particularly for large mirrors. Technology that increases remove rate (to reduce processing time) while producing smoother surfaces (less mid- and high-spatial frequency error) are potentially enhancing. Potential technologies for improvement include (but are not limited to): computer-controlled grinding/polishing, electrolytic in-process dressing (ELID) processes, electrochemical processes, on-machine in-process metrology feedback, etc.

Regarding precision, this subtopic encourages proposals to develop technology that makes a significant advance in the ability to fabricate and test an optical system.

One area of current emphasis is the ability to nondestructively characterize coefficient of thermal expansion (CTE) homogeneity in 4-m-class Zerodur(R) and 2-m-class ULE(R) mirror substrates to an uncertainty of 1 ppb/K and a spatial sampling of 100×100. This characterization capability is needed to select mirror substrates before undergoing the expense of turning them into a lightweight space mirror.

Regarding stability, to achieve high-contrast imaging for exoplanet science using a coronagraph instrument, systems must maintain wavefront stability to <10 pm rms over intervals of ~10 min during critical observations. The ~10-min time of this stability is driven by current wavefront sensing and control techniques that rely on stellar photons from the target object to generate estimates of the system wavefront. This subtopic aims to develop new technologies and techniques for wavefront sensing, metrology, and verification and validation of optical system wavefront stability.

Current methods of wavefront sensing include image-based techniques such as phase retrieval, focal-plane contrast techniques such as electric field conjugation and speckle nulling, and low-order and out-of-band wavefront sensing that use nonscience light rejected by the coronagraph to estimate drifts in the system wavefront during observations. These techniques are limited by the low stellar photon rates of the dim objects being observed (~5 to 11 Vmag), leading to tens of minutes between wavefront control updates.

New methods may include new techniques of using out-of-band light to improve sensing speed and spatial frequency content, new control laws incorporating feedback and feedforward for more optimal control, new algorithms for estimating absolute and relative wavefront changes, and the use of artificial guide stars for improved sensing signal-to-noise ratio and speed.

Current methods of metrology include edge sensors (capacitive, inductive, or optical) for maintaining segment cophasing, and laser distance interferometers for absolute measurement of system rigid-body alignment. Development of these techniques to improve sensitivity, speed, and component reliability is desired. Low-power, high-reliability electronics are also needed. Metrology techniques for system verification and validation at the picometer level during integration and test (I&T) are also needed. High-speed spatial and speckle interferometers are currently capable of measuring single-digit picometer displacements and deformations on small components in controlled environments. Extension of these techniques to large-scale optics and structures in typical I&T environments is needed.

Finally, mirror segment actuators are needed to align and cophase segmented aperture mirrors to diffraction-limited tolerances. Depending upon the mission, these mechanisms may need to operate at temperatures as low as 10 K. Potential technologies include superconducting optomechanisms.

**Expected TRL or TRL Range at completion of the Project**

2 to 4

**Primary Technology Taxonomy**

**Level 1**

TX 08 Sensors and Instruments

**Level 2**
TX 08.2 Observatories

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Hardware
- Software
- Prototype

**Desired Deliverables Description**

- An ideal Phase I deliverable would be a prototype demonstration of a fabrication, test, or control technology leading to a successful Phase II delivery; or a reviewed preliminary design and manufacturing plan that demonstrates feasibility.
- Although the detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.

**State of the Art and Critical Gaps**

Deterministic optical fabrication is relatively mature. There are multiple small and large companies offering commercial products and services. The Webb and Roman telescopes were/are being fabricated by deterministic processes. However, these processes are expensive. Technology advances are required to enhance these processes and reduce their cost—particularly for large mirrors.

Wavefront (WF) sensing using star images, including dispersed-fringe and phase-retrieval methods, is at TRL 6, qualified for space by the James Webb Space Telescope (JWST). WF sensing and control for coronagraphs, including electric field conjugation and low-order WF sensing (LOWFS), is at TRL4 and is being developed and demonstrated by the Wide Field Infrared Survey Telescope Coronagraph Instrument (WFIRST/CGI).

Laser-distance interferometers for point-to-point measurements with accuracies from nanometers to picometers have been demonstrated on the ground by the Space Interferometry Mission and other projects, and in orbit by the LISA Pathfinder and Grace Follow-On missions. Application to telescope alignment metrology has been demonstrated on testbeds to TRL 4 for nanometer accuracy. Picometer accuracy for telescopes awaits demonstration.

Edge sensors are in use on segmented ground telescopes but are not yet on space telescopes. New designs are needed to provide picometer sensitivity and millimeter range in a space-qualified package.

Higher order WF sensing for coronagraphs using out-of-band light is beginning development, with data limited to computer simulations.

Mechanism SOA is defined by the JWST actuators. They provide ample range for far-IR applications but have more precision than necessary. Thus, they are expensive.

**Relevance / Science Traceability**

Fabrication and testing technologies for deterministic optical manufacturing are enabling/enhancing for monolithic aperture missions ranging from UV to optical to far-IR. Control technologies are enabling for coronagraph-equipped space telescopes and segmented space telescopes. The Large UV/Optical/IR Surveyor (LUVOIR), Habitable Exoplanet Observatory (HabEx), and Origins Space Telescope (OST) mission concepts currently provide good examples.

**References**
Optical Components and Telescopes for Infrared/Far-Infrared Missions

Scope Description

Potential far-infrared (IR) space missions require telescopes with apertures ranging from 1 to 4 m monolithic or 3 to 10 m segmented with diffraction-limited performance as good as 5 µm operating at lower than 10 K (survival temperature from 4 to 315 K). Mirror substrate thermal conductivity at 4 K must be greater than 2 W/m·K. Mirror systems (mirror substrate and mount) need to have a cryodeformation of less than 100 nm rms. Mirror areal density goal is 15 kg/m² for the primary mirror substrate and 35 kg/m² for the primary mirror assembly (including structure). Areal cost goal is total cost of the primary mirror at or below $100K/m².

Key technologies to enable such a mirror include new and improved:

- Mirror substrate materials and/or architectural designs.
- Processes to rapidly fabricate and test far-IR quality mirrors.
- Mirror support structures, joints, and mechanisms that are athermal or have matched coefficients of thermal expansion (CTEs) at the desired scale.
- Mirror support structures with low mass that can survive launch at the desired scale.

Also needed is the ability to fully characterize surface errors and predict optical performance via integrated optomechanical modeling.

Potential solutions for substrate material/architecture include but are not limited to: mirror materials with low CTE, homogenous CTE, and high thermal conductivity. Potential solutions for mirrors and support structure material include, but are not limited to metal alloys, nanoparticle composites, carbon fiber, graphite composites, ceramic or SiC materials, etc. Potential solutions for new fabrication processes include, but are not limited to additive manufacture, direct precision machining, rapid optical fabrication, roller embossing at optical tolerances, slumping, or replication technologies to manufacture 1- to 2-m- (or larger) precision quality components.

Expected TRL or TRL Range at completion of the Project

2 to 5

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II

- Research
- Prototype
- Hardware

Desired Deliverables Description
An ideal Phase I deliverable would be a cryogenic optical system of at least 0.25 m and suitable for a far-IR mission or a relevant subcomponent of a system. Although detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.

An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 m; a relevant subcomponent (with a TRL in the 4 to 5 range); or a working fabrication, test, or control system. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase II would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly that can be integrated into the potential mission as well as demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analyses).

State of the Art and Critical Gaps

Current state of the art (SOA) is represented by the Herschel Space Observatory (3.5-m monolith; SiC) and the James Webb Space Telescope (6.5-m segmented primary mirror; beryllium). Technologies are needed to advance the fabrication precision and the size of the mirrors, both monolithic and segmented, beyond the current SOA.

Relevance / Science Traceability

NASA needs telescopes and interferometers that reach fundamental sensitivity limits imposed by astrophysical background photon noise. Only telescopes cooled to a cryogenic temperature can provide such sensitivity. Novel approaches to fabrication and test developed for a far-IR astrophysics mission may be applicable to far-IR optical systems employed in other divisions of the NASA Science Mission Directorate (SMD), or to optical systems designed to operate at wavelengths shorter than the far-IR.

References

- Program Annual Technology Reports (PATR) can be downloaded from the NASA Physics of the Cosmos and Cosmic Origins (PCOS/COR) Technology Development website: https://apd440.gsfc.nasa.gov/technology/ [73]
- The Origins Space Telescope (OST) final report: https://asd.gsfc.nasa.gov/firs/ [64]
- The Space Infrared Interferometric Telescope (SPIRIT) and its optical system requirements: https://asd.gsfc.nasa.gov/cosmology/spirit/ [74]

Scope Title

Telescopes for CubeSAT Missions

Scope Description

The need exists for a low-cost, compact (e.g., CubeSat-class), scalable, diffraction-limited, and athermalized off-axis reflective and on-axis telescopes. A particular interest of this Scope is off-axis reflective telescopes for near-infrared/short-wave-infrared- (NIR/SWIR-) band optical communication.

Typically, specialty optical aperture systems are designed and built as “one-offs,” which are inherently high in cost and often out of scope for smaller projects. A Phase I effort would investigate current compact off-axis reflective designs and develop a trade space to identify the most effective path forward. The work would include a strategy for aperture diameter scalability, athermalization, and low-cost fabrication. Detailed optical designs would be developed along with detailed structural, thermal, optical performance (STOP) analyses confirming diffraction-limited operation across a wide range of operational disturbances, both structural dynamic and thermal. Phase II
may follow up with development of prototypes, built at multiple aperture diameters and fidelities.

NIR/SWIR optical-communication-support hardware should be assumed towards an integrated approach, including fiber optics, fast-steering mirrors, and applicable detectors.

Expected TRL or TRL Range at completion of the Project

2 to 4

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II

- Prototype
- Hardware
- Analysis

Desired Deliverables Description

- An ideal Phase I deliverable would be a prototype unobscured telescope with the required performance and size or a reviewed preliminary design and manufacturing plan that demonstrates feasibility. Although detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analyses will be done to show compliance with all requirements. Experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.
- An ideal Phase II project would further advance the technology to produce a flight-qualifiable optical system with the required performance for a CubeSat mission. Phase I and Phase II mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission-oriented Phase II would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly that can be integrated into the potential mission as well as demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analyses).

State of the Art and Critical Gaps

Currently, the state of the art for reflective optical system for communications applications are:

1. On-axis or axisymmetric designs are typically used for (space) optical communications and imaging, which inherently are problematic because of the central obscuration.
2. Off-axis designs provide superior optical performance because of the clear aperture; however, they are rarely considered because of the complex design, manufacturing, and metrology procedures.

Relevance / Science Traceability

Optical communications enable high-data-rate downlink of science data. The initial motivation for this scalable off-axis optical design approach is for bringing high-performance reflective optics within reach of laser communication projects with limited resources. However, this exact optical hardware is applicable for any diffraction-limited,
athermalized, science imaging application. Any science mission could potentially be able to select from a “catalog” of optical aperture systems that would already have (flight) heritage and reduced risks.

References

- 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](https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10096/100960V/Discovery-deep-space-optical-communications-DSOC-transceiver/10.1117/12.2256001.full)

S12.04 X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics

Lead Center: GSFC

Participating Center(s): JPL, MSFC

Scope Title

X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics

Scope Description

The National Academy Astro2010 Decadal Report identifies studies of optical components and ability to manufacture, coat, and perform metrology needed to enable future x-ray observatory missions.

The Astrophysics Decadal Report specifically calls for optical coating technology investment for future ultraviolet (UV), optical, exoplanet, and infrared (IR) missions, and the Heliophysics 2009 Roadmap identifies the coating technology for space missions to enhance rejection of undesirable spectral lines and improve space/solar-flux durability of extreme UV (EUV) optical coatings, as well as coating deposition to increase the maximum spatial resolution.

Future optical systems for NASA's low-cost missions, CubeSat, and other small-scale payloads, are moving away from traditional spherical optics to nonrotationally symmetric surfaces with anticipated benefits of free-form optics such as fast wide-field and distortion-free cameras.

This subtopic solicits proposals in the following three focus areas:

- X-ray manufacturing, coating, testing, and assembling complete mirror systems in addition to maturing the current technology.
- Coating technology including carbon nanotubes (CNTs) for a wide range of wavelengths from x-ray to IR (x-ray, EUV, Lyman UV (LUV), vacuum UV (VUV), visible, and IR).
- Free-form optics design, fabrication, and metrology for CubeSat, SmallSat, and various coronagraph instruments.

Expected TRL or TRL Range at completion of the Project

3 to 6

Primary Technology Taxonomy
Level 1
TX 08 Sensors and Instruments

Level 2
TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description

Typical deliverables based on subelements of this subtopic:

Phase I:

- X-ray optical mirror system: analysis, reports, prototype.
- Coating: analysis, reports, software, demonstration of the concept and prototype.
- Free-form optics: analysis, design, software and hardware prototype of optical components.

Phase II:

- X-ray optical mirror system: analysis and prototype.
- Coating: analysis, reports, software, demonstration of the concept and prototype.
- Free-form optics: analysis, design, software and hardware prototype of optical components.

State of the Art and Critical Gaps

This subtopic focuses on three areas of technology development:

- This work is a very costly and time consuming. Most of the state of the art (SOA) requiring improvement is ~10 arcsec angular resolution. SOA stray light suppression is bulky and ineffective for wide-field-of-view telescopes. We seek significant reduction in both expense and time. Reduce the areal cost of telescope by 2× such that the larger collecting area can be produced for the same cost or half the cost.
- Coating technology for wide range of wavelengths from x-ray to IR (x-ray, EUV, LUV, VUV, visible, and IR). The current x-ray coating is defined by NuSTAR. Current EUV is defined by Heliophysics (80% reflectivity from 60 to 200 nm). Current UVOIR is defined by Hubble. MgF$_2$-overcoated aluminum on a 2.4-m mirror has birefringence concerns and only marginally acceptable reflectivity between 100 to 200 nm.
- Free-form optics design, fabrication, and metrology for package-constrained imaging systems. This field is in early stages of development. Improving the optical surfaces with large field of view and fast F/#s is highly desirable.

Relevance / Science Traceability

This subtopic supports a variety of Astrophysics Division missions. The technologies in this subtopic encompasses fields of x-ray, coating technologies ranging from UV to IR, and free-form optics in preparation for Decadal missions such as HabEx, LUVOIR, and OST.

Optical components, systems, and stray-light suppression for x-ray missions: The 2010 National Academy Decadal
Report specifically identifies optical components and the ability to manufacture and perform precise metrology on them needed to enable several different future missions (Next Generation x-ray Optics, NGXO). The National Research Council (NRC) NASA Technology Roadmap Assessment ranked advanced mirror technology for new x-ray telescopes as the #1 Object C technology requiring NASA investment.

Free-form optics: NASA missions with alternative low-cost science and small-size payload are increasing. However, the traditional interferometric testing as a means of metrology are unsuited to free-form optical surfaces because of changing curvature and lack of symmetry. Metrology techniques for large fields of view and fast F/#s in small-size instruments is highly desirable, specifically if they could enable cost-effective manufacturing of these surfaces (CubeSat, SmallSat, NanoSat, various coronagraph instruments).

Coating for x-ray, EUV, LUV, UV, visible, and IR telescopes: The Astrophysics Decadal specifically calls for optical coating technology investment for future UV/optical and exoplanet missions (Habitable Exoplanet Observatory (HabEx) or Large Ultraviolet Optical Infrared Surveyor (LUVOIR)). The Heliophysics 2009 Roadmap identifies optical coating technology investments for Origins of Near-Earth Plasma (ONEP); Ion-Neutral Coupling in the Atmosphere (INCA); Dynamic Geospace Coupling (DGC); Fine-scale Advanced Coronal Transition-Region Spectrograph (FACTS); Reconnection and Micro-scale (RAM); and Solar-C Nulling polarimetry/coronagraph for exoplanet imaging and characterization, dust and debris disks, extra-galactic studies, and relativistic and nonrelativistic jet studies.

References

The study pages are available at:

- The Habitable Exoplanet Observatory (HabEx) is a concept for a mission to directly image planetary systems around Sun-like stars. HabEx will be sensitive to all types of planets; however, its main goal is, for the first time, to directly image Earth-like exoplanets, and characterize their atmospheric content. By measuring the spectra of these planets, HabEx will search for signatures of habitability such as water and be sensitive to gases in the atmosphere possibility indicative of biological activity, such as oxygen or ozone. Habitable Exoplanet Observatory (HabEx): [https://www.jpl.nasa.gov/habex/][63]
- The Large UV/Optical/IR Surveyor (LUVOIR) is a concept for a highly capable, multiwavelength space observatory with ambitious science goals. This mission would enable great leaps forward in a broad range of science, from the epoch of re-ionization, through galaxy formation and evolution, star and planet formation, to solar system remote sensing. LUVOIR also has the major goal of characterizing a wide range of exoplanets, including those that might be habitable—or even inhabited. The LUVOIR Interim Report: [https://asd.gsfc.nasa.gov/luvoir/][62]
- The LYNX Mission Concept: [https://wwwastro.msf.nasa.gov/lynx/][79]
- The Origins Space Telescope (OST) is the mission concept for the Far-IR Surveyor study. The Origins Space Telescope: [https://asd.gsfc.nasa.gov/firs/][64]
- NASA's Astrophysics Roadmap, Enduring Quests, Daring Visions, recognized the need for an OST mission with enhanced measurement capabilities relative to those of the Herschel Space Observatory, such as a 3-order-of-magnitude gain in sensitivity, angular resolution sufficient to overcome spatial confusion in deep cosmic surveys or to resolve protoplanetary disks, and new spectroscopic capability. The NASA Astrophysics Roadmap: [https://science.nasa.gov/science-committee/subcommittees/nac-astrophysics-subcommittee/astrophysics-roadmap][80]

Scope Title

X-Ray Mirror Systems Technology

Scope Description

NASA large x-ray observatory requires low-cost, ultrastable, lightweight mirrors with high-reflectance optical coatings and effective stray-light suppression. The current state of the art of mirror fabrication technology for x-ray missions is very expensive and time consuming. Additionally, a number of improvements such as 10 arcsec angular resolutions and 1 to 5 m² collecting area are needed for this technology. Likewise, the stray-light
suppression system is bulky and ineffective for wide-field-of-view telescopes.

In this area, we are looking to address the multiple technologies, including: improvements to manufacturing (machining, rapid optical fabrication, slumping, or replication technologies), improved metrology, performance prediction and testing techniques, active control of mirror shapes, new structures for holding and actively aligning of mirrors in a telescope assembly to enable x-ray observatories while lowering the cost per square meter of collecting aperture, and effective design of stray-light suppression in preparation for the Decadal Survey of 2020. Additionally, we need epoxies made of silicon to bond mirrors. The epoxies should absorb infrared (IR) radiation (with wavelengths between 1.5 and 6 µm that traverse silicon with little or no absorption) and therefore be cured quickly with a beam of IR radiation. Currently, x-ray space mirrors cost $4 million to $6 million per square meter of optical surface area. This research effort seeks a cost reduction for precision optical components by 5 to 50 times, to less than $1M to $100K per square meter.

Additionally, proposals are solicited to develop new advanced-technology computer-numerical-control (CNC) machines to polish inside and/or outside full-shell substrate (between 100 and 1,000 mm in height, 100 to 2,800 mm in diameter, varying radial prescription along azimuth, ~2 mm in thickness), grazing-incidence optics to x-ray-quality surface tolerances (with surface figure error <1 arcsec half-power diameter (HPD), radial slope error <1 µrad, out-of-round <2 µm). Current state-of-the-art technology in CNC polishing of full-shell substrate, grazing-incidence optics yields 2.5 arcsec HPD on the outside of a mandrel used for replicating shells. Technology advances beyond current state of the art include application of CNC and deterministic polishing techniques that (1) allow for direct force closed-loop control, (2) reduce alignment precision requirements, and (3) optimize the machine for polishing cylindrical optics through simplifying the axis arrangement and the layout of the cavity of the CNC polishing machine.

**Expected TRL or TRL Range at completion of the Project**

3 to 6

**Primary Technology Taxonomy**

**Level 1**

TX 08 Sensors and Instruments

**Level 2**

TX 08.2 Observatories

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description**

Typical deliverable based on subelements of this subtopic:

X-ray optical mirror system—Demonstration, analysis, reports, software, and hardware prototype:

- Phase I deliverables: Reports, analysis, demonstration, and prototype.
- Phase II deliverables: Analysis, demonstration, and prototype.

**State of the Art and Critical Gaps**

X-ray optics manufacturing, metrology, coating, testing, and assembling complete mirror systems in addition to
maturing the current technology: This work is very costly and time consuming. Most of the SOA (state of the art) requiring improvement is ~10 arcsec angular resolution. SOA stray-light suppression is bulky and ineffective for wide-field-of-view telescopes. We seek a significant reduction in both expense and time. Reduce the areal cost of a telescope by 2× such that the larger collecting area can be produced for the same cost or half the cost.

The gaps to be covered in this track are:

- Lightweight, low-cost, ultrastable mirrors for large x-ray observatory.
- Stray-light suppression systems (baffles) for large, advanced x-ray observatories.
- Ultrastable, inexpensive, lightweight x-ray telescope using grazing-incidence optics for high-altitude balloon-borne and rocket-borne missions.

Relevance / Science Traceability

The 2010 National Academy Decadal Report specifically identifies optical components and the ability to manufacture and perform precise metrology on them needed to enable several different future missions (Lynx and Advanced X-ray Imaging Satellite (AXIS)).

The National Research Council NASA Technology Roadmap Assessment ranked advanced mirror technology for new x-ray telescopes as the #1 Object C technology requiring NASA investment.

References

NASA High Energy Astrophysics (HEA) mission concepts including x-ray missions and studies are available at:

- [https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/concepts.html](https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/concepts.html) [81]

Scope Title

Coating Technology for X-Ray-UV-OIR

Scope Description

The optical coating technology is a mission-enabling feature that enhances the optical performance and science return of a mission. Lowering the areal cost of coating determines if a proposed mission could be funded in the current cost environment. The most common forms of coating used on precision optics are antireflective (AR) coating and high-reflective (HR) coating.

The current coating technology of optical components is needed to support the 2020 Astrophysics Decadal process. Historically, it takes 10 years to mature mirror technology from TRL 3 to 6.

Achieving these objectives requires sustained systematic investment.

The telescope optical coating needs to meet a low-temperature operation requirement. It is desirable to achieve 35 K in the future.

Many future NASA missions require suppression of scattered light. For instance, the precision optical cube utilized in a beam-splitter application forms a knife-edge that is positioned within the optical system to split a single beam into two halves. The scattered light from the knife-edge could be suppressed by carbon nanotube (CNT) coating. Similarly, scattered light suppression for gravitational-wave observatories and lasercom systems where simultaneous transmit/receive operation is required could be achieved by a highly absorbing coating such as CNT. Ideally, the application of CNT coatings needs to:

- Achieve broadband (visible plus near-infrared (IR)) reflectivity of 0.1% or less.
- Resist bleaching or significant albedo changes over a mission life of at least 10 years.
- Withstand launch conditions such as vibration, acoustics, etc.
- Tolerate both high continuous-wave (CW) and pulsed power and power densities without damage: ~10 W for CW and ~0.1 GW/cm² 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 $1 \times 10^{-7}$ in the range of 500 to 1064 nm. The advancement of this technology is desired to obtain ultralow reflectivity:

- Improve the specular reflectance to $1 \times 10^{-10}$ and hemispherical reflectance to better than 0.1%.
- Improve the cryogenic etching process to provide a variation of the reflectance (apodization effect) by increasing or decreasing the height of the features.
- Explore etching process and duration.

**Expected TRL or TRL Range at completion of the Project**

3 to 6

**Primary Technology Taxonomy**

**Level 1**

TX 08 Sensors and Instruments

**Level 2**

TX 08.2 Observatories

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description**

Coating—Analysis, reports, software, demonstration of the concept, and prototype:

- Phase I deliverables: Report, analysis, demonstration, and prototype.
- Phase II deliverables: Analysis, demonstration, and prototype.

**State of the Art and Critical Gaps**

Coating technology (for wide range of wavelengths from x-ray to IR: x-ray, extended ultraviolet (EUV), Lyman UV (LUV), vacuum UV (VUV), visible, and IR):

- The current x-ray coating is defined by Nuclear Spectroscopic Telescope Array (NuSTAR).
• Current EUV is defined by Heliophysics (80% reflectivity from 60 to 200 nm).
• Current UV-optical-IR (UVOIR) is defined by Hubble. MgF$_2$-overcoated aluminum on 2.4-m mirror. This coating has birefringence concerns and marginally acceptable reflectivity between 100 and 200 nm.

Metrics for x-ray:

• Multilayer high-reflectance coatings for hard x-ray mirrors.
• Multilayer depth-gradient coatings for 5 to 80 keV with high broadband reflectivity.
• Zero-net-stress coating of iridium or other high-reflectance elements on thin substrates (<0.5 mm).

Metrics for EUV:

• Reflectivity >90% from 6 to 90 nm onto a <2 m mirror substrate.

Metrics for Large UV/Optical/IR Surveyor (LUVOIR):

• Broadband reflectivity >70% from 90 to 120 nm (LUV) and >90% from 120 nm to 2.5 µm (VUV/visible/IR).
• Reflectivity non-uniformity <1% from 90 nm to 2.5 µm.
• Induced polarization aberration <1% for 400 nm to 2.5 µm spectral range from mirror coating applicable to a 1- to 8-m substrate.

Metrics for LISA:

• HR: Reflectivity >99% at 1064+/−2 nm with very low scattered light and polarization-independent performance over apertures of ~0.5 m.
• AR: Reflectivity <0.005% at 1064+/−2 nm.
  ○ Low-absorption, low-scatter, laser-line optical coatings at 1064 nm.
  ○ High reflectivity, R > 0.9995.
  ○ Performance in a space environment without significant degradation over time due, for example, to radiation exposure or outgassing.
  ○ High polarization purity, low optical birefringence over a range of incident angles from ~5° to ~20°.
  ○ Low coating noise (thermal, photothermal, etc.) for high-precision interferometric measurements.
  ○ Ability to endure applied temperature gradients (without destructive effects, such as delamination from the substrate).
  ○ Ability to clean and protect the coatings and optical surfaces during mission integration and testing. Cleaning should not degrade the coating performance.

Nonstationary optical coatings:

• Used in reflection and transmission that vary with location on the optical surface.

CNT coatings:

• Broadband visible to near-IR (NIR), total hemispherical reflectivity of 0.01% or less, adhere to the multilayer dielectric or protected metal coating.

Black-silicon cryogenic etching (new):

• Broadband UV+visible+NIR+IR, reflectivity of 0.01% or less, adhere to the multilayer dielectric (silicon) or protected metal.

Software tools to simulate and assist the anisotropic etching by employing a variety of modeling techniques such as
rigorous coupled wave analysis (RCWA), method of moments (MOM), finite-difference time domain (FDTD), finite element method (FEM), transfer matrix method (TMM), and effective medium theory (EMT).

Relevance / Science Traceability

- Coating for x-ray, EUV, LUV, UV, visible, and IR telescopes: Astrophysics Decadal specifically calls for optical coating technology investment for future UV/optical and exoplanet missions.
- Heliophysics 2009 Roadmap identifies optical coating technology investments for Origins of Near-Earth Plasma (ONEP), Ion-Neutral Coupling in the Atmosphere (INCA), Dynamic Geospace Coupling (DGC), Fine-scale Advanced Coronal Transition-Region Spectrograph (FACTS), Reconnection and Microscale (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, extragalactic studies, and relativistic and nonrelativistic jet studies.

References

Laser Interferometer Space Antenna (LISA) is a space-based gravitational wave observatory building on the success of LISA Pathfinder and Laser Interferometer Gravitational-Wave Observatory (LIGO). Led by the European Space Agency (ESA), the new LISA mission (based on the 2017 L3 competition) is a collaboration between ESA and NASA.

More information can be found at:

- [https://lisa.nasa.gov](https://lisa.nasa.gov) [82]

Scope Title

Free-Form Optics

Scope Description

Future NASA science missions demand wider fields of view in a smaller package. These missions could benefit greatly by free-form optics as they provide nonrotationally symmetric optics, which allow for better packaging while maintaining desired image quality. Currently, the design and fabrication of free-form surfaces is costly. Even though various techniques are being investigated to create complex optical surfaces, small-size missions highly desire efficient small packages with lower cost that increase the field of view and expand operational temperature range of unobscured systems. In addition to the free-form fabrication, the metrology of free-form optical components is difficult and challenging because of the large departure from planar or spherical shapes accommodated by conventional interferometric testing. New methods such as multibeam low-coherence optical probe and slope-sensitive optical probe are highly desirable.

Specific metrics are:

- Design: Innovative design methods/tools for free-form systems, including applications to novel reflective optical designs with large fields of view (>30°) and fast F/#s (<2.0).
- Fabrication: 10-cm-diameter optical surfaces (mirrors) with free-form optical prescriptions >1 mm, spherical departure with surface figure error <10 nm rms, and roughness <5 Å. 10-cm-diameter blazed optical reflective gratings on free-form surface shapes with >1 mm departure from a best-fit-sphere and grating spacings from 1 to 100 µm. Larger mirrors are also desired for flagship missions for ultraviolet (UV) and coronagraphic applications, with 10-cm- to 1-m-diameter surfaces having figure error <5 nm rms and roughness <1 Å rms.
- Metrology: Accurate metrology of free-form optical components with large spherical departures (>1 mm), independent of requiring prescription-specific null lenses or holograms.
Expected TRL or TRL Range at completion of the Project
3 to 6

Primary Technology Taxonomy

Level 1
TX 08 Sensors and Instruments

Level 2
TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description

Optical components—Demonstration, analysis, design, metrology, software, and hardware prototype:

- Phase I deliverables: Report, analysis, demonstration, and prototype.
- Phase II deliverables: Analysis, demonstration, and prototype.

State of the Art and Critical Gaps

Free-form optics design, fabrication, and metrology for package-constrained imaging systems. This field is in early stages of development. Improving the optical surfaces with large field of view and fast F/#s is highly desirable.

Relevance / Science Traceability

NASA missions with alternative low-cost science and small-size payload are increasing. However, the traditional interferometric testing as a means of metrology is unsuited to free-form optical surfaces due to changing curvature and lack of symmetry. Metrology techniques for large fields-of-view and fast F/#s in small size instruments are highly desirable—specifically if they could enable cost-effective manufacturing of these surfaces. (CubeSat, SmallSat, and NanoSat). Additionally, design studies for large observatories such as Origins Space Telescope (OST) and Large UV/Optical/IR Surveyor (LUVOIR, currently being proposed for the 2020 Astrophysics Decadal Survey) have demonstrated improved optical performance over a larger field-of-view afforded by free-form optics. Such programs will require advances in free-form metrology to be successful.

References

- Applications for Freeforms Optics at NASA: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170010419.pdf [83]
- Alignment and Testing for a Freeform Telescope: https://ntrs.nasa.gov/citations/20180007557 [84]
- Freeform Surface Characterization and Instrument Alignment for Freeform Space Applications: https://ntrs.nasa.gov/citations/20190025929 [85]
Scope Title:

Detectors

Scope Description:

This subtopic covers detector requirements for a broad range of wavelengths from ultraviolet (UV) through to gamma ray for applications in Astrophysics, Earth Science, Heliophysics, and Planetary Science. Requirements across the board are for greater numbers of readout pixels, lower power, faster readout rates, greater quantum efficiency, single photon counting, and enhanced energy resolution. The proposed efforts must be directly linked to a requirement for a NASA mission. These include Explorers, Discovery, Cosmic Origins, Physics of the Cosmos, Solar-Terrestrial Probes, Vision Missions, and Decadal Survey missions. Proposals should reference current NASA missions and mission concepts where relevant. Specific technology areas are:

- Large-format, solid-state single-photon-counting radiation-tolerant detectors in charge-coupled device (CCD) or complementary metal-oxide-semiconductor (CMOS) architecture—including 3D stacked architecture—for astrophysics, planetary, and UV heliophysics missions. Detectors with fast readout that can support high count rates and large incident flux from the extreme UV (EUV) and x-rays for heliophysics applications, especially solar-flare measurements.
- Solid-state detectors with polarization sensitivity relevant to astrophysics as well as planetary and Earth science applications; for example, in spectropolarimetry as well as air quality and aerosol monitoring.
- Solid-state detector arrays (2x128) with high sensitivity from 120 to 350 nm in one semiconductor chip; in particular, higher quantum efficiency (QE) and lower dark current than currently available silicon devices for this wavelength range. The active area of the photodiode should not exceed 40 µm in the 128-element direction, but it can be larger in the cross-array direction. To minimize noise from stray capacitance, the first stage of amplification shall be integrated on the same chip directly adjacent to the photodiode area, in an active pixel sensor configuration with at least three transistors to enable multiplexing between individual pixels. The design shall be amenable to scaling to smaller pixel sizes and larger format two-dimensional arrays in the future.
- UV detectors for O$_3$, NO$_2$, SO$_2$, H$_2$S, and ash detection. Refer to National Research Council's Earth Science Decadal Survey (2018).
- Supporting technologies that would enable the next-generation x-ray Observatory (Flagship- and Probe-class) that may require the development of x-ray microcalorimeter arrays with much larger field of view, \(\sim 10^5 \) to \(10^6 \) pixels, of pitch \(\sim 25 \) to 100 µm, and ways to read out the signals. For example, modular superconducting magnetic shielding is sought that can be extended to enclose a full-scale focal plane array. All joints between segments of the shielding enclosure must also be superconducting. Improved long-wavelength blocking filters are needed for large-area, x-ray microcalorimeters.
- Significant improvement in wide-band-gap semiconductor materials (such as AlGaN, ZnMgO, and SiC), individual detectors, and detector arrays for astrophysics missions and planetary science composition measurements. For example, SiC avalanche photodiodes (APDs) must show:
  - EUV photon counting, a linear mode gain \(>10 \times 10^6\) at a breakdown reverse voltage between 80 and 100 V.
  - Detection capability of better than 6 photons/pixel/sec down to 135 nm wavelength.
- Solar-blind (visible-blind) UV, far-UV (80 to 200 nm), and EUV sensor technology with high pixel resolution, large format, high sensitivity and high dynamic range, and low voltage and power requirements—with or without photon counting.
- UV detectors suitable for upcoming ultra-high-energy cosmic ray (UHECR) mission concepts.
- Solar x-ray detectors with small independent pixels (10,000 count/sec/pixel) over an energy range from <5 to 300 keV.
Filters with supporting grids are sought that, in addition to increasing filter strength, also enhance electromagnetic interference (EMI) shielding (1 to 10 GHz) and thermal uniformity for decontamination heating. X-ray transmission of greater than 80% at 600 eV per filter is sought, with infrared transmissions less than 0.01% and UV transmission of less than 5% per filter. A means of producing filter diameters as large as 10 cm should be considered.

Expected TRL or TRL Range at completion of the Project:

3 to 5

Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

Phase I deliverables: results of tests and analysis of designs, as described in a final report.

Phase II deliverables: prototype hardware or hardware for further testing and evaluation is desired.

State of the Art and Critical Gaps:

This subtopic aims to develop, and advance detector technologies focused on UV, x-ray, and gamma-ray spectral ranges. The science needs in this range span a number of fields, focusing on astrophysics, planetary science, and UV heliophysics. A number of solid-state detector technologies promise to surpass the traditional image-tube-based detectors. Silicon-based detectors leverage enormous investments and promise high-performance detectors, and more complex materials such as gallium nitride and silicon carbide offer intrinsic solar blind response. This subtopic supports efforts to advance technologies that significantly improve the efficiency, dynamic range, noise, radiation tolerance, spectral selectivity, reliability, and manufacturability in detectors.

Relevance / Science Traceability:

NASA Science Mission Directorate (SMD) applications:

- NASA Astrophysics: https://science.nasa.gov/astrophysics/ [86]
- The Explorers Program: https://explorers.gsfc.nasa.gov/ [87]
- Planetary Missions Program Office: https://www.nasa.gov/planetarymissions/index.html [88]
- Heliophysics: https://science.nasa.gov/heliophysics [89]

Missions under study (Large Ultraviolet Optical Infrared Surveyor (LUVOIR), Habitable Exoplanet Observatory (HabEx), Lynx, and New Frontiers-Io Observer):
- Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/ [63]
- The LYNX Mission Concept: https://wwwastro.msfc.nasa.gov/lynx/ [79]
- Lunar Science/Missions: UV spectroscopy to understand Lunar water cycle and minerology (water detection using edge at 165 nm, H₂ at 121.6 nm, and OH⁻ at 308 nm); LRO-LAMP (Lyman Alpha Mapping Project).
- Gravitational Wave Science: Swift detection of X-ray and UV counterparts of gravitation wave sources; Dorado mission to detect early UV counterpart.
- Planetary Science: Europa Clipper (water/plume detection); Enceladus; Venus (sulfur lines in the 140 to 300 nm range).
- Earth Science: ozone mapping, pollution studies.

References:

2. Explorers and Heliophysics Projects Division (EHPD): https://ehpd.gsfc.nasa.gov/ [91]


S13.01 Robotic Mobility, Manipulation and Sampling

Lead Center: JPL

Participating Center(s): ARC, GRC, GSFC

Scope Title
Robotic Mobility, Manipulation, and Sampling

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

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

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

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

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

**Expected TRL or TRL Range at completion of the Project**

2 to 4

**Primary Technology Taxonomy**

**Level 1**

TX 04 Robotics Systems

**Level 2**

TX 04.3 Manipulation

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description**

Hardware, software, and designs for component robotic systems:

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

**State of the Art and Critical Gaps**

Scoops, powder drills, and rock core drills and their corresponding handling systems have been developed for sample acquisition on Mars and asteroids. Nonflight systems have been developed for sampling on comets, Venus, and Earth's Moon. Some of these environments still present risk and have gaps that need to be addressed. Ocean worlds exploration presents new environments and unique challenges not met by existing mobility and sampling systems. New mobility, manipulation, and sampling technologies are needed to enable new types of
missions and missions to different and challenging environments.

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

**Relevance / Science Traceability**

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

**References**

- Mars Exploration—Program & Missions: [https://mars.nasa.gov/programmissions/](https://mars.nasa.gov/programmissions/) [93]
- Solar System Exploration: [https://solarsystem.nasa.gov/](https://solarsystem.nasa.gov/) [94]
- Ocean Worlds website: [https://www.nasa.gov/specials/ocean-worlds/](https://www.nasa.gov/specials/ocean-worlds/) [95]
- Ocean Worlds article: [https://science.nasa.gov/news-articles/ocean-worlds](https://science.nasa.gov/news-articles/ocean-worlds) [96]

**S13.02 Spacecraft Technology for Sample Return Missions**

**Lead Center:** JPL

**Participating Center(s):** GRC, GSFC, LaRC, MSFC

**Scope Title**

Critical Technologies for Sample-Return Missions

**Scope Description**

This subtopic focuses on technologies for robotic sample-return (SR) missions that require landing on large bodies (e.g., the Moon, Mars, Vesta, Ceres, Phobos, Europa), as opposed to particulate-class SR missions (e.g., Genesis, Hayabusa) or touch-and-go (TAG) missions to relatively small asteroids or comets (e.g., OSIRIS-Rex, Hayabusa2). The mission destinations envisioned are dwarf planets (e.g., Vesta, Ceres) and planet or planet moons (e.g., Phobos, Europa). These are the most challenging missions in NASA's portfolio but also the most scientifically promising, given the vast array of instruments available on Earth to study the retrieved samples. Specifically, technologies are sought to address the following challenges associated with these SR missions: (1) Mass-efficient spacecraft architectures (e.g., efficient propulsion or materials that significantly reduce the mass of the launch payload required), (2) Sample integrity (e.g., surviving reentry), and (3) Planetary protection/contamination control (PP/CC) (e.g., preventing leakage into the Mars Sample Return (MSR) mission's orbital sample (OS) canister).

The heightened need for mass-efficient solutions in these SR missions stems from their extreme payload mass “gear ratio.” For example, the entire MSR campaign will probably require four heavy launch vehicle launches with rough spacecraft mass of 5,000 kg each in order to bring back multiple samples with an estimated total mass of 0.5 kg. Clearly, any mass savings in the ascent vehicle's gross liftoff mass (GLOM) or in the mass of either the lander or the Earth Return Orbiter, for example, would yield many times more savings in the launch payload mass,
enhancing the feasibility of these missions. Examples of propulsion technologies that may reduce overall mass include the development of lightweight, restartable ignition techniques for hybrid and solid rocket motors, lightweight spin motors, lightweight vectoring systems, lightweight insulation materials, and lightweight expandable nozzle designs to increase nozzle area ratios.

Once acquired, samples must be structurally and thermally preserved through safe landing and transport to Johnson Space Center (JSC) for analyses. Sample integrity technology solutions that address the long, high-radiation return trip, as well as the dynamic and high-temperature environment of reentry, are sought. Potential solutions include near-isotropic and crushable high-strength energy-absorbent materials that can withstand the ballistic impact landing. Materials that offer thermal isolation in addition to energy absorption are highly desirable given the reentry environment. In the case of cryogenically preserved samples, the technical challenge includes development of thermal control systems to ensure volatiles are conserved.

Finally, acquired samples must be chemically and biologically preserved in their original condition. Examples of PP/CC technology solutions sought include:

- Materials selection: selection of metallic materials (non-organic) for the interior of the OS canister as well as materials that allow preferable surface treatments and bake-out sterilization approaches.
- Surface science topics: Adsorber coatings/materials for contaminant adsorption (getter-type materials, such as aluminum oxide, porous polymer resin) and/or low-surface-energy materials to minimize contaminant deposition.
- Characterization of contamination sources on lander, rover, capsule, ascent vehicle, and orbiter, for design of adequate mitigation measures.

**Expected TRL or TRL Range at completion of the Project**

3 to 6

**Primary Technology Taxonomy**

**Level 1**

TX 04 Robotics Systems

**Level 2**

TX 04.3 Manipulation

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype

**Desired Deliverables Description**

A Phase I deliverable would be a final report that describes the requisite research and detailed design accomplished under the project.

A Phase II deliverable would be successful demonstration of an appropriate-TRL performance test, such as at representative scale and environment, along with all the supporting analysis, design, and hardware specifications.

**State of the Art and Critical Gaps**

The kind of SR missions targeted in this solicitation are those that require landing on an extraterrestrial body. This most challenging kind of SR mission has only been successfully done in the Soviet Luna program that returned 326 g of Moon samples in three missions—out of eleven attempts—in the early 1970s. Hayabusa2 and OSIRIS-Rex are
TAG SR missions. The former returned asteroid Ryugu samples to Earth in December 2020; the latter is expected to follow suit in September 2023 from asteroid Bennu. The first segment of NASA’s MSR mission is the sample-collection rover Perseverance, which landed on Mars in February 2021. The MSR sample retrieval segment (lander, fetch rover, Mars Ascent Vehicle) is currently in Phase A development and expected to launch in 2028.

The content and breadth of this solicitation is informed by lessons learned in MSR over the pre-Phase A years. Future SR missions are in need of technology improvements in each of the critical areas targeted: mass efficiency, sample integrity, and planetary protection.

This solicitation seeks proposals that have the potential to increase the TRL from 3 or 4 to 6 within 5 years and are within the cost constraints of the Phases I, II, and III of this SBIR Program. Such progress would allow full flight qualification of the resulting hardware within 5 to 10 years.

**Relevance / Science Traceability**

Medium- and large-class SR missions address fundamental science questions such as whether there is evidence of ancient life or prebiotic chemistry in the sampled body. Table S.1 of *Vision and Voyages for Planetary Science in the Decade 2013-2022* (2011) correlates 10 "Priority Questions" drawn from three Crosscutting Science Themes, with "Missions in the Recommended Plan that Address Them." SR missions are shown to address 8 out of the 10 questions and cover every crosscutting theme, including Building New Worlds, Planetary Habitats, and Workings of Solar Systems.

**References**

- Vision and Voyages for Planetary Science in the Decade 2013-2022: [http://nap.edu/13117](http://nap.edu/13117) [97]
- Comet Nucleus Sample Return (CNSR): [https://ntrs.nasa.gov/search.jsp?R=20180002990](https://ntrs.nasa.gov/search.jsp?R=20180002990) [100]

**S13.03 Extreme Environments Technology**

Lead Center: JPL

Participating Center(s): GRC, GSFC, LaRC

**Scope Title**

Extreme Environments Technology

**Scope Description**

This subtopic addresses NASA’s need to develop technologies for producing space systems that can operate without environmental protection housing in the extreme environments of NASA missions. Key performance parameters of interest are survivability and operation under the following conditions:

1. Very low temperature environments (e.g., temperatures at the surfaces of Titan and of other ocean worlds as low as -180 °C; and in permanently shadowed craters on the Moon).
2. Combination of low-temperature and radiation environments (e.g., surface conditions at Europa of -180 °C with very high radiation).
3. Very high temperature, high pressure, and chemically corrosive environments (e.g., Venus surface conditions, having very high pressure and a temperature of 486 °C).

NASA is interested in expanding its ability to explore the deep atmospheres and surfaces of planets, asteroids, and comets through the use of long-lived (days or weeks) balloons and landers. Survivability in extreme high temperatures and high pressures is also required for deep-atmospheric probes to the giant planets. Proposals are sought for technologies that are suitable for remote-sensing applications at cryogenic temperatures and in situ atmospheric and surface explorations in the high-temperature, high-pressure environment at the Venusian surface (485 °C, 93 atm) or in low-temperature environments such as those of Titan (-180 °C), Europa (-220 °C), Ganymede (-200 °C), Mars, the Moon, asteroids, comets, and other small bodies.

Also, Europa-Jupiter missions may have a mission life of 10 years, and the radiation environment is estimated at 2.9 Mrad total ionizing dose (TID) behind 0.1-in-thick aluminum. Proposals are sought for technologies that enable NASA's long-duration missions to extreme wide-temperature and cosmic radiation environments. High reliability, ease of maintenance, low volume, low mass, and low outgassing characteristics are highly desirable. Special interest lies in development of the following technologies that are suitable for the environments discussed above:

- Wide-temperature-range precision mechanisms: for example, beam-steering, scanner, linear, and tilting multi-axis mechanisms.
- Radiation-tolerant/radiation-hardened low-power, low-noise, mixed-signal mechanism control electronics for precision actuators and sensors.
- Wide-temperature-range feedback sensors with sub-arcsecond/nanometer precision.
- Long-life, long-stroke, low-power, and high-torque force actuators with sub-arcsecond/nanometer precision.
- Long-life bearings/tribological surfaces/lubricants.
- High-temperature analog and digital electronics, electronic components, and in-circuit energy storage (capacitors, inductors, etc.) elements.
- High-temperature actuators and gear boxes for robotic arms and other mechanisms.
- Low-power and wide-operating-temperature radiation-tolerant/radiation-hardened radio-frequency (RF) electronics.
- Radiation-tolerant/radiation-hardened low-power/ultralow-power, wide-operating-temperature, low-noise mixed-signal electronics for spaceborne systems such as guidance and navigation avionics and instruments.
- Radiation-tolerant/radiation-hardened wide-operating-temperature power electronics.
- Radiation-tolerant/radiation-hardened electronic packaging (including shielding, passives, connectors, wiring harness, and materials used in advanced electronics assembly).

**Expected TRL or TRL Range at completion of the Project**

3 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 04 Robotics Systems

**Level 2**

TX 04.2 Mobility

**Desired Deliverables of Phase I and Phase II**

- Prototype
- Hardware
- Research
- Analysis
**Desired Deliverables Description**

Provide research and analysis for Phase I as a final report. Deliverables for Phase II should include proof-of-concept working prototypes that demonstrate the innovations defined in the proposal and enable direct operation in extreme environments.

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware demonstration, and when possible, deliver a demonstration unit for functional and environmental testing at the completion of the Phase II contract.

**State of the Art and Critical Gaps**

Future NASA missions to high-priority targets in our solar system will require systems that have to operate at extreme environmental conditions. NASA missions to the surfaces of Europa and other ocean worlds bodies will be exposed to temperatures as low as -180 °C and radiation levels that are at megarad levels. Operation in permanently shadowed craters on the Moon is also a region of particular interest. In addition, NASA missions to the Venus surface and deep atmospheric probes to Jupiter or Saturn will be exposed to high temperatures, high pressures, and chemically corrosive environments.

Current state-of-practice for development of space systems for the above missions is to place hardware developed with conventional technologies into bulky and power-inefficient environmentally protected housings. The use of environmental-protection housing will severely increase the mass of the space system and limit the life of the mission and the corresponding science return. This solicitation seeks to change the state of the practice by support technologies that will enable development of lightweight, highly efficient systems that can readily survive and operate in these extreme environments without the need for the environmental protection systems.

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

**Relevance / Science Traceability**

Relevance to SMD (Science Mission Directorate) is high.

Low-temperature survivability is required for surface missions to Titan (-180 °C), Europa (-220 °C), Ganymede (-200 °C), small bodies, and comets. Mars diurnal temperatures range from -120 °C to +20 °C. For the Europa Clipper baseline concept with a mission life of 10 years, the radiation environment is estimated at 2.9 Mrad TID behind 0.1-in-thick aluminum. Lunar equatorial region temperatures swing from -180 °C to +130 °C during the lunar day/night cycle, and shadowed lunar pole temperatures can drop to -230 °C.

Advanced technologies for high-temperature systems (electronic, electromechanical, and mechanical) and pressure vessels are needed to ensure NASA can meet its long-duration (days instead of hours) life target for its science missions that operate in high-temperature and high-pressure environments.

**References**


Proceedings of the meetings of the Venus Exploration Analysis Group (VEXAG): [https://www.lpi.usra.edu/vexag/][102]

Proceedings of the meetings of the Outer Planet Assessment Group (OPAG): [https://www.lpi.usra.edu/opag/][103]
S13.04 Contamination Control and Planetary Protection

Lead Center: JPL

Participating Center(s): GSFC

Scope Title:

Contamination Control (CC) and Planetary Protection (PP) Implementation and Verification

Scope Description:

The CC and PP subtopic develops new technologies or supports new applications of existing technologies to clean spacecraft, instrumentation, or hardware, while assessing for molecular and biological contaminants to improve NASA's ability to prevent forward and backward contamination.

CC prevents the degradation of the performance of space systems due to particulate and molecular contamination. For CC efforts, understanding and controlling particulate and molecular contaminants supports the preservation of sample and science integrity and ensures spacecraft function nominally. NASA is seeking analytical and physics-based modeling technologies and techniques to quantify and validate submicron particulate contamination; low-energy surface material coatings to prevent contamination; modeling and analysis of particles and molecules to ensure hardware and instrumentation meet organic contamination requirements; and improved technologies for the detection and verification of low levels of organic compounds on spacecraft surfaces.

PP prevents forward and backward contamination to protect planetary bodies, including the Earth, during responsible exploration. Forward contamination is the transfer of viable organisms and bacterial endospores from Earth to another planetary body. Backward contamination is the transfer of biological material, with the potential to cause harm, from a planetary body to Earth's biosphere. Understanding potential CC and PP contaminants and preventing the contamination of our spacecraft and instruments in general also supports the integrity of NASA sample science and mitigates other potential impacts to spacecraft function.

NASA is seeking innovative approaches to address these challenges through:

- Improvements to spacecraft cleaning and sterilization that are compatible with spacecraft materials and assemblies.
- Prevention of recontamination and cross contamination throughout the spacecraft lifecycle.
- Advanced technologies for the detection and verification of organic compounds and biologicals on spacecraft, specifically for microbial detection and assessments for viable organism and deoxyribonucleic-acid- (DNA-) based verification technologies and that may encompass sampling devices, sample processing, and sample analysis pipelines.
- Active in situ recontamination/decontamination approaches (e.g., in situ heating of sample containers to drive off volatiles prior to sample collection) and in situ/in-flight sterilization approaches (e.g., UV or plasma) for surfaces.
- Development of analytical and modeling-based methodologies to address bioburden and probabilistic risk assessment biological parameters to be used as alternatives to demonstrate requirement compliance.
- Enabling end-to-end sample return functions to ensure containment and pristine preservation of materials gathered on NASA missions (e.g., development of technologies that support in-flight verification of sample containment or in-flight correctable sealing technologies).

Examples of outcomes:

- End-to-end microbial reduction/sterilization technology for larger spacecraft subsystems.
- Microbial reduction/sterilization technology for spacecraft components.
- Ground-based biological contamination/recontamination mitigation system that can withstand spacecraft assembly and testing operations.
- In-flight spacecraft component-to-component cross-contamination mitigation system.
- Spacecraft sterilization systems for target body ground operations.
- Viable organism and/or DNA sample collection devices, sample processing (e.g., low biomass extraction), and sample analysis (e.g., bioinformatics pipelines for low biomass).
- Real-time, rapid device for detection and monitoring of viable organism contamination on low-biomass surfaces or in cleanroom air.
- Bioburden spacecraft cleanliness monitors for assessing surface cleanliness throughout flight and surface operations during missions.
- DNA-based system to elucidate abundance, diversity, and planetary protection relevant functionality of microbes present on spacecraft surfaces.
- An applied molecular identification technology to tag/label biological contamination on outbound spacecraft.
- Molecular mapping and detection technology for organic contamination on outbound and returned spacecraft and spaceflight hardware.
- Low surface area energy coatings.
- Molecular adsorbers ("getters").
- Technologies to assess human contamination vectors and safety for missions traveling to the Earth’s Moon and human missions traveling to Mars.
- Experimental technologies for measurement of outgassing rates lower than $1.0 \times 10^{-15}$ g/cm²/sec with mass spectrometry, under flight conditions (low and high operating temperatures) and with combined exposure to natural environment (e.g., high-energy radiation, ultraviolet radiation, atomic oxygen exposure).
- Physics-based technologies for particulate and molecular transport modeling and analysis for complex geometries with moving elements (e.g., rotating solar arrays, articulating robotic arms) in continuum, rarefied, and molecular flow environments, with additional physics (e.g., electrostatic, vibro-acoustic, particle detachment and attachment capabilities).
- A ground-based containment system that protects the Earth from restricted Earth-return samples, protects the samples from terrestrial contamination and allows for hardware manipulation and preliminary characterization of samples (e.g., double-walled isolators).

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

2 to 6

**Primary Technology Taxonomy:**

Level 1: TX 07 Exploration Destination Systems
Level 2: TX 07.3 Mission Operations and Safety

**Desired Deliverables of Phase I and Phase II:**

- Research
- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description:**

- Phase I deliverable: As relevant to the proposed effort—proof-of-concept study for the approach to include data validation and modeling.
- Phase II deliverable: As relevant to the proposed effort—detailed modeling/analysis or prototype for testing.
Areas to consider for deliverables: technologies, approaches, techniques, models, and/or prototypes, including accompanying data validation reports and modeling code demonstrating how the product will enable spacecraft compliance with PP and CC requirements.

State of the Art and Critical Gaps:

PP state of the art encompasses technologies from the 1960s to 1970s Viking spacecraft assembly and test era along with some more recent advancements in sterilization and sampling technologies. The predominant means to control biological contamination on spacecraft surfaces is to use some combination of heat microbial reduction processing and mechanical removal via solvent cleaning processes (e.g., isopropyl alcohol cleaning). Notably, vapor hydrogen peroxide is a NASA-approved process, but the variability of the hydrogen peroxide concentration, delivery mechanism, and material compatibility concerns still tends to be a hurdle to infuse it on a flight mission with complex hardware and multiple materials for a given component. Upon microbial reduction, during spacecraft integration and assembly, the hardware then is protected in a cleanroom environment (ISO 8 or better) using protective coverings when hardware is not being assembled or tested. For example, terminal sterilization has been conducted with recontamination prevention for in-flight biobarriers employed for the entire spacecraft (Viking) or a spacecraft subsystem (Phoenix spacecraft arm). In addition to the hardware approaches developed for compliance, environmental assessments are implemented to understand recontamination potential for cleanroom surfaces and air. Biological cleanliness is then verified through the NASA standard assay, which is a culture-based method. Although the NASA standard assay is performed on the cleanroom surfaces, DNA-based methodologies have been adopted by some spaceflight projects to include 16S and 18S ribosomal-ribonucleic-acid- (rRNA-) targeted sequencing, with metagenomic approaches currently undergoing development. Rapid cleanliness assessments can be performed, but are not currently accepted as a verification methodology, to inform engineering staff about biological cleanliness during critical hardware assembly or tests that include the total adenosine triphosphate (tATP) and limulus amoebocyte lysate (LAL) assays. Variability in detector performance thresholds in the low biomass limit remain a hurdle in the infusion of ATP luminometers for spaceflight verification and validation. Moreover, with recent missions leveraging probabilistic modeling for biological contamination, modeling has become a key tool in demonstrating compliance and helping to drive biological assurance cases for spacecraft cleanliness. Given the complexity of upcoming missions, this is rapidly becoming an emerging need in the discipline to help define parameters and develop upstream models for understanding biological cleanliness, distributions of biological contamination, behaviors of these biologicals on spacecraft surfaces, transport models, etc. In summary, the critical PP gaps include the assessment of DNA from low-biomass surfaces (<0.1 ng/µL DNA, using current technologies, from 1 to 5 m² of surface); sampling devices that are suitable for reproducible (at a certification level) detection of low biomass and compounds (e.g., viable organisms, DNA) but also compliant with spaceflight environmental requirements (e.g., cleanroom particulate generation, electrostatic discharge limits); quantification of the widest spectrum of viable organisms; enhanced microbial reduction/sterilization modalities that are compatible with flight materials and ground-/flight-/planetary-body-based recontamination prevention/mitigation systems.

CC requirements and practices are also evolving rapidly as mission science objectives targeting detection of organics and life are driving stricter requirements and improved characterization of flight-system- and science-instrument-induced contamination. State-of-the-art CC includes:

- Testing and measurement of outgassing rates down to 3.0×10^{-15} g/cm²/sec with mass spectrometry, under flight conditions (low and high operating temperatures) and with combined exposure to natural environment (high-energy radiation, ultraviolet radiation, atomic oxygen exposure).
- Particulate and molecular transport modeling and analysis for forward contamination scenarios of simple and complex spacecraft geometries with electrostatic, vibro-acoustic, particle detachment and attachment capabilities in continuum, rarefied, and molecular flow environments.
- Modeling and analysis of particulate flux for assessment of backward contamination scenarios using dynamic approaches (e.g., direct simulation Monte Carlo (DSMC) and Bhatnagar–Gross–Krook (BGK) formulations).

Relevance / Science Traceability:
With increased interest in investigating bodies with the potential for life detection such as Europa, Enceladus, Mars, and maybe other bodies, and the potential for sample return from such bodies, there is increased need for novel technologies associated with planetary protection and contamination control. The development of such technologies would enable missions to be able to be responsive to PP and CC requirements as they would be able to assess viable organisms and other particulate and organic contaminants; establish microbial reduction and protective technologies to achieve acceptable microbial bioburden and organic contamination levels for sensitive life detection in spacecraft and instruments to mitigate risk and inadvertent “false positives”; ensure compliance with sample return planetary protection and science requirements; and support model-based assessments of planetary protection requirements for biologically sensitive missions (e.g., outer planets and sample return).

References:

1. Planetary Protection: https://planetaryprotection.nasa.gov/ [104]
2. JPL Planetary Protection Center of Excellence: https://planetaryprotection.jpl.nasa.gov/ [105]


S13.05 In Situ Instruments/Technologies for Lunar and Planetary Science

Lead Center: JPL

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

Scope Title:

In- Situ Instruments/ Technologies for Planetary Science

Scope Description:

This subtopic solicits development of advanced instrument technologies and components suitable for deployment on in situ planetary and lunar missions. These technologies must be capable of withstanding operation in space and planetary environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance—for both conventional missions as well as for small-satellite missions. In addition, technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are solicited. For examples of NASA science missions, see https://science.nasa.gov/missions-page [107]. For details of the specific requirements see the National Research Council report "Vision and Voyages for Planetary Science in the Decade 2013-2022" (http://solarsystem.nasa.gov/2013decadal/ [92], hereafter referred to as the Planetary Decadal Survey). Of particular interest are technologies to support future missions under the New Frontiers and Discovery programs.

Specifically, this subtopic solicits instrument development that provides significant advances in the following areas, broken out by planetary body:

- Mars:
  - Subsystems relevant to current in situ instrument needs (e.g., lasers and other light sources from UV to microwave, x-ray and ion sources, detectors, mixers, mass analyzers, and front-end ion/neutrals separation/transport technologies, etc.) or electronics technologies (e.g., field-
programmable gate array (FPGA) and application-specific integrated circuit (ASIC) implementations, advanced array readouts, miniature high-voltage power supplies).

- Technologies that support high precision in situ measurements of the elemental, mineralogical, and organic composition of planetary materials.
- Conceptually simple, low-risk technologies for in situ sample extraction and/or manipulation including fluid and gas storage, pumping, and chemical labeling to support analytical instrumentation.
- Seismometers, mass analyzers, technologies for heat flow probes, and atmospheric trace gas detectors. Improved robustness and g-force survivability for instrument components, especially for geophysical network sensors, seismometers, and advanced detectors (intensified charge-coupled devices (iCCDs), photomultiplier tube (PMT) arrays, etc.).
- Instruments geared towards rock/sample interrogation prior to sample return. Sensors to measure dimensions of laser ablation pits in natural rock samples with unprepared rough surfaces to support geochronology measurements on rock samples collected by a rover (spatial and depth resolution of 10 µm or better from a working distance of tens of centimeters desired to characterize ~1-mm-deep by ~0.5-mm-wide pits).
- Technologies, concepts, or components related to active source imaging systems (e.g., light detection and ranging; lidar) for accurate and precise mobile 3D terrain mapping and navigation, with additional sensor capabilities such as velocimetry.

- **Venus:**
  - Sensors, mechanisms, and environmental chamber technologies for operation in Venus's high-temperature, high-pressure environment with its unique atmospheric composition.
  - Approaches that can enable precision measurements of surface mineralogy and elemental composition and precision measurements of trace species, noble gases, and isotopes in the atmosphere.

- **Small bodies:**
  - Technologies that can enable sampling from asteroids, and from within comet nuclei to provide improved *in situ* analysis of comets.
  - Imagers and spectrometers that provide high performance in low-light environments.
  - Dust environment measurements and particle analysis, small-body resource identification, and/or quantification of potential small-body resources (e.g., oxygen, water, and other volatiles; hydrated minerals; carbon compounds; fuels; metals; etc.).
  - Advancements geared toward instruments that enable elemental or mineralogy analysis (such as high-sensitivity x-ray and UV-fluorescence spectrometers, UV-fluorescence systems, scanning electron microscopy with chemical analysis capability, mass spectrometry, gas chromatography and tunable diode laser sensors, calorimetry, imaging spectroscopy, and laser-induced breakdown spectroscopy (LIBS)).

- **Saturn, Uranus, and Neptune and their moons:**
  - Components, sample acquisition, and instrument systems that can enhance mission science return and withstand the low temperatures/high pressures of the atmospheric probes during entry. Note that in situ instruments and components focused on ocean worlds life detection are specifically solicited in S13.06 and are encouraged to be submitted to S13.06.

- **The Moon:**
  - This topic seeks advancement of concepts and components to develop a Lunar Geophysical Network as envisioned in the Planetary Decadal Survey. Understanding the distribution and origin of both shallow and deep moonquakes will provide insights into the current dynamics of the lunar interior and its interplay with external phenomena (e.g., tidal interactions with Earth). The network is envisioned to comprise multiple free-standing seismic stations that would operate over many years in even the most extreme lunar temperature environments.
  - Technologies to advance all aspects of the network including sensor emplacement, power, and communications in addition to seismic, heat flow, magnetic field and electromagnetic sounding sensors are desired.
  - This topic also seeks technologies for quantifying lunar water and measuring the D/H ratio in lunar water. Much evidence points to the presence of water ice at cold spots in the permanently shadowed regions at the lunar poles, with estimated abundance of ~5 to 10 wt%.
  - Technologies, concepts, or components related to active source (e.g., lidar) imaging systems for accurate and precise mobile 3D terrain mapping and navigation in lunar South Pole regions with extreme solar incidence conditions (e.g., long persistent shadows and direct solar interference), extreme lunar temperature variation, velocimetry, and with low size, weight, and power (SWaP) and
solid-state or minimal moving parts.

- General to Mars, Venus, Small bodies, Saturn and Uranus and Neptune and their moons, and the Moon:
  - Development of mass spectrometer front ends utilizing ion and acoustophoretic guides for a wide range of ions and macromolecules; Miniaturization of mass spectrometers by developing low-loss resonant inductive radio-frequency (RF) tanks at minimized volume and utilization of microelectromechanical system (MEMS) processes.

Novel instrument concepts are encouraged particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired. Proposers should show an understanding of relevant space science needs and present a feasible plan to fully develop a technology and infuse it into a NASA mission.

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

**Primary Technology Taxonomy:**

Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

**Desired Deliverables of Phase I and Phase II:**

- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description:**

The Phase I project should focus on feasibility and proof-of-concept demonstration (TRL 2-3). The required Phase I deliverable is a report documenting the proposed innovation, its status at the end of the Phase I effort, and the evaluation of its strengths and weaknesses compared to the state of the art. The report can include a feasibility assessment and concept of operations, simulations and/or measurements, and a plan for further development to be performed in Phase II.

The Phase II project should focus on component and/or breadboard development with the delivery of specific hardware for NASA (TRL 4-5). Phase II deliverables include a working prototype of the proposed hardware, along with documentation of development, capabilities, and measurements.

**State of the Art and Critical Gaps:**

In situ instruments and technologies are essential bases to achieve Science Mission Directorate's (SMD's) planetary science goals summarized in the Planetary Decadal Survey. In situ instruments and technologies play an indispensable role for NASA’s New Frontiers and Discovery missions to various planetary bodies (Mars, Venus, small bodies, Saturn, Uranus, Neptune, Moon, etc.).

There are currently various in situ instruments for diverse planetary bodies. However, there are ever-increasing science and exploration requirements and challenges for diverse planetary bodies. For example, there is urgent need for exploring RSL (recurring slope lineae) on Mars and plumes from planetary bodies, as well as a growing demand for in situ technologies amenable to small spacecraft.

To narrow the critical gaps between the current state of art and the technology needed for the ever-increasing science/exploration requirements, in situ technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities with lower mass, power, and volume.

**Relevance / Science Traceability:**

In situ instruments and technologies are essential bases to achieve the Science Mission Directorate's (SMD's) planetary science goals summarized in the Planetary Decadal Survey. In situ instruments and technologies play an
indispensable role for NASA’s New Frontiers and Discovery missions to various planetary bodies.

In addition to Phase III opportunities, SMD offers several instrument development programs as paths to further development and maturity. These include the Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) Program, which invests in low-TRL technologies and funds instrument feasibility studies, concept formation, proof-of-concept instruments, and advanced component technology, as well as the Maturation of Instruments for Solar System Exploration (MatISSE) Program and the Development and Advancement of Lunar Instrumentation (DALI) Program, which invest in mid-TRL technologies and enable timely and efficient infusion of technology into planetary science missions.

References:


S13.06 In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection

Lead Center: JPL

Participating Center(s): ARC, GRC, GSFC

Scope Title:

In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection

Scope Description:

This subtopic solicits development of in situ instrument technologies and components to advance the maturity of science instruments and plume sample collection systems focused on the detection of evidence of life, especially extant life, in the ocean worlds (e.g., Europa, Enceladus, Titan, Ganymede, Callisto, Ceres, etc.). Technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are of particular interest. Technologies that allow collection during high-speed (>1 km/sec) passes through a plume are solicited as are technologies that can maximize total sample mass collected while passing through tenuous plumes. This fly-through sampling focus is distinct from S13.01, which solicits sample collection technologies from surface platforms.

These technologies must be capable of withstanding operation in space and planetary environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance.

Specifically, this subtopic solicits instrument technologies and components that provide significant advances in the following areas, broken out by planetary body:

- General to Europa, Enceladus, Titan, and other ocean worlds:
Technologies and components relevant to life detection instruments (e.g., microfluidic analyzer, microelectromechanical systems (MEMS) chromatography/mass spectrometers, laser-ablation mass spectrometer, fluorescence microscopic imager, Raman spectrometer, tunable laser system, liquid chromatography/mass spectrometer, x-ray fluorescence spectrometer, digital holographic microscope-fluorescence microscope, antibody microarray biosensor, nanocantilever biodetector, etc.). Technologies for high-radiation environments (e.g., radiation mitigation strategies, radiation-tolerant detectors, and readout electronic components), which enable orbiting instruments to be both radiation hard and undergo the planetary protection requirements of sterilization (or equivalent).

Collecting samples for a variety of science purposes is also sought. These include samples that allow for determination of the chemical and physical properties of the source ocean, samples for detailed characterization of the organics present in the gas and particle phases, and samples for analysis for biomarkers indicative of life. Front-end system technologies include sample collection systems and subsystems capable of capture, containment, and/or transfer of gas, liquid, ice, and/or mineral phases from plumes to sample processing and/or instrument interfaces. This includes cold double-walled isolators for sample manipulation at –80 °C and Biohazard Safety Level (BSL)-4 conditions.

Technologies for characterization of collected sample parameters including mass, volume, total dissolved solids in liquid samples, and insoluble solids. Sample collection and sample capture for in situ imaging. Sampling mechanisms and/or containers capable of gas-solid separation or venting water to space (concentration, lyophilization) without altering the sample, including weighing ice samples to measure mass loss under vacuum, cold, microgravity conditions. Systems capable of high-velocity sample collection with minimal sample alteration to allow for habitability and life detection analyses. Microfluidic sample collection systems that enable sample concentration and other manipulations. Plume material collection technologies that minimize risk of terrestrial contamination, including organic chemical and microbial contaminants. These technologies would enable high-priority sampling and potential sample return from the plumes of Enceladus with a fly-by mission. This would be a substantial cost savings over a landed mission.

- Europa: Life detection approaches optimized for evaluating and analyzing the composition of ice matrices with unknown pH and salt content. Instruments capable of detecting and identifying organic molecules (in particular biomolecules), salts, and/or minerals important to understanding the present conditions of Europa's ocean are sought (such as high-resolution gas chromatograph or laser desorption mass spectrometers, dust detectors, organic analysis instruments with chiral discrimination, etc.). These developments should be geared towards analyzing and handling very small sample sizes (microgram to milligram) and/or low column densities/abundances. Also of interest are imagers and spectrometers that provide high performance in low-light environments (visible and near-infrared (NIR) imaging spectrometers, thermal imagers, etc.), as well as instruments capable of improving our understanding of Europa’s habitability by characterizing the ice, ocean, and deeper interior and monitoring ongoing geological activity such as plumes, ice fractures, and fluid motion (e.g., seismometers, magnetometers). Improvements to instruments capable of gravity (or other) measurements that might constrain properties such as ocean and ice shell thickness will also be considered.

- Enceladus (including plume material and E-ring particles): Life detection approaches optimized for analyzing plume particles as well as for determining the chemical state of Enceladus icy surface materials (particularly near plume sites). Instruments capable of detecting and identifying organic molecules (in particular biomolecules), salts, and/or minerals important to understand the present conditions of the Enceladus ocean are sought (such as high-resolution gas chromatograph or laser desorption mass spectrometers, dust detectors, organic analysis instruments with chiral discrimination, etc.). These developments should be geared towards analyzing and handling very small sample sizes (microgram to milligram) and/or low column densities/abundances. Also of interest are imagers and spectrometers that provide high performance in low-light environments (visible and NIR imaging spectrometers, thermal imagers, etc.), as well as instruments capable of monitoring the bulk chemical composition and physical characteristics of the plume (density, velocity, variation with time, etc.). Improvements to instruments capable of gravity (or other) measurements that might constrain properties such as ocean and ice shell thickness will also be considered.

- Titan and other ocean worlds targets, which may include Ganymede, Callisto, Ceres, etc. (1) Life detection approaches optimized for searching for biosignatures and biologically relevant compounds in Titan's lakes, including the presence of diagnostic trace organic species, and also for analyzing Titan's complex aerosols and surface materials, are needed. (2) Mechanical and electrical components and subsystems that work in cryogenic (95 K) environments, sample extraction from liquid methane/ethane, sampling from organic
"dunes" at 95 K, and robust sample preparation and handling mechanisms that feed into mass analyzers are sought. (3) Balloon instruments such as IR spectrometers, imagers, meteorological instruments, radar sounders, solid, liquid, and air sampling mechanisms for mass analyzers, and aerosol detectors are solicited. (4) Low-mass and low-power sensors, mechanisms, and concepts for adapting terrestrial instruments such as turbidimeters and echo sounders for lake measurements, weather stations, surface (lake and solid) properties packages, etc., to cryogenic environments (95 K) are sought.

Proposers are strongly encouraged to relate their proposed development to:

- NASA's future ocean worlds exploration goals (see references).
- Existing flight instrument capability, to provide a comparison metric for assessing proposed improvements.

Proposed instrument architectures should be as simple, reliable, and as low risk as possible while enabling compelling science. Novel instrument concepts are encouraged, particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired.

Proposers should show an understanding of relevant space science needs, present a feasible plan to fully develop a technology, and infuse it into a NASA program.

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

**Primary Technology Taxonomy:**

Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.3 In-Situ Instruments/Sensor

**Desired Deliverables of Phase I and Phase II:**

- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description:**

The Phase I project should focus on feasibility and proof-of-concept demonstration (TRL 2-3). The required Phase I deliverable is a report documenting the proposed innovation, its status at the end of the Phase I effort, and the evaluation of its strengths and weaknesses compared to the state of the art. The report can include a feasibility assessment and concept of operations, simulations and/or measurements, and a plan for further development to be performed in Phase II.

The Phase II project should focus on component and/or breadboard development with the delivery of specific hardware for NASA (TRL 4-5). Phase II deliverables include a working prototype of the proposed hardware along with documentation of development, capabilities, and measurements.

**State of the Art and Critical Gaps:**

In situ instruments and technologies are essential to achieve NASA's ocean worlds exploration goals. There are currently some in situ instruments for diverse ocean worlds bodies. However, there are ever-increasing science and exploration requirements and challenges for diverse ocean worlds bodies. For example, there are urgent needs for the exploration of icy or liquid surfaces on Europa, Enceladus, Titan, Ganymede, Callisto, etc., and plumes from planetary bodies such as Enceladus.

To narrow the critical gaps between the current state of art and the technology needed for the ever-increasing science/exploration requirements, in situ technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities, and at the same time with lower resource (mass,
power, and volume) requirements.

Relevance / Science Traceability:

In situ instruments and technologies are essential to achieve Science Mission Directorate’s (SMD) planetary science goals summarized in the Decadal Study (National Research Council’s Vision and Voyages for Planetary Science in the Decade 2013-2022). In situ instruments and technologies play indispensable roles for NASA’s New Frontiers and Discovery missions to various planetary bodies.

NASA SMD has two programs to bring this subtopic technologies to higher level: PICASSO and MatISSE. The Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) Program invests in low-TRL technologies and funds instrument feasibility studies, concept formation, proof-of-concept instruments, and advanced component technology. The Maturation of Instruments for Solar System Exploration (MatISSE) Program invests in mid-TRL technologies and enables timely and efficient infusion of technology into planetary science missions. The PICASSO and MatISSE are in addition to Phase III opportunities.

References:

1. The NASA Roadmap for Ocean World Exploration: [http://www.lpi.usra.edu/opag/ROW](http://www.lpi.usra.edu/opag/ROW) [109]
2. In situ instruments and technologies for NASA’s ocean worlds exploration goals: [https://www.nasa.gov/specials/ocean-worlds/](https://www.nasa.gov/specials/ocean-worlds/) [95]

S13.07 Energy Storage for Extreme Environments

Lead Center: GRC

Participating Center(s): JPL

Scope Title

Energy Storage for Extreme Environments

Scope Description

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

Future science missions will require advanced primary and secondary battery systems capable of operating at temperature extremes and improved specific energy. Advancements to battery energy storage capabilities that address operation for one of the listed missions (Venus, deep space, or lunar) combined with high specific energy and energy density (cell-level goals: >250 Wh/kg and >500 Wh/L for secondary; >800 Wh/kg and >1,000 Wh/L for primary) are of interest. For deep space missions, operation to -200 °C and an operational duration of 30 to 60 days for environments such as Europa, Enceladus, and Titan are required. For Venus surface missions, operation
from 460 to 500 °C and an operational duration of 30 to 60 days are required. For lunar surface applications, operation at a temperature range of -230 to +120 °C and during 14-day eclipses for lunar night survival and operations are required. Novel battery-pack-level designs and technologies that enhance battery reliability and safety as well as support improved thermal management are also of interest. Combinations of cell-level improvements and/or battery-system-level improvement for enhanced temperature capability will be considered.

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

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

**Primary Technology Taxonomy**

**Level 1**
TX 03 Aerospace Power and Energy Storage

**Level 2**
TX 03.2 Energy Storage

**Desired Deliverables of Phase I and Phase II**
Prototype Research

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

**State of the Art and Critical Gaps**
State-of-the-art primary and rechargeable cells are limited in both capacity and temperature range. Typical primary Li-SO2 and Li-SOCl2 operate within a maximum temperature range of -40 to 80 °C but suffer from capacity loss, especially at low temperatures. At -40 °C, the cells will provide roughly half the capacity available at room temperature. Similarly, rechargeable Li-ion cells operate within a narrow temperature range of -20 to 40 °C and also suffer from capacity loss at lower temperatures. The lower limit of temperature range of rechargeable cells can be extended through the use of low-temperature electrolytes, but with limited rate capability and concerns about lithium plating on charge. There is currently a gap that exists for high-temperature batteries, primary and rechargeable, that can operate at Venus atmospheric temperatures. In addition, there is a gap in the ability to accurately predict or measure the amount of usable capacity of primary battery cells, particularly after a long mission cruise with exposure to varying temperatures and ionizing radiation dose. This solicitation is aimed at the development of cells that can maintain performance at extreme temperatures to minimize or eliminate the need for strict thermal management of the batteries (which adds complexity and mass to the spacecraft) as well as instrumentation or modeling to predict state of charge/state of health of primary batteries for deep space missions.

**Relevance / Science Traceability**
These batteries are applicable over a broad range of science missions. Low-temperature batteries are needed for potential NASA decadal missions to ocean worlds (Europa, Enceladus, Titan) and the icy giants (Neptune, Uranus). These batteries are also needed for science missions on the lunar surface. Low-temperature batteries developed under this subtopic would enhance these missions and could be potentially enabling if the missions are mass or volume limited. There is also significant interest in a Venus surface mission that will require primary and/or rechargeable batteries that can operate for 60+ days on the surface of Venus. A high-temperature battery that can meet these requirements is enabling for this class of missions.
References
NASA Science: https://science.nasa.gov/ [112]
Solar Electric Propulsion: https://www1.grc.nasa.gov/space/sep/ [113]

S14.01 Space Weather Research-to-Operations/Operations-to-Research (R2O/O2R) Technology Development

Lead Center: JPL

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

Scope Title
Space Weather Research-to-Operations/Operations-to-Research (R2O/O2R) Technology Development and Commercial Applications

Scope Description
Space weather has the potential to disrupt telecommunications; aircraft and satellite systems; electric power subsystems; and position, navigation, and timing services. Given the importance of these systems to our national well-being, NASA’s Heliophysics Division invests in activities to improve the understanding of these phenomena and to enable new monitoring, prediction, and mitigation strategies.

The national direction for this work is organized by the Space Weather Operations, Research, and Mitigation (SWORM) Working Group, which is a Federal interagency coordinating body organized under the Space Weather, Security, and Hazards (SWSH) Subcommittee. The SWSH is a part of the National Science and Technology Council (NSTC) Committee on Homeland and National Security, organized under the Office of Science and Technology Policy (OSTP). The SWORM coordinates Federal Government departments and agencies to meet the goals and objectives specified in the National Space Weather Strategy and Action Plan [114] (NSWSAP) and in the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow [115] (PROSWIFT) Act.

NASA’s role under the NSWSAP and PROSWIFT Act is to provide increased understanding of the fundamental physics of the Sun-Earth system through space-based observations and modeling, the development of new space-based space-weather technologies and missions, and through monitoring of space weather for NASA’s space missions. This includes research that advances operational and commercial space-weather science and technology.

This subtopic solicits new, enabling space-weather technologies as part of NASA’s response to these national objectives. While this subtopic will consider all concepts demonstrably related to NASA’s R2O/O2R responsibilities outlined in the NSWSAP, four areas have been identified for priority development (not in priority order):

(1) Space-weather forecasting technologies, techniques, and applications: Innovative technologies and techniques are solicited that explore and enable the transition of tools, models, data, and knowledge from research to operational environments. This includes the preparation and validation of existing science models that may be suitable for transition to operational use. Coordination with existing NASA capabilities, such as the Space Radiation Analysis Group (SRAG) at Johnson Space Center (JSC), the Community Coordinated Modeling Center (CCMC) at Goddard Space Flight Center (GSFC), and the Short-term Prediction Research and Transition (SPoRT) Center at Marshall Space Flight Center (MSFC), is appropriate and encouraged. Areas of special interest include, but are not limited to:

- Lunar space environment characterization tools that can be employed by NASA to enhance protection of crewed and uncrewed missions to cis-lunar and lunar surface missions.
- Specifications and/or forecasts of the energetic particle and plasma conditions encountered by spacecraft within Earth’s magnetosphere, as well as products that directly aid spacecraft anomaly resolution and
benefit end users such as spacecraft operators.

- Approaches that potentially lead to 2- to 3-day forecasts of atmospheric drag effects on satellites and improvement in the quantification of orbital uncertainties in low-Earth-orbit (LEO) altitude ranges (up to ~2,000 km).
- Techniques that enable the characterization and prediction of ionospheric variability that induces scintillations, which impact communication and global navigation and positioning systems.
- Longer range (2 to 3 days) forecasting of solar particle events (SPEs) and an improved all-clear, SPE-forecasting capability.

(2) Commercial and decision-making applications for space-weather technologies: Innovative techniques and solutions are solicited that extend to commercial entities the use of new technology and knowledge about space weather. The NSWSAP and the PROSWIFT Act specifically call out the need to test, evaluate, and deploy technologies and devices to mitigate the effects of space weather on communication systems, geomagnetic disturbances on the electrical power grid, or radiation events on satellites. In addition, the policy and legislation include the development of processes to improve the transition of research approaches to operations, to support operational partners, and to serve society. Proposals of interest could include, but are not limited to:

- Descriptions and development of standards and best practices to improve the resilience of equipment to space-weather events.
- Efforts to bridge the gap between heliophysics science and society; these proposals would apply NASA data to the decision-making process of an end user to improve life on Earth. This work will power innovative projects through the use in novel ways of NASA space-weather data and will support decision making by a diverse community of users that NASA may not frequently engage. Integrating NASA data into the decision-making process of a particular user or user community is important for this solicitation.
- A description of a decision that will be the focus of a project, how the organization currently makes that decision, and how NASA data will be integrated into and will benefit that process.

Of specific interest are non-operational applications (i.e., not NOAA or DoD) with nontraditional users (e.g., a user who has not used NASA data before). Success could be an organization using NASA space-weather data to inform a decision they make, so that the use of these data tangibly benefits the performance of the organization. Both commercial applications and noncommercial applications are of high interest and are encouraged.

(3) Space weather advanced data-driven discovery techniques: A particular challenge is to combine the sparse, vastly distributed data sources available with realistic models of the near-Earth space environment. Data assimilation and other cutting-edge, data-driven discovery innovations are solicited that enable tools and protocols for the operational space-weather community. Priority will be given to proposals that:

- Develop data assimilation space-weather applications or technologies desired by established space-weather operational organizations.
- Integrate data from assets that typically do not share similar time series, utilize different measurement techniques (e.g., imaging vs. in situ particles and fields), or are distributed throughout the heliosphere.
- Provide new data-driven operational forecasting tools that can be straightforwardly validated by the CCMC or another equally robust validation methodology.
- Integrate underutilized, unexplored, or nontraditional resources.

Many existing or planned commercial constellations may include useful space-weather-exploitable data (e.g., iridium system magnetometer data or space-based radio occultation for ionospheric specification). Other possible data sources are global-navigation-satellite-system- (GNSS-) equipped constellations (for total electron content (TEC) and/or drag information) and imaging constellations (tapping into unused nighttime observations of aurorae).

(4) Space Weather Instrumentation: Heliophysics science relies on a wide variety of instrumentation for its research and often makes its data available in near real time for space-weather forecasting purposes. Ideas are solicited for instrument concepts, flight architectures, and reporting systems that enable enhanced, more informative, robust, and effective measurements for space-weather monitoring and forecasting systems. Opportunities for improving measurements include increased spatial and temporal resolution, fidelity, promptness, and measurement-system reliability. This includes the miniaturization of existing systems and/or technologies deployable as an array of CubeSats. To be considered for investment, SBIR technologies should demonstrate comparable, or better,
precision and accuracy when compared to the current state of the art. Further, SBIR instrument designs should avoid duplicating current NASA research spacecraft arrays or detector systems, including those currently in formulation or development, such as, but not limited to Interstellar Mapping and Acceleration Probe (IMAP), Geospace Dynamics Constellation (GDC), Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC), Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI), Explorer concepts, Advanced Composite Solar Sail System (ACS3), Heliophysics Environmental and Radiation Measurement Experiment Suite (HERMES), Solar Cruiser, and Global Lyman-alpha Imagers of the Dynamic Exosphere (GLIDE).

Proposals must demonstrate an understanding of the current state of the art, describe how the proposed innovation is superior, and provide a feasible plan to develop the technology and infuse into a specific activity listed within the NSWSAP and the PROSWIFT Act.

**Expected TRL or TRL Range at completion of the Project**

3 to 8

**Primary Technology Taxonomy**

**Level 1**

TX 11 Software, Modeling, Simulation, and Information Processing

**Level 2**

TX 11.X Other Software, Modeling, Simulation, and Information Processing

**Desired Deliverables of Phase I and Phase II**

- Prototype
- Hardware
- Software

**Desired Deliverables Description**

Space weather is a broad umbrella encompassing science, engineering, applications, and operations. The goal of this SBIR is to generate products or services (“deliverables”) that enable end-user action. The deliverables can be applied, for example, to space-weather hazard assessments, real-time situational awareness, or to plan protective mitigation actions. Deliverables can be in the form of new data, new techniques, new instrumentation, and/or predictive models that are prepared/validated for transition into operations:

- Phase I deliverables are proof-of-concept data and/or detailed technique, instrument, or model development plans that have sufficient fidelity to assess technical, management, cost, and schedule risk. Phase I deliverables should also delineate the scope and benefit of the proposed products that could be realized as a result of Phase II and what further scope and benefit necessarily requires further development after Phase II.
- Phase II deliverables are functioning prototype versions of the proposed technologies that have been tested in a realistic environment or within a standard space-weather-community development and validation framework. The extent of the prototype development and testing will vary with the technology and will be evaluated as part of the Phase II proposal. Phase II deliverables should also include/delineate any further work that would be required to bring the technologies to full operational and commercial use.

**State of the Art and Critical Gaps**

- We do not yet know how to predict what phenomena need to be predicted.
- We do not yet know how quantitatively good/bad our operational capabilities (metrics) are.
• Mechanisms do not yet exist to enable a broad range of the community to participate in the improvement of operational models.
• The research environment advances understanding rather than the improvement of operational products.

Space weather poses a constant threat to the Nation’s critical infrastructure, our satellites in orbit, and our crewed and uncrewed space activities. Extreme space-weather events can cause substantial harm to our Nation’s security and economic vitality. Preparing for space-weather events is an important aspect of American resilience that bolsters national and homeland security, and facilitates continued U.S. leadership in space. A robust space-weather program and its associated forecasting capabilities are essential for NASA’s future exploration success.

Relevance / Science Traceability

This SBIR subtopic enables NASA to demonstrate progress against NASA Goal 1.4: Understand the Sun and its interactions with Earth and the solar system, including space weather.

These applied research projects directly address NASA's role within the SWORM Working Group, which is a Federal interagency coordinating body organized under the SWSH Subcommittee. The SWSH is a part of the NSTC Committee on Homeland and National Security, organized under the OSTP. The SWORM coordinates Federal Government departments and agencies to meet the goals and objectives specified in the NSWSAP and in the PROSWIFT Act.

The Heliophysics Space Weather Science Application (SWxSA) establishes an expanded role for NASA in space-weather science under a single element, consistent with the recommendation of the National Research Council (NRC) Decadal Survey and the OSTP/SWORM 2019-NSWSAP. SWxSA competes ideas and products, leverages existing agency capabilities, collaborates with other agencies, and fosters partnership with user communities. SWxSA is distinguishable from other Heliophysics research elements in that it is specifically focused on investigations that significantly advance understanding of space weather; this progress is applied to enable more accurate characterization and predictions with longer lead time. The Heliophysics Living With a Star (LWS) Program has established a path forward to meet NASA’s obligations to the research relevant to space weather and is a significant source of input to SWxSA. Further involvement by the emerging Heliophysics space-weather commercial community has the potential to significantly advance the space-weather application obligations portion of the mandate.

Astronauts in Earth orbit are not protected by the Earth's atmosphere and are exposed to space radiation such as galactic cosmic rays and solar-energetic particles. Further, when astronauts travel outside Earth's magnetosphere, they are exposed to even more radiation. A robust space-weather program and associated forecasting capabilities is essential for NASA's future exploration success.

References

Public Law 116-181—Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act [115]: The Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act was signed into law October 21, 2020. This law establishes the policy of the United States to protect its citizens from the effects of space weather on in-space resources and ground-based infrastructure by supporting space-weather research to include forecasts and predictions. Using a strategy of interagency collaboration, within and outside the Federal Government to include international partners, the PROSWIFT Act seeks to ameliorate social and financial impacts of space-weather events to society.

Executive Order 13744 – Coordinating Efforts to Prepare the Nation for Space Weather Events [116] describes the policy of the United States with respect to preparations for space-weather events so that economic loss and human hardship will be minimized.

The SWORM Working Group [117] is a Federal interagency coordinating body organized under the SWSH Subcommittee. The SWSH is a part of the NSTC Committee on Homeland and National Security, organized under the OSTP. The SWORM coordinates Federal Government departments and Agencies to meet the goals and objectives specified in the National Space Weather Strategy and Action Plan released in March 2019.

National Space Weather Strategy and Action Plan [114]: The White House Executive OSTP released the NSWSAP on March 26th, 2019, during the National Space Council meeting in Huntsville, Alabama. This strategy
and action plan is an update to the original NSWSAP, released in October 2015.

Space Weather Phase 1 Benchmarks [118] is a document created by the SWORM subcommittee, and the benchmarks describe a space-weather event’s ability to affect the United States. The purpose of the benchmarks is to provide input for creating engineering standards, to develop risk assessments and estimates, establish thresholds for action, develop mitigation procedures, and enhance planning for response and recovery.

An Executive Order (EO) on Coordinating National Resilience to Electromagnetic Pulses (EMPs) [119] was released by the White House on March 26, 2019. The EO identifies the disruptive impacts an EMP has on technology and critical infrastructure systems, whether the EMP is human made or naturally occurring. The EO outlines how the Federal Government will prepare for and mitigate the effects of EMPs by an efficient and cost-effective approach.

S14.02 Particle and Field Sensors and Instrument-Enabling Technologies

Lead Center: JPL
Participating Center(s): MSFC

Scope Title

Particles and Fields Sensors and Instrument Enabling Technologies

Scope Description

The 2013 National Research Council's "Solar and Space Physics: A Science for a Technological Society" motivates this subtopic: “Deliberate investment in new instrument concepts is necessary to acquire the data needed to further solar and space physics science goals, reduce mission risk, and maintain an active and innovative hardware development community.” This subtopic solicits development of advanced in situ instrument technologies and components suitable for deployment on heliophysics missions. Advanced sensors for the detection of neutral and ionized gases (atoms, molecules, and ions) and their motions (winds and ion drifts); energetic particles (electrons and ions), including their energy distribution and pitch angles; thermal plasma populations, including their temperature; and direct current (DC) and wave electric and magnetic fields in space along with associated instrument technologies are often critical for enabling transformational science from the study of the Sun's outer corona, to the solar wind, to the trapped radiation in Earth's and other planetary magnetic fields, and to the ionospheric and upper atmospheric composition of the planets and their moons.

These technologies must be capable of withstanding operation in space environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures. Technology developments that result in a reduction of mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance. In addition, technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are solicited.

Improvements in particle and field sensors and associated instrument technologies enable further scientific advancement for upcoming NASA missions such as CubeSats, Explorers, Solar Terrestrial Probe (STP), Living With a Star (LWS), and planetary exploration missions. Specifically, this year the subtopic solicits instrument development that provides significant advances in the following areas:

- Compactly stowed, lightweight, long, straight, and rigid booms, magnetically clean, that can deploy a sensor with embedded electronics to distances of 2 m or longer on CubeSat and SmallSat constellations in order to measure DC magnetic fields.
- Compactly stowed, lightweight, long, straight, and rigid booms that can deploy a sensor with embedded electronics to distances of 6 m or longer on satellites and sounding rockets in order to measure DC electric
fields and plasma waves. Mass target: 1 kg or less.

- Solar-blind solid-state detectors (SSDs) for direct solar viewing energetic particle detection. The SSDs should be able to handle the intense ultraviolet (UV) and visible solar radiation without saturation, with low noise while addressing thermal issues. Typically, a metalized foil is used for UV suppression, but this gives an energy threshold of 1 MeV or more. The target energy threshold for the SSD is ~50 keV or lower with the upper energy range in the several to tens of megaelectronvolts. Pushing the threshold down will increase performance and reduce cost over the current instrument designs.
- Rapid electrostatic analyzer production/high-tolerance assembly for plasma instruments. This will be especially useful for multiple instrument production for constellation missions.

Expected TRL or TRL Range at completion of the Project

2 to 4

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II

- Prototype
- Hardware

Desired Deliverables Description

Phase I deliverables: Concept study report, preliminary design, and test results.

Phase II deliverables: Detailed design, prototype test results, and a prototype deliverable with guidelines for in-house integration and test (I&T).

State of the Art and Critical Gaps

- Compactly stowed, lightweight, long, straight, and rigid booms, magnetically clean, that can deploy a sensor with embedded electronics to distances of 2 m or longer on CubeSat and SmallSat constellations in order to measure DC magnetic fields.
- Compactly stowed, lightweight, long, straight, and rigid booms that can deploy a sensor with embedded electronics to distances of 6 m or longer on satellites and sounding rockets in order to measure DC electric fields and plasma waves. Mass target: 1 kg or less.
- Solar-blind SSDs for direct solar viewing energetic particle detection. The SSDs should be able to handle the intense UV and visible solar radiation without saturation, with low noise while addressing thermal issues. Typically, a metalized foil is used for UV suppression, but this gives an energy threshold of 1 MeV or more. The target energy threshold for the SSD is ~50 KeV or lower with the upper energy range in the several to tens of megaelectronvolts. Pushing the threshold down will increase performance and reduce cost over the current instrument designs.
- Rapid electrostatic analyzer production/high-tolerance assembly for plasma instruments. This will be especially useful for multiple instrument production for constellation missions.

Relevance / Science Traceability

Particle and field instruments and technologies are essential bases to achieve the Science Mission Directorate's (SMD's) Heliophysics goals summarized in the National Research Council's, Solar and Space Physics: A Science
for a Technological Society. In situ instruments and technologies play indispensable roles for NASA’s LWS and STP mission programs, as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for particle and field technologies amenable to CubeSats and SmallSats. NASA SMD has two excellent programs to bring this subtopic technologies to higher level: Heliophysics Instrument Development for Science (H-TiDeS) and Heliophysics Flight Opportunities for Research and Technology (H-FORT). H-TiDeS seeks to advance the development of technologies and their application to enable investigation of key heliophysics science questions and space weather. This is done through incubating innovative concepts and development of prototype technologies. It is intended that Phase II and III technologies, further developed through H-TiDeS, would then be proposed to H-FORT to mature by demonstration in a relevant environment. The H-TiDeS and H-FORT programs are in addition to Phase III opportunities. Further opportunities through SMD include Explorer Missions, New Frontiers Missions, and the upcoming Geospace Dynamics Constellation.

References

- Example missions (e.g., NASA Magnetospheric Multiscale (MMS) mission, Fast Plasma Instrument; Solar Probe; STEREO; and Geospace Dynamics Constellation): [http://science.nasa.gov/missions](http://science.nasa.gov/missions) [121]

S14.03 Remote Sensing Instrument Technologies for Heliophysics

Lead Center: JPL

Scope Title:

Remote-Sensing Instruments/ Technologies for Heliophysics

Scope Description:

The 2013 National Research Council’s Solar and Space Physics: A Science for a Technological Society ([http://nap.edu/13060](http://nap.edu/13060) [122]) motivates this subtopic: “Deliberate investment in new instrument concepts is necessary to acquire the data needed to further solar and space physics science goals, reduce mission risk, and maintain an active and innovative hardware development community.” This subtopic solicits development of advanced remote-sensing instrument technologies and components suitable for heliophysics missions. These technologies must be capable of withstanding operation in space environments, including the expected pressures, radiation levels, launch and impact stresses, and range of survival and operational temperatures for Low Earth Orbit (LEO) and beyond. Technologies that reduce mass, power, volume, and data rates for instruments and instrument components without loss of scientific capability are of particular importance. In addition, technologies that can increase instrument resolution and sensitivity or achieve new and innovative scientific measurements are solicited. Space-qualifying new commercial sensor technologies for Heliophysics observations is an approach that can both reduce accommodation needs as well as bring improved measurement capabilities. For a list of currently operating and past missions, see [https://science.nasa.gov/missions-page?field_division_tid=5&field_phase_tid=All](https://science.nasa.gov/missions-page?field_division_tid=5&field_phase_tid=All) [123]. Another valuable reference is the 2013 Heliophysics Decadal Survey [https://www.nationalacademies.org/our-work/a-decadal-strategy-for-solar-and-space-physics-heliophysics](https://www.nationalacademies.org/our-work/a-decadal-strategy-for-solar-and-space-physics-heliophysics) [124]. Technologies that support science aspects of missions in NASA’s Living With a Star and Solar-Terrestrial Probe programs are of top priority, including long-term missions like an Interstellar Probe mission (as called out in the Decadal Survey).

Remote-sensing technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities. Remote-sensing technologies amenable to CubeSats and SmallSats are also encouraged. Specifically, this subtopic solicits instrument development that provides significant advances in the following areas:
Light detection and ranging (lidar) systems for high-power, high-frequency geospace remote sensing, such as sodium and helium lasers.

Technologies or components enabling auroral, airglow, geospace, and solar imaging at visible, far and extreme ultraviolet (FUV/EUV), and soft x-ray wavelengths (e.g., mirrors and gratings with high-reflectance coatings, multilayer coatings, narrowband filters, blazed gratings with high ruling densities, diffractive and metamaterial optics).

Electromagnetic sounding of ionospheric or magnetospheric plasma density structure at radio-frequencies from kHz to >10 MHz.

Passive sensing of ionospheric and magnetospheric plasma density structure using transmitters of opportunity (e.g., global navigation satellite system (GNSS) or ground-based transmissions).

Technologies that enable observations of bright solar flares without saturation in wavelength range from EUV to x-rays. This includes but is not limited to:

- Fast-cadence solid-state detectors (e.g., CCD, CMOS) for imaging in the EUV with or without intrinsic ion suppression.
- Fast-cadence solid-state detectors for imaging soft or hard x-ray (~0.1 to hundreds of kiloelectron volts) imaging preferably with the ability to detect the energy of individual photons.
- Technologies that attenuate solar x-ray fluxes by flattening the observed spectrum by a factor of 100 to 1,000 across the energy range encompassing both low- and high-energy x-rays—preferably flight programmable.

Technologies to either reduce the size, complexity, or mass or to improve the imaging resolution of solar telescopes used for imaging solar x-rays in the ~1 to 300 keV range.

- Technologies capable of smoothly laminating silicon micropore optics with materials that enhance the grazing incidence reflectivity of soft x-rays in the energy range from 0.1 to 2 keV.

Technologies, including metamaterials and micro-electro-mechanical systems (MEMS) that enable polarization, wavelength, or spatial discrimination without macroscale moving parts.

Technologies for precise radiometry at terahertz bands corresponding to upper atmosphere thermal emissions in the 1 to 5 THz range, particularly at 4.7 THz. This includes, but is not limited to:

- Technologies that reduce size, mass, and power of terahertz radiometry instrumentation, for example by increasing the operating temperature of terahertz detectors.
- Technologies that enable terahertz spectroscopy, for example, by use of a terahertz local oscillator for heterodyne mixing.
- Technologies that improve signal-to-noise ratio of terahertz instrumentation, particularly at 4.7 THz.

Proposers are strongly encouraged to relate their proposed development to NASA's future heliophysics goals as set out in the Heliophysics Decadal Survey (2013-2022) and the NASA Heliophysics Roadmap (2014-2033). Proposed instrument components and/or architectures should be as simple, reliable, and low risk as possible, while enabling compelling science. Novel instrument concepts are encouraged, particularly if they enable a new class of scientific discovery. Technology developments relevant to multiple environments and platforms are also desired. Proposers should show an understanding of relevant space science needs and present a feasible plan to fully develop a technology and infuse it into a NASA program. Detector technology proposals should be referred to the S116 subtopic.

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

Primary Technology Taxonomy:

Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I deliverables may include an analysis or test report, a prototype of an instrument subcomponent, or a full working instrument prototype.

Phase II deliverables must include a prototype or demonstration of a working instrument or subcomponent and may also include analysis or test reports.

**State of the Art and Critical Gaps:**

Remote-sensing instruments and technologies are essential bases to achieve Science Mission Directorate's (SMD) Heliophysics goals summarized in National Research Council's "Solar and Space Physics: A Science for a Technological Society." These instruments and technologies play indispensable roles for NASA’s Living With a Star (LWS) and Solar Terrestrial Probe (STP) mission programs as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for remote-sensing technologies amenable to CubeSats and SmallSats. To narrow the critical gaps between the current state of art and the technology needed for the ever-increasing science/exploration requirements, remote-sensing technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities—and at the same time with lower mass, power, and volume.

**Relevance / Science Traceability:**

Remote-sensing instruments and technologies are essential bases to achieve SMD's Heliophysics goals summarized in National Research Council’s, Solar and Space Physics: A Science for a Technological Society. These instruments and technologies play indispensable roles for NASA’s LWS and STP mission programs, as well as for a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for remote-sensing technologies amenable to CubeSats and SmallSats. NASA SMD has two excellent programs to bring this subtopic’s technologies to a higher level: Heliophysics Technology and Instrument Development for Science (H-TIDeS) and Heliophysics Flight Opportunities for Research and Technology (H-FORT). H-TIDeS seeks to advance the development of technologies and their application to enable investigation of key heliophysics science questions. This is done through incubating innovative concepts and development of prototype technologies. It is intended that technologies developed through H-TIDeS would then be proposed to H-FORT to mature by demonstration in a relevant environment. The H-TIDeS and H-FORT programs are in addition to Phase III opportunities.

**References:**

1. For example missions: [https://science.nasa.gov/missions-page?field_division_tid=5&field_phase_tid=All](https://science.nasa.gov/missions-page?field_division_tid=5&field_phase_tid=All) [125]
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](http://nap.edu/13060) [120]
3. For details of NASA’s Heliophysics roadmap, see the NASA Heliophysics Roadmap: [https://explorers.larc.nasa.gov/HPSMEX/MO/pdf_files/2014_HelioRoadmap_Final_Reduced_0.pdf](https://explorers.larc.nasa.gov/HPSMEX/MO/pdf_files/2014_HelioRoadmap_Final_Reduced_0.pdf) [126]

**S15.01 Plant Research Capabilities in Space**

Lead Center: JPL

Participating Center(s): ARC, JPL, JSC

**Scope Title**

CO2 Collection and Dosing Technologies for Plant Chambers
**Scope Description**

Carbon dioxide is an essential gas to sustain plant photosynthesis. Spacecraft cabins with humans often have very high CO$_2$ levels (e.g., 2,000 to 7,000 ppm or 0.2 to 0.7 kPa on the International Space Station, ISS), and this has been used for CO$_2$ supply to open plant chambers like the Russian Lada and NASA’s Veggie unit. This does not provide precise control of the CO$_2$ concentration, however: the levels are always floating with the cabin, which makes it difficult to replicate for ground controls and optimize for plant growth. NASA Advanced Plant Habitat (APH) is a closed chamber capable of tight CO$_2$ control, but instead of using cabin air, compressed cylinders of CO$_2$ are shipped to space, adding mass consumables and pressurized containers to operate APH.

NASA needs a system for selectively scrubbing CO$_2$ from cabin air, which can vary from 2,000 to 7,000 ppm (0.2 to 0.7 kPa), and then dosing or adding the CO$_2$ in a controlled fashion to closed plant chambers like APH to maintain constant CO$_2$ concentrations. Such a capability could eliminate the need for shipping compressed CO$_2$ cylinders continuously to ISS to operate APH and/or stabilize fluctuating CO$_2$ levels for open chambers like Veggie. A starting example of such an approach might be something like the ISS Carbon Dioxide Removal Assembly (CDRA), which uses zeolite beds to remove and then release CO$_2$. For closed plant chambers, the technology would need to be miniaturized, require low power, and capable of being attached or connected directly to the chamber or its internal air plenum and then releasing the CO$_2$ to inside of the chamber to balance CO$_2$ removal by the plants. Internal plant chamber concentrations are typically optimal between 1,000 and 2,000 ppm (0.1 and 0.2 kPa), but the plants rapidly remove the CO$_2$ during the light cycle while they are photosynthetically active; hence the need for controlled CO$_2$ additions.

**Expected TRL or TRL Range at completion of the Project**

2 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 08 Sensors and Instruments

**Level 2**

TX 08.3 In-Situ Instruments/Sensor

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype

**Desired Deliverables Description**

The Phase I project should focus on feasibility and proof-of-concept demonstration. The required Phase I deliverable is a report documenting the proposed innovation, its status at the end of the Phase I effort, and the evaluation of its strengths and weaknesses compared to the state of the art.

Following Phase II, a working prototype that could be attached to a closed chamber similar to the NASA APH would be desirable.

**State of the Art and Critical Gaps**

The state of the art is to send compressed CO$_2$ gas in cylinders into space and use these to add controlled amounts to closed chambers like APH. For open chambers like Veggie, the SOA is using cabin air for CO$_2$ supply, but this does not provide very precise CO$_2$ control. The proposed capability could replace the need to deliver compressed CO$_2$ to APH and help "smooth" or buffer CO$_2$ changes in Veggie.
Accurate CO₂ control is essential for careful research and optimal growth of plants in space. This is possible by supplying compressed CO₂ from Earth, but this is costly and is ironic when the closed plant chambers are already surrounded by a cabin atmosphere with very high levels of CO₂.

References


Scope Title

Miniature Elemental Analyzer for Water Analysis and Support of Plant Research

Scope Description

As plant-growing systems mature and expand for future exploration missions and enhanced research capabilities, the ability to generate, analyze, and manage nutrient (fertilizer) solutions will increase. As of now, we can only take “grab” samples of water from systems like the Advanced Plant Habitat (APH) or the proposed Passive Orbital Nutrient Delivery System (PONDS) nutrient delivery system for Veggie, return them to Earth, and then analyze them for the elemental composition. An in-situ capability is needed to analyze plant nutrient solutions or feed water to better understand and manage plant nutrient delivery on a near-real-time basis. Inductively coupled plasma (ICP) spectroscopy is one proven approach for elemental analysis, but ion chromatography (IC) or high-performance liquid chromatography (HPLC) might have overlapping capabilities. Regardless, the technology would need to be robust and miniaturized, operate with low power, and have minimal consumables to augment plant growth and research capabilities for the future missions. The system would also need to be safe for operating in spaceflight environments. Ideally, the technology could provide rapid analysis of elemental composition of water samples. Essential elements for plants include (in approximately descending order): N, K, Mg, Ca, P, S (all typically in tens to hundreds of parts per million), and Mn, Fe, Cl, B, Zn, Cu, and Mo (all typically in parts per billion). Detection of as many of these elements as possible would be desirable. In addition, it would be desirable to detect other non-essential elements, such as Ni, Cr, Ag, V, and I, that might be contaminants from chamber materials, plumbing, or supply water. Discrimination between ionic species (e.g., NH₄ and NO₃ forms of nitrogen) would be helpful but not required. A miniaturized elemental analyzer/sensing capability could also have applications beyond those just for plants, where knowledge of the elemental composition of fluids, such as urine or tissue samples, could provide valuable data for supporting research or habitat operations.

Expected TRL or TRL Range at completion of the Project

2 to 4

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments
Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype

Desired Deliverables Description

The Phase I project should focus on feasibility and proof-of-concept demonstration. The required Phase I deliverable is a report documenting the proposed innovation, its status at the end of the Phase I effort, and the evaluation of its strengths and weaknesses compared to the state of the art.

A Phase II deliverable may include a working prototype or engineering development unit (EDU) to demonstrate a miniaturized elemental analyzer system as part of a plant-growth system like the APH, the proposed PONDS watering systems for growing plants in the Veggie plant chamber on ISS, or future proposed "hydroponic" systems being considered for growing plants in space.

State of the Art and Critical Gaps

Laboratory-scale ICP or IC systems that operate with a plasma torch or high pressure to get the needed emission spectra are a standard state-of-the-art approach for elemental analysis.

Relevance / Science Traceability

As longer duration plant research tests are conducted in space, there will be a need for addition of nutrient or fertilizer solutions to sustain the plants; for example, the current APH test with chili peppers is scheduled to go for >100 days. Although this uses time-release fertilizer, in situ water analysis could provide information on backwash of nutrients into the water delivery system and verification of the water quality of cabin potable water used for the tests. For the proposed PONDS watering system for Veggie, initial nutrients will come from time-release fertilizer as well, but having in situ nutrient/elemental analysis could assess needs for further nutrient additions. For proposed "hydroponic" systems for space, capabilities to analyze nutrient solutions would be needed throughout the experiment or plant production trial.

References

Participating Center(s): JPL

**Scope Title**

Photovoltaic Energy Conversion

**Scope Description**

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

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

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

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

**Expected TRL or TRL Range at completion of the Project**

3 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 03 Aerospace Power and Energy Storage

**Level 2**

TX 03.1 Power Generation and Energy Conservation

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Hardware
Desired Deliverables Description

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

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

State of the Art and Critical Gaps

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

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

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

Relevance / Science Traceability

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


NASA Science Missions: https://science.nasa.gov/missions-page?field_division_tid=All&field_phase_tid=3951 [128]

References

- NASA Science Missions: https://science.nasa.gov/missions-page [107]

S16.03 Guidance, Navigation, and Control

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

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

Scope Description:

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

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

Advances in the following areas are sought:

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

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

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

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

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

**Desired Deliverables of Phase I and Phase II:**

- Prototype
- Hardware
- Software

**Desired Deliverables Description:**

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

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

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

**State of the Art and Critical Gaps:**

Capability area gaps:

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

**Relevance / Science Traceability:**

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

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

References:

1. 2020 NASA Technology Taxonomy: https://go.nasa.gov/3hGhFJf [130]
2. 2017 NASA Strategic Technology Investment Plan: https://go.usa.gov/xU7sE [131]

Scope Title

Star-Tracker Technologies for CubeSats

Scope Description:

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

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

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

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

Desired Deliverables of Phase I and Phase II:

• Prototype
• Hardware

Desired Deliverables Description:

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

State of the Art and Critical Gaps:

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

Relevance / Science Traceability:

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

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

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

References:


S16.04 Unpiloted Aerial Platforms and Technologies for NASA Science Missions

Lead Center: JPL

Participating Center(s): AFRC, GSFC, JPL, LaRC

Scope Title:

Unpiloted Aerial Platforms for High-Altitude, Long-Endurance (HALE) Missions

Scope Description:

NASA is interested in increased utilization of innovative, cost-effective, unpiloted, aerial platforms, including ones that are heavier and lighter than air, to perform NASA missions in the stratosphere in order to supplement current piloted and satellite platforms. Unmanned aerial platforms are especially suited for HALE missions that occur at or above 50,000 to 90,000 ft and can support continuous flights of 30 days or more at altitude.
HALE missions enable new Earth and space science applications and an opportunity for testing spaceborne-like measurements in the stratosphere. High spatial and temporal resolution observations from HALE can improve measurements of Earth system processes or phenomena requiring sustained observations, including: air quality monitoring, coastal zone and ocean imaging and monitoring, mapping of geologically active regions, forest and agricultural monitoring, and imaging of polar regions. The NASA Surface Biology and Geology mission, for example, is anticipating the need for measurements of leaf canopy chemistry during the growing season, and significant changes can happen between overpasses of polar orbiting satellites. Similarly, the Surface Topography and Vegetation Incubation team recently released a report citing the need for more frequent observations of areas prone to landslides and other ephemeral or episodic events where time series observations can improve Earth system models.

HALE Platforms offer several key challenges, including solar/battery technologies, operation in regions of harsh radiation and temperatures, vehicle health monitoring, and mission deployment/support at remote locations. Methods for accurate stationkeeping in areas of interest would also have to be developed.

Proposals are solicited for both heavier- and lighter-than-air innovative stratospheric platforms that can operate at an altitude of 60,000 ft or above, for a mission of 30 or more days in duration. The proposed vehicle must be able to carry a scientific instrumentation payload of 22lbs or more on all science missions. The combined system must be able to maintain position within 100 nautical miles of a fixed point on the ground and be able to provide at least 100+ W of sustained power (28 Vdc) to payloads. The platform must also have high band width, line-of-sight payload telemetry, and SATCOM capability to enable beyond visual line of site command and control. Proposals can be based on new design platforms or extensively modified existing platforms to meet the above HALE mission requirements.

The primary focus of proposal should be on vehicle design towards a flight test prototype in Phase II. Other aspects such as concept of operations, vehicle maintenance, vehicle transport and deployment, ground station design, and flight-test planning should also be addressed.

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

**Primary Technology Taxonomy:**
Level 1: TX 04 Robotics Systems
Level 2: TX 04.2 Mobility

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

**Desired Deliverables Description:**
It is expected that a Phase I effort will consist of a system-level design and a proof-of-concept experiment on one or more key components. Deliverable items for Phase I shall be a final report describing the results of the concept analysis and demonstration of any key component technology developed.

The Phase II effort will focus on the development of a concept prototype and feasibility testing. The Phase II deliverable should include a final report on design concept documentation, test reports, and photos of any prototypes that were built and tested.

**State of the Art and Critical Gaps:**
NASA Global Hawk unmanned aircraft system (UAS) previously provided HALE capability for NASA Earth Science missions but was retired from this mission in 2020. NASA presently has no UAS platforms serving in this role and is reliant on satellites and piloted aircraft to fly these missions. Currently, NASA Earth Science has needs but no platforms to meet this.

While NASA continues development of super-pressure balloons with extended duration, several lighter-than-air vehicles have recently been developed that can provide capabilities to meet NASA science needs.

Several prototype and proof-of-concept HALE vehicles are under development and flight testing. These next-generation HALE vehicles under development have had a focus on communications, and so payloads relevant to Earth Science have not been demonstrated. These existing platforms, which include both heavier- and lighter-than-air platforms could be modified to meet requirements of this solicitation, or new designs could meet them as well.

Relevance / Science Traceability:

As the impacts of climate change become more pronounced through long-term drought, more frequent and intense wildfires, and an increase in severe weather occurrences, there is increased emphasis on Earth Science missions by NASA, other Government Agencies, and private industry. This includes new technologies and capabilities to enhance our ability to observe and predict effects on the environment and the economy of these more frequently occurring events.

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

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

References:


2. Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space National Academies of Sciences, Engineering 2018:  

3. Observing Earth's changing surface topography and vegetation structure 2021:  

Scope Title:

Unpiloted Aerial Platforms for Extreme Environment Missions on Earth

Scope Description:

NASA is interested in increased utilization of unpiloted aerial platforms, both lighter and heavier than air, for Earth Science missions to supplement current piloted and satellite platforms, taking advantage of unpiloted aerial platforms to perform dull, dirty, difficult, and dangerous missions. These platforms are especially suited for extreme environment missions such as volcano, storm, and wildfire penetration as there would be no risk to humans compared to piloted aircraft.
Numerous Earth Science missions require aircraft to operate in situ or in close proximity to extreme environments. This includes flights into volcano plumes to compare sulfur dioxide concentration measurements with those measured by satellites. Another application is storm penetration where unmanned aircraft system (UAS) platforms are flown into thunderstorms and hurricanes to obtain measures of air pressure, wind conditions, temperatures, and other data used for storm forecasting and weather model development. A third example is operation in wildfires where unmanned aerial vehicles (UAVs) can gather information on emissions and fire behavior.

UAS Platforms designed for operation in extreme environments offer several key challenges to developers. Strong winds in the area of these missions usually ground smaller UAS platforms. Turbulence could cause vehicle upset and loss of control in addition to structural damage. Many UAS platforms are not weather resistant and so cannot operate in visible precipitation. For operation in extremely cold conditions, icing could cause loss of the aircraft.

Proposals are solicited for both heavier- and light-than- air aerial platforms that can operate in the extreme environments described above. Proposed platforms should address the operational challenges described to enable missions to be accomplished with minimal vehicle loss. The proposed vehicle must be able to carry a scientific instrumentation payload on all science missions. The proposal can be based on new design platforms or extensively modified existing platforms to meet the above mission requirements.

The primary focus of the proposal should be on vehicle design. However, other aspects such as concept of operations, vehicle maintenance, vehicle transport and deployment, ground station design, and flight test planning should also be addressed.

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

**Primary Technology Taxonomy:**
Level 1: TX 04 Robotics Systems
Level 2: TX 04.2 Mobility

**Desired Deliverables of Phase I and Phase II:**

- Research
- Analysis
- Prototype
- Hardware

**Desired Deliverables Description:**

It is expected that a Phase I effort will consist of a system-level design and a proof-of-concept experiment on one or more key components or enabling technologies. Deliverable items for Phase I shall be a final report describing the results of the concept analysis and demonstration of any key component technology developed.

The Phase II effort will focus on the development of a concept prototype and feasibility testing. Phase II deliverables should include a final report on design concept documentation, test reports, and photos of any prototypes that were built and tested.

**State of the Art and Critical Gaps:**

Currently, most UAS platforms can operate only in the proximity of extreme environments but do not have capability for actual penetration other than with a high probability of vehicle loss. The strong winds and turbulence associated with these environments usually grounds smaller UAS platforms or could cause vehicle upset and loss of control as well as structural damage.
Many UAS platforms are not weather resistant and so cannot operate in precipitation. For operation in extremely cold conditions such as polar regions, icing could cause loss of the vehicle.

Because of the capability and operational limits of current UAS platforms, it may not be possible to capture important Earth Science data in hazardous environments.

NASA ARMD (Aeronautics Research Mission Directorate) and NASA ARMD SBIR technologies as well as technologies developed by universities could be utilized by the proposed to address some of these challenges such as icing detection and removal; gust load alleviation; upset prevention, detection, and recovery; see-and-avoid systems; technologies for beyond visual line of sight operation; and others.

**Relevance / Science Traceability:**

Because of global warming and associated effects such as long-term drought, more frequent and intense wildfires, and an increase in severe weather occurrences, there is an increased priority of Earth Science missions by NASA, other Government Agencies, and private industry. This includes prediction of, detection of, response to, and measurement of effects on the environment and the economy of these more frequently occurring events.

NASA, other Government Agencies, and private companies have also shown increased interest in utilizing unmanned aircraft system (UAS) platforms, both heavier and lighter than air, for Earth Science data collection, supplementing satellite and piloted Earth Science aircraft. This is largely due to the ability of UAS to perform dull, dirty, difficult, and dangerous missions more easily than other platforms. In addition, simpler UAS platforms could be more easily deployed to quickly respond to events of interest.

In addition, there is interest from the highest levels of government to invest in the domestic UAS manufacturing base to reduce reliance on foreign manufacturers such as DJI as well as security concerns with foreign UAS platforms and technologies.

Historically it has been difficult to operate UAS platforms in the National Airspace, primarily because of safety concerns. A large amount of planning, coordination, and approvals were required, making a quick response nearly impossible. Less restrictive operational requirements as developed by the NASA UAS in the NAS program and advances in UAS Air Traffic Technologies developed under the NASA UAS Traffic Management (UTM) Project have enabled simpler, safer, and more efficient UAS flight operations both for private companies and for NASA Earth Science missions.

Advances in UAS technologies, developed under the NASA Aeronautics Research Mission Directorate (ARMD), have enables more capable, less expensive, and higher performing platforms, resulting in an increase of small, innovative, domestic UAS manufacturers. This pool of UAS companies have the expertise and capabilities to develop UAS platforms for future NASA Earth Science missions as well as to commercialize these platforms for non-NASA users.

**References:**


**Scope Title:**

Lighter-than-air platform subsystems for Earth and Venus
Scope Description:

1. Venus lighter-than-air platform:

NASA is interested in scientific exploration of Venus using aerial vehicles to perform in situ investigations of its atmosphere and is currently developing concepts for variable-altitude balloons operating at an altitude range between 52 and 62 km.

One concept for a variable-altitude balloon features a super-pressure (SP) balloon located within a zero-pressure (ZP) balloon. The configuration can be described as one small balloon inside a large balloon that are co-located at the bottom. Altitude changes are made by transfer of helium between the two balloons. Pumping helium from the ZP balloon into the SP balloon reduces buoyancy to descend in altitude. Venting helium from the SP balloon into the ZP balloon increases buoyancy to ascend in altitude. Isolating the ZP and SP balloons when neither the pump or vent is operated enables the balloon to float at constant altitude. Details on the variable-altitude balloon system concept can be found in [Hall 2021].

Proposals for an innovative balloon altitude modulation system featuring a lightweight, high-efficiency pump, isolation valves, and venting orifices are desired. The performance requirements of the balloon altitude modulation system will vary depending on the size of the balloon system and payload. For the purposes of adequately scaling this effort, the following specifications represent the requirements for a current Venus balloon concept (the fluid medium is helium gas):

- The pump shall have a nominal flow rate of 250 liters per minute at a pressure rise of 30 kPa.
- The vent shall have a nominal flow rate of 1,000 liters per minute at a pressure drop of 5 kPa.

For reliability purposes, the mission operating lifetime is about 100 days of continuous operations.

Typical commercial pumps with this pressure rise and flow rate have a mass around 15 kg and require 250 W of power. Ground-breaking solutions to reduce pump mass to <7 kg and reduce power to <120 W are goals for the specified flow rate and operating pressure.

The specified pressure and flow requirements are current best estimates and will not change during the Phase I proposal development period but may be updated for Phase II.

Venus features a challenging atmospheric environment that significantly impacts the design and operation of devices on aerial vehicles. Proposers should be familiar with the properties of the Venus atmosphere as described in this call. Additional information on the Venus atmospheric environment can be found in the References section.

2. Earth Lighter-than-air platform:

NASA is also looking for an innovative way to reduce the termination dispersions from a few miles to within 1/2 to 1/4 mile of the predicted termination point by the use of a steerable parachute recovery system (SPRS). The SPRS will need to be able to maneuver around infrastructure (e.g., oil wells, power lines, wind mills), protected areas (e.g., national parks, special habitats), natural resources (e.g., rivers, mountains, lakes), and other areas of interest (e.g., farm land). The SPRS will need to provide real-time maneuverability for a science gondola from a remote operations control room using the communications and telemetry systems provided by the Columbia Scientific Balloon Facility (CSBF). The system should be lightweight—no more than 75 lb—including power.

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

Primary Technology Taxonomy:
Level 1: TX 15 Flight Vehicle Systems
Level 2: TX 15.6 Vehicle Concepts
Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware

Desired Deliverables Description:

The deliverables for Phase I include a trade study of the potential systems, a simulation of how each system should work, and a report on the recommendation of one to two systems to be further developed in Phase II. It is anticipated that these products are achievable given the SBIR time and funding constraints.

The deliverables for Phase II include an engineering development unit and flight testing with a report of the results.

State of the Art and Critical Gaps:

1. Venus lighter-than-air platform state of the art:

   There are few commercially available pumps in the market today that have the pressure rise and flow rate capabilities needed for a Venus balloon. Most pumps are not built to be lightweight or efficient, which are of critical importance on a balloon mission. Commercial pumps with the targeted flow rate and pressure capability typically have a mass around 15 kg and require 250 W of power. Isentropic pumping power analysis shows that only 80 W of power are required to achieve the desired flow rate and pressure rise. Therefore, the thermodynamic efficiency of commercial pumps is only about 33%. The Venus balloon system desires a system that is at least 65% efficient (2x over commercial products) and half the mass of commercial pump systems to maximize resource availability on the balloon system.

2. Earth lighter-than-air platform state of the art:

   A scientific balloon floats at an average altitude of 110,000 ft or more and carries science payloads up to 8,000 lb. At the end of a scientific balloon mission, the science payload on the gondola ("science gondola" from this point on) is separated from the balloon and falls to Earth on a parachute, following the wind currents at the time of release, and then lands on cardboard crush pads. In most cases this allows recovery of the science gondola, although the payload and gondola may be in areas that are hard to reach using conventional recovery trucks. However, there are rare cases where the science gondola falls either into water or in areas that require special equipment or are difficult for recovery (i.e., inaccessible area). Currently, trajectory predictions for termination are within a few miles and are dependent on models, map overlays (showing restricted air space, national/state parks), and observations from a plane on areas along the trajectory to determine the best area to terminate the balloon and bring the science gondola safely to the ground. Some items that are considered during the termination discussions are science mission minimums, trajectory predications (e.g., national or state parks, lakes, mountains, rivers, infrastructure, crop lands), weather conditions, and risk to the public.

   Current state of the art does not include steerable systems in balloon parachutes. Success in this endeavor will primarily entail steerability, and will also frequently result in a safety analysis, which will allow more "green lights" for launch than would otherwise be the case.

Relevance / Science Traceability:

1. Venus Lighter-than-air platform relevance:

   The Mars Helicopter, Ingenuity, and the Titan Dragonfly mission show there is significant interest in planetary aerial vehicles for science investigations. It is in NASA's interest through the SBIR program to continue fostering innovative ideas to extend our exploration capabilities by developing technologies for Venus aerial mission concepts.

The NASA Jet Propulsion Laboratory's (JPL's) Solar System Mission Formulation Office and Science Mission
Directorate’s (SMD’s) Planetary Science Division advocate Venus aerial vehicle platform development. NASA recently completed the Venus Flagship Mission concept study, which included a balloon system for the Planetary Decadal Survey [Gilmore, 2020].

Science traceability: The 2019 VEXAG Venus Strategic Plan identified several key science investigations that are ideally suited to aerial platforms. The areas of scientific interest include Atmospheric Gas Composition, Cloud and Haze Particle Characterization, Atmospheric Structure, Surface Imaging, and Geophysical Investigations. The variable-altitude aerial vehicle platform is ideal for investigating these science goals and objectives. Building the variable-altitude balloon requires the development of several key components such as the helium transfer system identified in this call.

2. Earth Lighter-than-air platform relevance:

This subtopic will be relevant to any mission directorate, commercial entity, or other government agency that drops payloads from an altitude, including the Balloon Program. Other potentially interested projects include NASA sounding rockets, unmanned aerial vehicles (UAVs), and aircraft programs.

References:

Venus Lighter-than-air platform:


Earth Lighter-than-air platform:


**S16.05 Thermal Control Systems**

Lead Center: GSFC

Participating Center(s): JPL, JSC, LaRC, MSFC

**Scope Title**
Coatings for Lunar Regolith Dust Mitigation for Thermal Radiators and Extreme Environments

Scope Description

Thermal coatings are an integral part of a space mission and are essential to the survivability of the spacecraft and instrument. Radiator surface coatings with desired emissivity and absorptivity provide a passive means for instrument temperature control. The utilization of variable-emittance devices further enables active control of the instrument temperature when the heat output from the instrument or the thermal environment of the radiator changes. With NASA's new initiative to return to the Moon, a new coating technology that will keep surfaces clean and sanitary is needed. New coating formulations utilizing durable, anticontamination, and self-cleaning properties that will disallow the accumulation of dust, dirt, and foreign materials are highly desirable. These coatings can have low absorptance and high infrared (IR) emittance properties or be transparent for use on existing thermal coating systems. The goal of this technology is to preserve optimal long-term performance of spacecraft and habitation components and systems. Furthermore, coatings that can survive and operate in extreme environments (cryogenic or high temperature) are desirable.

Expected TRL or TRL Range at completion of the Project

2 to 5

Primary Technology Taxonomy

Level 1

TX 14 Thermal Management Systems

Level 2

TX 14.3 Thermal Protection Components and Systems

Desired Deliverables of Phase I and Phase II

- Analysis
- Prototype
- Hardware

Desired Deliverables Description

Phase I Deliverables:

- Successful development of coating formulations that lead to the desired dust mitigation.
- Deliverable of coupon.
- Samples of the hardware for further testing at NASA facilities.
- Final report.

Phase II Deliverables:

- Results of performance characterization tests.
- Results of stability test of the coating formulations and their mechanical durability test under the influence of simulated space and lunar environmental conditions.
- Test coupon.
- Final report.

State of the Art and Critical Gaps

There are limited options for durable, stable thermal control coatings that are dust shedding in charging
environments. Current state-of-the-art, sprayable radiation-stable coatings are able to coat complex, irregular surfaces, but they are porous and will become imbedded with dust and particulates. Other surface films tend to be less optically stable and may charge in the plasma environment, thereby attracting lunar regolith to their surfaces. Mirrors have the limitations of requiring flat surfaces and are not conformal in nature. Currently, no single thermal control surface appears to provide stability, durability, and meet optical property requirements for sustained durations in space and lunar environments.

Relevance / Science Traceability

Many Sciences Mission Directorate (SMD) missions will greatly benefit from this dust mitigation thermal coating technology: any lunar-related project and projects involved with robotic science rovers and landers.

References

- References for dust mitigation coatings such as lotus thermal coatings: https://ntrs.nasa.gov/search.jsp?R=20150020486 [137]
- References in Subtopic Z13.01, Active and Passive Dust Mitigation Surfaces.

Scope Title

Heat Pumps for High-Temperature Sink Environments

Scope Description

Operations in extreme environments where the environment sink temperature exceeds spacecraft hardware limits will require active cooling if long-duration survivability is expected. Robotic science rovers operating on the lunar surface over diurnal cycles face extreme temperature environments. Landers with clear views of the sky can often achieve sufficient heat rejection with a zenith or, if sufficiently far from the equator, an anti-Sun-facing radiator. However, science rovers must accommodate random orientations with respect to the surface and Sun. Terrain features can then result in hot environment sink temperatures beyond operating limits, even with shielded and articulated radiator assemblies. Lunar dust degradation on radiator thermo-optical properties can also significantly affect effective sink temperatures. During the lunar night, heat rejection paths must be turned off to preclude excessive battery mass or be properly routed to reclaim nuclear-based waste heat.

Science needs may drive rovers to extreme terrains where steady heat rejection is not otherwise possible. The paradigm of swarms or multiple smaller rovers enabled by commercial lander opportunities will need to leverage standard rover bus designs to permit flexibility. A heat pump provides the common extensibility for thermal control over the lunar diurnal. Active cooling systems or heat pumps are commonly used on spacecraft. Devices used include mechanical cryocoolers and thermoelectric coolers. For higher loads, vapor compression systems have been flown, and more recently, reverse turbo-Brayton-cycle coolers are being developed under NASA’s Game Changing program for high-load, high-temperature-lift cryocoolers. However, technology gaps exist for midrange heat pumps that are suitable for small science rovers where internal heat dissipation may range from 20 to 100 W.

Expected TRL or TRL Range at completion of the Project

2 to 5

Primary Technology Taxonomy

Level 1

TX 14 Thermal Management Systems

Level 2

TX 14.X Other Thermal Management Systems
Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype

Desired Deliverables Description

- Conceptual design (Phase I).
- Physics-based analysis or model (Phase I).
- Proof-of-concept hardware (Phase I).
- Proof-of-concept hardware tested against simulated loads in proposed environments (Phase II).
- Final report (Phase I, Phase II).

State of the Art and Critical Gaps

Specifically, heat pump systems are needed with the following:

- Temperature lift from a cold side at <50 °C to an environmental sink temperature as high as 75 °C (temperature lift of 50 °C or heat rejection rate of 230 W/m²), with a system coefficient of performance >2.5.
- Tolerance to being powered down during the lunar night and restarted during the day reliably over multiple diurnals.
- Minimal exported vibrations, if any, for compatibility with science instruments.

Novel heat-pump systems are desired. Enabling improvements to state-of-the-art systems are also welcome.

Relevance / Science Traceability

NASA’s lunar initiative and Planetary Science Division form the primary customer base for this technology. Missions that directly address the National Research Council Planetary Science Decadal Survey may be users of this technology.

References

- Apollo Lunar Roving Vehicle Documentation: [https://www.hq.nasa.gov/alsj/alsj-LRVdocs.html](https://www.hq.nasa.gov/alsj/alsj-LRVdocs.html) [139]
- Apollo Experience Report—Thermal Design of Apollo Lunar Surface Experiments Package: [https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720013192.pdf](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720013192.pdf) [140]

Scope Title

Advanced Manufacturing of Loop Heat Pipe Evaporator

Scope Description

A loop heat pipe (LHP) is a very versatile heat transport device that has been used on many spacecrafts. At the heart of the LHP is the evaporator and reservoir assembly. During the manufacturing, tedious processes are required to machine the porous primary wick and insert it into the evaporator, and both ends of the wick need to be sealed for liquid and vapor separation. One commonly used method for vapor seal is to use a bimetallic knife-edge joint, which is more prone to failure over long-term exposure to thermal cycles and shock and vibration. These tedious manufacturing processes add to the cost of the traditional LHP. A new manufacturing technique that will allow the primary wick to be welded directly to the reservoir without the use of a knife-edge seal is needed in order
to reduce the cost and enhance the reliability.

**Expected TRL or TRL Range at completion of the Project**

4 to 6

**Primary Technology Taxonomy**

**Level 1**

TX 14 Thermal Management Systems

**Level 2**

TX 14.X Other Thermal Management Systems

**Desired Deliverables of Phase I and Phase II**

- Analysis
- Prototype
- Hardware

**Desired Deliverables Description**

- Successfully develop advanced techniques to manufacture the LHP evaporator and reservoir assembly (Phase I).
- Demonstrate the performance of the evaporator/reservoir performance in an LHP setup (Phase I).
- Demonstrate the performance of the evaporator/reservoir performance in an LHP setup optimized to operate in simulated realistic environments with appropriate cycling (Phase II).
- Final report (Phase I, Phase II).

**State of the Art and Critical Gaps**

The LHP evaporator contains a porous wick, which provides the capillary pumping capability to sustain the fluid flow in the loop. The smaller the pore size of the wick, the higher its capillary pumping capability. However, a smaller pore size results in a higher flow resistance that must be overcome by the capillary force. Traditional sintered metal wicks have a pore size on the order of 1 µm and porosity around 0.4 to 0.6. In order to replace the traditional porous wick, the new wick produced by the advanced manufacturing technology must have comparable pore size and porosity. The smallest pore size currently produced by direct metal laser sintering is on the order of 10 µm.

**Relevance / Science Traceability**

Traditional LHPs are used on many NASA missions including the Ice, Cloud, and Land Elevation Satellite (ICESat), ICESat-2, Swift, Aura, Geostationary Operational Environmental Satellite (GOES), Geostationary Operational Environmental Satellite-R Series (GOES-R), and Surface Water and Ocean Topography (SWOT). Similar future Science Mission Directorate (SMD) missions, especially those using small satellites, can greatly benefit from this technology.

**References**


**Scope Title**

Approaches and Techniques for Lunar Surface Payload Survival
Scope Description

The lunar environment poses significant challenges to small, low-power (~100 W or less) payloads, rovers, and landers required for lunar science. The lunar day/night cycle is approximately one Earth month. During that time, surface temperatures on the lunar surface can reach 400 K at local solar noon or drop to below 100 K during the lunar night—and even colder in permanently shadowed regions. These hot and cold conditions can last several Earth days, because of the slow rotation of the Moon, or permanently in shadowed craters. Lunar dust deposited on heat-rejection surfaces and coatings will increase the heat absorbed from the Sun, thus reducing the effectiveness of radiators for heat rejection. The lunar gravity, which is 1/6th of the Earth’s, will limit the ability of typical low-power heat transport devices, but the gravity field may provide advantages that could be utilized. Higher heat dissipation capacity should be addressed in Z2.01. This call seeks to solicit innovative proposals to enable lunar science in the difficult lunar environment. Example technologies may include, but are not limited to, active loops that may be turned off and are freeze tolerant, zero- or low-power nonconsumable/regenerative heat generation sources, high-thermal-capacitance thermal storage, advanced insulation, and passive switching with high turndown ratios (e.g., >400:1). Furthermore, small form factors are also desired. Technologies should show substantial increase over the state of the art. Technology proposals should address power usage in day and night/shadow, mass, heat transport when turned on, heat leak when turned off, temperature drops through the system, heat storage/release amount, sensitivity to lunar topography and orientation, and so forth.

Expected TRL or TRL Range at completion of the Project

3 to 4

Primary Technology Taxonomy

Level 1

TX 14 Thermal Management Systems

Level 2

TX 14.2 Thermal Control Components and Systems

Desired Deliverables of Phase I and Phase II

- Analysis
- Prototype
- Hardware

Desired Deliverables Description

Thermal management approaches, techniques, and hardware components to enable the accommodation of temperature extremes encountered in the lunar environment. Concept model deliverable for Phase I and prototype demonstration in relevant environment in Phase II.

State of the Art and Critical Gaps

Missions like Surveyor and Lunokhod hibernated during the night or reduced operational power near noon, in attempts to survive single or multiple lunar cycles. ALSEPs (Apollo Lunar Surface Experiments Packages) were deployed on several Apollo missions and had select experiments that operated for many lunar cycles. However, both Lunokhod and ALSEP benefited from radioisotope heat and power sources, which are either too expensive or not likely to be available for near-term future lunar science experiments. In fact, most modern lunar surface mission planning is based on solar power and batteries and typically avoids the challenges associated with surviving the full lunar cycle or shadowed regions. Because interest in lunar science and the development of abilities to deliver payloads to the lunar surface is resurgent, the capability to operate through the entire lunar environment is critical. In the absence of perpetual power supplies like radioisotope thermoelectric generators (RTGs), thermal management approaches to accommodate the lunar extremes, extended day/night cycles, and shadowed regions...
are seen as enabling.

Relevance / Science Traceability

Science Mission Directorate (SMD) lunar surface science investigations will employ small, low-power payloads that will require advanced thermal control approaches and techniques to survive and operate for extended duration through extreme thermal environments on the lunar surface. NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2021, and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References

- The Surveyor Program: https://history.nasa.gov/TM-3487/ch2-1.htm [144]
- The Surveyor Program: https://www.lpi.usra.edu/lunar/missions/surveyor/(link is external) [145]
- Missions - Lunokhod 01: https://solarsystem.nasa.gov/missions/lunokhod-01/in-depth/ [146]
- Missions - Lunokhod 02: https://solarsystem.nasa.gov/missions/lunokhod-02/in-depth/ [147]

S16.06 Command, Data Handling, and Electronics

Lead Center: JPL

Participating Center(s): JPL, LaRC, MSFC

Scope Title:

Analog-to-Digital Conversion Components

Scope Description:

NASA's space-based observatories, flyby spacecraft, orbiters, landers, and robotic and sample-return missions require robust command and control capabilities. Advances in technologies relevant to command and data handling and instrument electronics are sought to support NASA's goals and several missions and projects under development. The 2022 subtopic goals are to develop platforms for the implementation of miniaturized highly integrated avionics and instrument electronics that:

- Are consistent with the performance requirements for NASA missions.
- Minimize required mass/volume/power as well as development cost/schedule resources.
- Can operate reliably in the expected thermal and radiation environments.
Successful proposal concepts should significantly advance the state of the art. Furthermore, proposals developing hardware should indicate an understanding of the intended operating environment, including temperature and radiation. Note that environmental requirements vary significantly from mission to mission. For example, some low-Earth-orbit missions have a total ionizing dose (TID) radiation requirement of less than 10 krad(Si), whereas planetary missions can have requirements well in excess of 1 Mrad(Si).

Specific technologies sought by this scope include:

- Radiation-hardened mixed-signal structured application-specific integrated circuit (ASIC) platforms to enable miniaturized and low-power science sensor readout and control, with sufficient capability to implement 12-bit digital-to-analog converters (DACs), monotonic and 12- to 16-bit analog-to-digital converters (ADCs) (<100 kHz 16-bit and 1 to 2 MHz 12-bit), and also charge-sensitive amplifiers for solid-state detectors and readout integrated circuit (ROIC) for silicon photomultipliers.
- Low-power, radiation-hardened ASIC devices to enable direct capture of analog waveforms.

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

**Primary Technology Taxonomy:**
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.1 Avionics Component Technologies

**Desired Deliverables of Phase I and Phase II:**

- Prototype
- Hardware
- Software
- Analysis
- Research

**Desired Deliverables Description:**

Desired Phase I deliverables include the design, simulation, and analysis to demonstrate viability of proposed component.

Desired Phase II deliverables include a prototype mixed-signal ASIC implemented with a proof-of-concept end-user design. The proof-of-concept design should demonstrate the stated performance capabilities of the ASIC.

**State of the Art and Critical Gaps:**

There is a need for a broader range of mixed-signal structured ASIC architectures. This includes the need for viable options for mixed ASICs with high-resolution, low-noise analog elements, especially 12-bit DACs and 12- to 16-bit ADCs. The current selection of mixed-signal structured ASICs is limited to 10-bit designs, which do not provide the accuracy or resolution to perform the science required of many of the instruments currently being flown. Mixed-signal structured ASICs can integrate many functions and therefore can save considerable size, weight, and power over discrete solutions—significantly benefiting NASA missions. The lack of parts with high-precision analog is greatly limiting their current application.

**Relevance / Science Traceability:**
Mixed-signal structured ASIC architectures are relevant to increasing science return and lowering costs for missions across all Science Mission Directorate (SMD) divisions. However, the benefits are most significant for miniaturized instruments and subsystems that must operate in harsh environments. These missions include interplanetary CubeSats and SmallSats, outer-planet instruments, and heliophysics missions to harsh radiation environments. For all missions, the higher accuracy would provide better science or allow additional science through the higher density integration.

References:

The following resources may be helpful for descriptions of radiation effects in electronics:

1. NASA Technical Reports Server: https://ntrs.nasa.gov/ [69]
2. NASA Electronic Parts and Packaging Program: https://nepp.nasa.gov/ [148]

Scope Title:

Low-Cost Data Acquisition System

Scope Description:

Destinations such as Mars, Venus, and Titan pose many challenges for entry, descent, and landing (EDL) data acquisition systems, including radiation, g-loading, and volume constraints. Recent notable examples of such systems are the Mars Entry, Descent, and Landing Instrumentation (MEDLI) and MEDLI2 sensor suites, which successfully acquired EDL data in 2012 and 2021, respectively. The NASA MEDLI and MEDLI2 data acquisition systems were very well designed and robust to the extreme environments of space transit and EDL but came at a great financial burden to these missions. The high cost prohibits smaller mission classes such as Discovery and New Frontiers from using MEDLI-like systems, therefore limits the EDL science that can be conducted by NASA. In an effort to bring EDL instrumentation to all missions, NASA seeks a low-cost, robust, high-accuracy data acquisition system. Wireless data acquisition capability would eliminate external radio-frequency interference coupling effects and represents a significant cost and mass savings opportunity on future NASA missions. For example, the sensor cable mass for the Orion Exploration Flight Test 1 (EFT-1) Developmental Flight Instrumentation (DFI) suite was 700 lb. of the entire 1200-lb DFI system. A wireless option for the low-cost data acquisition system is therefore highly desirable.

Data acquisition requirements:

- Compatibility: Minimum 15 thermocouples (minimum of 2 Type R and minimum of 8 Type K) and 8 pressure transducers (120- or 350-ohm bridge).
- Power: 16 W or less.
- Size: Modularity encouraged, max. module size of 10 cm$^3$, four modules max.
- Measurement resolution: 12 bit or higher.
- Acquisition rate: 8 Hz or higher.
- Weight: 5 kg or less.
- Accuracy: +/-0.5% of FSR (full scale range).
- Radiation tolerant by design: Minimum of 10 krad (30 krad or better desired).
- Axial loading capability: minimum 15g (Venus missions could require 100g to 400g).
- Temperature capability: -40 to +85 °C.
- Cost: Fully qualified target of ~$1M (recurring).

Optional wireless capability:
• Centralized or distributed architecture.
• Scalable architecture.
• 0.0% packet loss.
• Capable of operating independently for a minimum of 2 years.
• Completely wireless: data acquisition and communication powered by a battery or harvested energy (e.g., solar, thermal).

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

**Primary Technology Taxonomy:**
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.2 Avionics Systems and Subsystems

**Desired Deliverables of Phase I and Phase II:**

• Research
• Analysis
• Prototype
• Hardware
• Software

**Desired Deliverables Description:**

Phase I deliverables would include electrical system design, trade studies, component selections, requirements definitions, and systems analysis to result in a modeled and analyzed data acquisition system architecture. Early breadboard circuits or prototypes may be included.

Phase II deliverables would include production of a prototype low-cost data acquisition system and results from electrical performance testing. Testing may include some environmental and stress testing.

**State of the Art and Critical Gaps:**

The NASA MEDLI and MEDLI2 data acquisition systems were very well designed and robust to the extreme environments of space transit and EDL, but this comes at a great financial burden to these missions. The high cost prohibits smaller mission classes such as Discovery and New Frontiers from using MEDLI-like systems, therefore limiting the EDL science that can be conducted by NASA. To bring EDL instrumentation to all missions, NASA seeks a low-cost, robust, high-accuracy data acquisition system.

**Relevance / Science Traceability:**

This technology would be especially relevant to upcoming Science Mission Directorate (SMD) planetary missions, such as DAVINCI and VERITAS, but low-cost data acquisition systems with these capabilities would also be relevant to the other science lines of business, especially for future cost and volume-constrained and distributed-systems missions.

**References:**

1. MEDLI2: [https://www.nasa.gov/directorates/spacetech/gamechangingdevelopment/projects/MEDLI-2](https://www.nasa.gov/directorates/spacetech/gamechangingdevelopment/projects/MEDLI-2) [150]
The text from the image is as follows:

Scope Title:
Printed High Density Interconnects

Scope Description:

As the size of circuit boards continues to shrink and electronic component sizing continues to approach bare die form factors, NASA's need for high-reliability, high-density interconnection solutions is increasing. The ability to connect components or even larger assemblies together without the need for conventional connectors and harnessing stands to offer significant advantages to the size and weight requirements of command, data handling, and electronics systems. High-reliability interconnect methodologies that can operate in space environments (vacuum, vibration) and deliver hundreds of signal/power connections while using as little physical board area as possible are desired.

Chip-scale interconnection methodologies such as wirebonding are size and volume efficient, but present manufacturing, reliability, and handling challenges when applied in an exposed manner on otherwise conventional circuit board assemblies. NASA seeks manufacturing technologies that could be applied at the circuit board assembly level to create high-reliability, high-density electrical connections across three-dimensional (3D) topologies, such as connecting to the top surface of microcircuit die adhered to a substrate. Emerging additively manufactured and printed hybrid electronics technologies offer potential solutions that also address the reliability and handling challenges present with larger assembly implementations, but further development is needed to demonstrate performance and reliability for NASA applications.

Specifically, NASA is seeking:

- Capability to reliably print or produce 400 or more conductive traces, on the order of 50 to 100 µm width, with 100 to 200 µm pitch.
- Capability to reliably print or produce traces that can traverse a vertical shift to an elevated topology shifts of up to 1.5 mm in height. Printing or producing fillets or ramps to accommodate smooth transitions for the vertical topology shifts is acceptable.
- Electrical resistivity of the traces shall be no more than 300 ohm/mm, and isolation to adjacent traces shall be on the order of gigaohms.
- Printed or produced traces shall demonstrate alignment to target features on the substrates and the elevated topology surfaces.
- Demonstrated reliability and workmanship testing performance, such as vibration and thermal cycling.

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

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.2 Avionics Systems and Subsystems
Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Phase I deliverables would include development of prototype design, materials selection and trade studies, production of necessary equipment fixtures and tooling, and ultimately demonstration of the proposed interconnect manufacturing.

Phase II deliverables would include refinement of prototype designs, demonstration of consistent print production across multiple samples, electrical performance, and results of workmanship and reliability tests of produced designs.

State of the Art and Critical Gaps:

The current assembly process for arrays of die and sensors is wire bonding. However, as die become smaller and die pads become smaller and denser, this pushes the limits of wire bonding capabilities. The next generation of NASA science missions have needs for higher density interconnect solutions. Printed hybrid electronics technologies are emerging; however, they have not yet demonstrated suitable repeatability and reliability for use in NASA applications.

Relevance / Science Traceability:

These technologies would be broadly beneficial to command and data handling (C&DH) architectures on many NASA missions. There is also a crossover need for this technology on high-density detector systems that will be needed for NASA's next-generation science missions.

- Missions/Programs/Projects that could use the technology:
  - Large UV/Optical/IR Surveyor (LUVOIR).
  - Habitable Exoplanet Observatory (HabEx).
  - Cosmic Evolution Through UV Spectroscopy (CETUS).

References:

The following resources may be helpful for descriptions of radiation effects in electronics:

1. NASA Technical Reports Server: [https://ntrs.nasa.gov/](https://ntrs.nasa.gov/) [155]
2. NASA Electronic Parts and Packaging Program: [https://nepp.nasa.gov/](https://nepp.nasa.gov/) [148]
3. NASA/GSFC Radiation Effects and Analysis Home Page: [https://radhome.gsfc.nasa.gov/top.htm](https://radhome.gsfc.nasa.gov/top.htm) [149]
Scope Title:
Intelligent Hardware Supervisors

Scope Description:
The space radiation environment and single-event effects (SEEs) are known to cause errors and interruptions in electronics circuitry. NASA has an increasing need to achieve higher performance processing and microcircuits, and this often requires infusion of commercial electronic parts, which may not be explicitly designed for radiation tolerance. One critical aspect to successfully using these commercial technologies in a space system is being able to recognize when a component has been hit by a SEE and commanding that component to reset itself, without causing major disruption to the entire system.

To this goal, NASA seeks responsive or intelligent hardware supervisor components for SEEs. Ideally, a microcircuit that can monitor the operational profile of other components and intelligently determine what is and is not a latchup or other event versus a computationally intense processing state, especially for consumer/COTS (commercial-off-the-shelf) electronics.

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

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.1 Avionics Component Technologies

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:
Phase I deliverables would include system design, trade studies, component selections, requirements definitions, and systems analysis to result in a modeled and analyzed system architecture. Early breadboard circuits or prototypes may be included.

Phase II deliverables would include production of a prototype(s) and electrical performance testing. Testing may include some environmental and stress testing.

State of the Art and Critical Gaps:
Existing hardware supervisors do exist, but they do not fully address the needs of NASA missions seeking to infuse modern COTS components. Supervisor methodologies are either too conservative, and overly reset devices causing undue downtime and data loss or are more intelligent to distinguish upsets but require computationally intense processing and power resources to implement. NASA needs supervisor components that can intelligently determine latchups or other events without a computationally intense processing state.

Relevance / Science Traceability:
These technologies would be relevant to increasing science return and lowering costs for missions across all Science Mission Directorate (SMD) divisions. However, the benefits are most significant for miniaturized
instruments and subsystems that must operate in harsh environments. These missions include interplanetary CubeSats and SmallSats, outer planets instruments, and heliophysics missions to harsh radiation environments.

References:

The following resources may be helpful for descriptions of radiation effects in electronics:

1. NASA Technical Reports Server: https://ntrs.nasa.gov/ [69]
2. NASA Electronic Parts and Packaging Program: https://nepp.nasa.gov/ [148]


S16.07 Cryogenic Systems for Sensors and Detectors

Lead Center: JPL

Participating Center(s): JPL

Scope Title

Low-Temperature/High-Efficiency Cryocoolers

Scope Description

NASA seeks improvements to multistage low-temperature spaceflight cryocoolers. Coolers are sought with the lowest temperature stage typically in the range of 4 to 10 K, with cooling power at the coldest stage larger than currently available and with high efficiency. The desired cooling power is application specific, but an example is 0.2 W at 4 K. Devices that produce extremely low vibration, particularly at frequencies below a few hundred hertz, are of special interest. System- or component-level improvements that improve efficiency and reduce complexity and cost are desirable. Examples of target missions include Origins, a mid- to far-infrared observatory that includes a large cold (4 K) telescope, and low-temperature (≤0.1 K) detectors; and the Lynx X-ray Observatory, which has a large, very low-temperature (~0.05 K) array of x-ray microcalorimeters. In addition to the large coolers, there has recently been interest in small, low-power (~10-mW) 4 K coolers for quantum communication and sensing instruments.

Expected TRL or TRL Range at completion of the Project

2 to 5

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II

- Prototype
- Hardware
Desired Deliverables Description

Phase I: Proof-of-concept demonstration.

Phase II: Functioning hardware ready for functional and possibly environmental testing.

State of the Art and Critical Gaps

Current spaceflight cryocoolers for this temperature range include linear piston-driven Stirling cycle or pulse-tube cryocoolers with Joule-Thompson low-temperature stages. One such state-of-the-art cryocooler provides 0.09 W of cooling at 6 K. For large future space observatories, large cooling power and much greater efficiency will be needed. For cryogenic instruments or detectors on instruments with tight pointing requirements, orders-of-magnitude improvement in the levels of exported vibration will be required. Some of these requirements are laid out in the “Advanced cryocoolers” Technology Gap in the latest (2017) Cosmic Origins Program Annual Technology Report.

Relevance / Science Traceability

Science traceability (from NASA’s Strategic plan):

- Goal 1: Expand the frontiers of knowledge, capability, and opportunity in space.
- Objective 1.6: Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars.

Low temperature cryocoolers are listed as a “Technology Gap” in the latest (2017) Cosmic Origins Program Annual Technology Report. Future missions that would benefit from this technology include two of the large missions under study for the 2020 Astrophysics Decadal Survey: Origins Space Telescope and Lynx microcalorimeter instrument.

References

- For more information on the Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/ [64]
- For more information on LYNX: https://wwwastro.msfc.nasa.gov/lynx/docs/science/observatory.html [157]

Scope Title

Actuators and Other Cryogenic Devices

Scope Description

NASA seeks devices for cryogenic instruments, including:

- Small, precise motors and actuators, preferably with superconducting windings, that operate with extremely low power dissipation. Devices using standard NbTi conductors, as well as devices using higher temperature superconductors that can operate above 5 K, are of interest.
- Cryogenic heat pipes for heat transport within instruments. Heat pipes using hydrogen, neon, oxygen, argon, and methane are of interest. Length should be at least 0.3 m. Devices that have reduced gravitational dependence and that can be made low profile, or integrated into structures such as radiators, are of particular interest.

Expected TRL or TRL Range at completion of the Project

3 to 4

Primary Technology Taxonomy
Desired Deliverables of Phase I and Phase II

- Prototype
- Hardware

Desired Deliverables Description

Phase I: Proof-of-concept test on a breadboard-level device.

Phase II: Working prototypes ready for testing in the relevant environments.

State of the Art and Critical Gaps

Motors and actuators: Instruments often have motors and actuators, typically for optical elements such as filter wheels and Fabry-Perot interferometers. Current cryogenic actuators are typically motors with resistive (copper) windings. While heat generation is naturally dependent on the application, an example of a recent case is a stepper motor used to scan a Fabry-Perot cavity; its total dissipation (resistive + hysteretic) is ~0.5 W at 4 K. A flight instrument would need heat generation at least 20× smaller.

Cryogenic heat pipes: Heat transport in cryogenic instruments is typically handled with solid thermal straps, which do not scale well for larger heat loads. Currently available heat pipes are optimized for temperatures above ~120 K. They have limited capacity to operate against a gravitational potential.

Relevance / Science Traceability


Almost all instruments have motors and actuators for changing filters, adjusting focus, scanning, and other functions. On low-temperature instruments, for example on mid- to far-IR observatories, dissipation in actuators can be a significant design problem.

References

For more information on earlier low-temperature heat pipes:

- Prager, R.C.: AIAA paper 80-1484, [159]
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 75 W and a total mass of 400 g is desired. The ability to fit within the volume and power limitations of a SmallSat platform would be highly advantageous. Cryocooler electronics are also sought in two general categories: (1) low-cost devices that are sufficiently radiation hard for lunar or planetary missions, and (2) very low-cost devices for a relatively short term (~1 year) in low Earth orbit. The latter category could include controllers for very small coolers, such as tactical and rotary coolers.

For many infrared (IR) spectrometer instrument systems, the spectrometer can operate at a temperature more than 60 K higher than the focal plane array. A miniature two-stage cryocooler is ideal for this type of application to minimize the cooler input power. Therefore, NASA is seeking an innovative miniature two-stage cryocooler technology with low exported vibrations. The lowest cooling temperature of interest for the lower stage is 80 K, and the maximum cooling power is about 1 W. The cooling temperature of the second stage should be 60 to 80 K higher than the lower stage, and the cooling power should be about 2 W.

For future advanced heterodyne sensors for submillimeter-wave receivers, the mixer in each sensor requires 50 to 100 mW of cooling at 15 to 20 K, and the local oscillator requires 1 to 2 W cooling power at 80 to 120 K. NASA is seeking advanced multistage cryocooler technologies that will enable these sensors to operate in SmallSat platform. The cryocooler input power must be compatible with available power in SmallSat platform, which is typically several tens of watts.

It is desirable that the cooler can efficiently operate over a wide heat sink temperature range, from -50 to 70 ºC.

Expected TRL or TRL Range at completion of the Project

2 to 4

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.1 Remote Sensing Instruments/Sensors

Desired Deliverables of Phase I and Phase II

- Prototype
- Hardware

Desired Deliverables Description

Phase I: Proof-of-concept demonstration.

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

State of the Art and Critical Gaps

Present state-of-the-art capabilities provide 0.1 W of cooling capacity with heat rejection at 300 K at approximately 5 W input power with a system mass of 400 g.

Cryocoolers enable the use of highly sensitive detectors, but current coolers cannot operate within the tight power constraints of outer planetary missions. There are no lightweight cryocoolers (<3 kg) that can provide cooling below 20 K. Cryocooler power could be greatly reduced by lowering the heat rejection temperature, but presently there are no spaceflight systems that can operate with a heat rejection temperature significantly below ambient.
Relevance / Science Traceability


NASA is moving toward the use of small, low-cost satellites to achieve many of its Earth science—and some of its planetary—science goals. The development of cryocoolers that fit within the size and power constraints of these platforms will greatly expand their capability, for example, by enabling the use of infrared detectors.

In planetary science, progress on cryogenic coolers will enable the use of far- to mid-infrared sensors with orders-of-magnitude improvement in sensitivity for outer planetary missions. These will allow thermal mapping of outer planets and their moons.

References

An example of CubeSat mission using cryocoolers: https://www.jpl.nasa.gov/cubesat/missions/ciras.php [161]

Scope Title

Sub-Kelvin Cooling Systems

Scope Description

Future NASA missions will require sub-Kelvin coolers for extremely low-temperature detectors. Systems are sought that will provide continuous cooling with high cooling power (>5 µW at 50 mK), and high heat rejection temperature (10 K), while maintaining high thermodynamic efficiency and low system mass.

Improvements in components for adiabatic demagnetization refrigerators are also sought. Specific components include:

(1) Compact, lightweight, low-current superconducting magnets capable of producing a field of at least 4 tesla (T) while operating at a temperature of at least 10 K, and preferably above 15 K. Desirable properties include:

- A high engineering current density (including insulation and coil packing density), preferably >300 A/mm².
- A field/current ratio of >0.5 T/A, and preferably >0.66 T/A.
- Low hysteresis heating.
- Bore diameters ranging between 22 and 40 mm, and lengths ranging between 50 and 100 mm, depending on the application.

(2) Shielding requirements include:

- Lightweight active/passive magnetic shielding (for use with 4-T magnets) with low hysteresis and eddy current losses as well as low remanence. Shields should reduce stray field to <0.1 mT at 100 mm from the outer surface. In addition to simple cylinders, toroidal and other self-shielding geometries will be considered.
- Lightweight, highly effective outer shields that reduce the field outside an entire multistage device to <5 µT. Outer shields must operate at 4 to 10 K and must have penetrations for low-temperature, noncontacting heat straps.

(3) Heat switches with on/off conductance ratio >30,000 and actuation time of <10 s. Switches are sought to cover the temperature range 20 K > T > 0.03 K, though the hot/cold temperature ratio for any one switch is typically <5. They should have an on-state conductance of >(500 mW/K) x (T/4.5 K). Devices with no moving parts are preferred.

(4) High-cooling-power-density magnetocaloric materials. Examples of desired materials include GdLiF₄, Yb₃Ga₅O₁₂, GdF₃, and Gd elpasolite. High-quality single crystals are preferred because of their high conductivity at
low temperature, but high-density polycrystals are acceptable in some forms. Volume must be >40 cm³.

(5) Suspensions with the strength and stiffness, but lower thermal conductance from 4 to 0.050 K.

**Expected TRL or TRL Range at completion of the Project**

2 to 4

**Primary Technology Taxonomy**

**Level 1**

TX 08 Sensors and Instruments

**Level 2**

TX 08.1 Remote Sensing Instruments/Sensors

**Desired Deliverables of Phase I and Phase II**

- Prototype
- Hardware

**Desired Deliverables Description**

Phase I: For components, a subscale prototype that proves critical parameters. For systems, a proof-of-concept test.

Phase II: For components, functioning hardware that is directly usable in NASA systems. For systems, a prototype that demonstrates critical performance parameters.

**State of the Art and Critical Gaps**

The adiabatic demagnetization refrigerator in the Soft X-ray Spectrometer instrument on the Hitomi mission represents the state of the art in spaceflight sub-Kelvin cooling systems. The system is a 3-stage, dual-mode device. In the more challenging mode, it provides 650 µW of cooling at 1.625 K, while simultaneously absorbing 0.35 µW from a small detector array at 0.050 K. It rejects heat at 4.5 K. In this mode, the detector is held at temperature for 15.1-h periods, with a 95% duty cycle. Future missions with much larger pixel count will require much higher cooling power at 0.050 K or lower, higher cooling power at intermediate stages, and 100% duty cycle. Heat rejection at a higher temperature is also needed to enable the use of a wider range of more efficient cryocoolers.

**Relevance / Science Traceability**


Future missions that would benefit from this technology include:

1. Two of the large missions under study for the 2020 Astrophysics Decadal Survey:
   - Origins Space Telescope (contact: michael.j.dipirro@nasa.gov [162]).
   - LYNX (microcalorimeter instrument) (contact: simon.r.bandler@nasa.gov [163]).
(2) Probe of Inflation and Cosmic Origins (POC: Shaul Hanany, University of Minnesota).

References

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


For articles describing magnetic sub-Kelvin coolers and their components:


S16.08 Atomic Quantum Sensor and Clocks

Lead Center: JPL

Participating Center(s): JPL

Scope Title
Atomic Quantum Sensor and Clocks

Scope Description
Space exploration relies on sensors for science measurements as well as spacecraft operation. As sensing precisions push their limits, quantum phenomena inevitably must be exploited. It is expected that sensors utilizing quantum properties will offer new and significantly improved capabilities. NASA is interested in advancing quantum sensing technologies and infusing them into space science missions. In particular, this call seeks the development and maturation towards space application and qualification of atomic systems that leverage their quantum properties (e.g., optical atomic clocks, atom interferometers, Rydberg atom sensors, artificial atom-based sensors such as nitrogen-vacancy (NV) center point-defect sensors, etc.).

Recent developments of laser control and manipulation of atoms have led to new types of quantum sensors and clocks. Atomic particles, being intrinsically quantum mechanical, have demonstrated theirs unique advantages in metrology and sensing. Perhaps the most celebrated atomic metrology tool is the atomic clock. Atomic clocks in the optical frequency domain (i.e., optical primary frequency standards) have approached, and are expected to exceed, a frequency uncertainty beyond 1 part in $1 \times 10^{18}$. These optical clocks can be used, in turn, as precision sensors; e.g., sensitivity to the fundamental physics constants has been explored for detection of dark matter and time variations in those fundamental constants.

Similarly, Doppler-sensitive quantum measurements of atomic particles led to exquisite inertial sensors, mostly in the form of atom interferometers. Because the center of mass motion is involved, atom interferometers use atomic particles as test masses and quantum matter-wave interferometry for motional measurements. Indeed, clocks and sensors are two sides of the same coin, sharing many common physical processes, technology approaches, and salient performance features. Therefore, this subtopic combines the two subject areas for leveraged and coordinated technology advancement. For many measurements the sensitivity scales as the square of the interaction time with an atom in free space. As this time can be dramatically longer ($\times 100$) in microgravity, these technologies are a natural fit for space exploration.

The gaps to be filled and technologies to be matured include, but are not limited to, the following:
(1) Optical atomic clocks

- Subsystem and components for high-performance and high-accuracy optical clocks, mostly notably Sr and Yb lattice clocks as well as Sr+ and Yb+ singly trapped ion clocks. They comprise atomic physics packages, which are necessarily laser systems, and include clock lasers, optical frequency combs, as well as advanced electronics and controllers based on microprocessors or field-programmable gate arrays (FPGAs). They should have a path to a flight system.
- Space-qualifiable small-size low-power clock lasers at, or subsystems that can lead to, better than $3 \times 10^{-15}$ Hz/$\sqrt{s}$ near 0.1 to 10 s (wavelengths for Yb+, Yb, and Sr clock transitions are of special interest).
- Technical approaches and methods for beyond-state-of-the-art compact and miniature clocks for space with emphasis on the performance per size, power, and mass.

(2) Atom interferometers

- Space-qualifiable high-flux ultra-cold atom sources, related components, and methods (e.g., >$1 \times 10^6$ total atoms near the point at <1 nK for Rb, K, Cs, Yb, and Sr).
- Ultra-high vacuum technologies and approaches for atom interferometer applications that allow small-size and low-power, completely sealed, nonmagnetic enclosures with high-quality optical access and are capable of maintaining <$1 \times 10^{-9}$ Torr residual gas pressure. Consideration should be given to the inclusion of cold atom sources of interest, such as switchable and/or regulated atom vapor pressure or flux.
  - Beyond the state-of-the-art photonic components at wavelengths for atomic species of interest, particularly visible and ultraviolet (UV):
    - Efficient acousto-optic modulators: e.g., low radio-frequency (RF) power ~200 mW, low thermal distortion, ~80% or greater diffraction efficiency.
    - Efficient electro-optic modulators: e.g., low bias drift, residual AM, and return loss; fiber-coupled preferred.
    - Miniature optical isolators: e.g., ~30 dB isolation or greater, ~ -2 dB loss or less.
    - Robust high-speed high-extinction shutters: e.g., switching time <1 ms and extinction >60 dB are highly desired.
- Flight qualifiable: i.e., rugged and long-life lasers or laser systems of narrow linewidth, high tunability, and/or higher power for clock and cooling transitions of atomic species of interest. Also, cooling and trapping lasers of 10 kHz linewidth and ~1 W or greater total optical power are generally needed, but offerors may define and justify their own performance specifications.
- Analysis and simulation tool of a cold atom system in trapped and free-fall states relevant to atom interferometer and clock measurements in space.

(3) Other atomic and artificial atomic sensors

- Rydberg sensors or their subsystems/components for electric field or microwave measurements.
- Space-qualifiable NV diamond or chip-scale atomic magnetometers.
- High-performance, miniaturized or chip-scale optical frequency combs.
- Other innovative atomic quantum sensors for high-fidelity field measurements that have space applications and can be developed into a space-quantifiable instrument.

Because of the breadth and diversity of the portfolio, performers are expected to be aware of specific gaps for specific application scenarios. All proposed system performances may be defined by offeror with clear justifications. Subsystem technology development proposals should clearly state the relevance to the anticipated system-level implementation and performance; define requirements, relevant atomic species, and working laser wavelengths; and indicate its path to a space-borne instrument. Finally, for proposals interested in quantum sensing methodologies for achieving the optimal collection of light for photon-starved astronomical observations, it is suggested to consider the STTR subtopic T8.06.

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

Primary Technology Taxonomy
Level 1
TX 08 Sensors and Instruments

Level 2
TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II

- Prototype
- Hardware
- Research
- Analysis
- Software

Desired Deliverables Description

Phase I deliverables: results of a feasibility study, analysis, and preliminary laboratory demonstration, as described in a final report.

Phase II deliverables: prototype or demonstration hardware; summary of performance analysis; and applicable supporting documentation, data, and/or test reports.

State of the Art and Critical Gaps
Many technology gaps exist in the development state of atomic sensors and clocks intended for NASA space applications. These gaps are mainly in the areas of reducing size, mass, and power, while increasing their performance and advancing them towards space qualification. These gaps may pertain to components, subsystems, instruments/devices, novel approaches, and/or theoretical analysis tools. Most of the needed improvements are elements that are beyond the current state of the art. These needed improvements include high-flux ultra-cold atom sources, atomic physics packages and atomic vacuum cell technology specific to clock and atom interferometer applications, miniature optical isolators, efficient modulators, active wave front and polarization devices, fast high-extension-ratio switches, efficient detectors, and novel frequency conversion methods/devices. Also needed are lasers and laser-optics system approaches with a high degree of integration and robustness that are suitable for atomic devices, small ultra-stabilized laser systems, and miniature self-referenced optical frequency combs. These are examples and not an exhaustive list.

Relevance / Science Traceability
Currently, no technology exists that can compete with the (potential) sensitivity, (potential) compactness, and robustness of atom-optical-based gravity- and time-measurement devices. Earth science, planetary science, and astrophysics all benefit from unprecedented improvements in gravity and time measurement. Specific roadmap items supporting science instrumentation include, but are not limited to:

TX07.1.1: Destination Reconnaissance, Prospecting, and Mapping (gravimetry)
TX08.1.2: Electronics (reliable control electronics for laser systems)
TX08.1.3: Optical Components (reliable laser systems)
TX08.1.4: Microwave, Millimeter, and Submillimeter-Waves (ultra-low noise microwave output when coupled w/ optical frequency comb)
TX08.1.5: Lasers (reliable laser system w/ long lifetime)

References
2020 NASA Technology Taxonomy: [https://go.nasa.gov/3hGhFJf](https://go.nasa.gov/3hGhFJf) [130]

S17.02 Integrated Science Mission Modeling

Lead Center: JPL

Participating Center(s): GSFC
Scope Title

Innovative System Modeling Methods and Tools

Scope Description

NASA seeks innovative systems modeling methods and tools addressing the following needs:

1. Define, design, develop, and execute future science missions by developing and utilizing advanced methods and tools that empower more comprehensive, broader, and deeper system and subsystem modeling while enabling these models to be developed earlier in the lifecycle. Ideally, the proposed solutions should leverage MBSE (model-based systems engineering)/SysML (System Markup Language) approaches being piloted across NASA, allow for easier integration of disparate model types, and be compatible with current agile design processes.

2. Enable disciplined system analysis for the design of future missions, including modeling of decision support for those missions and integrated models of technical and programmatic aspects of future missions.

3. Evaluate technology alternatives and impacts, science valuation methods, and programmatic and/or architectural trades.

4. Specific areas of interest are listed below. Proposers are encouraged to address more than one of these areas with an approach that emphasizes integration with others on the list:

- Conceptual phase models and tools that allow design teams to easily develop, populate, and visualize very broad, multidimensional trade spaces; also, methods for characterizing and selecting optimum candidates from those trade spaces, particularly at the architectural level. There is specific interest in models and tools that facilitate comprehensive comparison of architectural variants of systems.

- Capabilities for rapid-generation models of function or behavior of complex systems at either the system or the subsystem level. Such models should be capable of eliciting robust estimates of system performance given appropriate environments and activity timelines, and should be tailored:
  - To support emerging usage of autonomy, both in mission operations and flight software as well as in growing usage of autocoding.
  - To operate within highly distributed collaborative design environments, where models and/or infrastructure that support/encourage designers are geographically separated (including open innovation environments). This includes considerations associated with near-real-time (concurrent) collaboration processes and associated model integration and configuration management practices.
  - To be capable of execution at variable levels of fidelity/uncertainty. Ideally, models should have the ability to quickly adjust fidelity to match the requirements of the simulation (e.g., from broad and shallow to in depth and back again).

- Target models (e.g., phenomenological, or geophysical models) that represent planetary surfaces, interiors, atmospheres, etc., and associated tools and methods that allow for integration into system design/process models for simulation of instrument responses. These models may be algorithmic or numeric but should be useful to designers wishing to optimize remote sensing systems for those planets.

Note that this topic area addresses a broad potential range of science mission-oriented modeling tools and methods. This includes the integration of these tools into broader model-based engineering frameworks, and also includes proposals with MBSE/SysML as the primary focus.

Expected TRL or TRL Range at completion of the Project

3 to 5

Primary Technology Taxonomy

Level 1

TX 11 Software, Modeling, Simulation, and Information Processing
Desired Deliverables of Phase I and Phase II

- Prototype
- Software
- Research

Desired Deliverables Description

Phase I will result in a final report that describes the methodology and a clear proof of concept demonstrating the relevance of the technology for NASA use and provides insight into the next phase of maturation.

At the completion of Phase II, NASA requires a working prototype suitable for demonstrations with "real" data to make a compelling case for NASA usage. Use and development of the model—including all work performed to verify and validate it—shall be documented. Also, at the end of Phase II, there will be a clear indication of the path to commercialization.

State of the Art and Critical Gaps

There are currently a variety of models, methods, and tools in use across the Agency and with our industry partners. These are often custom, phase-dependent, and poorly interfaced to other tools. The disparity between the creativity in the early phases and the detail-oriented focus in later phases has created phase transition boundaries, where missions not only change teams, but tools and methods as well. We aim to improve this.

As NASA continues its move into greater use of models for formulation and development of NASA projects and programs, there are recurring challenges to address. This subtopic focuses on encouraging solutions to these cross-cutting modeling challenges.

These cross-cutting challenges include greater modeling breadth (e.g., cost/schedule), depth (scalability), variable fidelity (precision/accuracy vs. computation time), trade space exploration (how to evaluate large numbers of options), and processes that link them together. The focus is not on specific tools, but demonstrations of capability and methodologies for achieving the above.

The explosion of MBx (model-based everything) has led to a proliferation of models, modeling processes, and the integration/aggregation thereof. The model results are often combined with no clear understanding of their fidelity/credibility. Whereas some NASA personnel are looking for greater accuracy and "single source of truth," others are looking for the generation and exploration of massive trade spaces. Both greater precision and greater robustness will require addressing the cross-cutting challenges cited above.

Relevance / Science Traceability

Several concept/feasibility studies for potential large (flagship) astrophysics missions are in progress: Large UV/Optical/IR Surveyor (LUVOIR), Origins Space Telescope (OST), Habitable Exoplanet Observatory (HabEx), and Lynx. Following the 2020 Astrophysics decadal rankings, one of these will likely proceed to early Phase A, where the infusion of new and advanced systems modeling tools and methods would be a potential game changer in terms of rapidly navigating architecture trades, requirements development and flow down, and design optimization.

A variety of planetary missions require significant modeling and simulation across a variety of possible trade spaces. The portions of this topic area focused on breadth and variable fidelity will support them.

References

S17.03 Fault Management Technologies

Lead Center: JPL

Participating Center(s): ARC, MSFC

Scope Title

Development, Design, and Implementation of Fault Management Technologies

Scope Description

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

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

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

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

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

1. Fault management operations approaches: This category encompasses FM “in-the-loop,” including algorithms, computing, state estimation/classification, machine learning, and model-based reasoning. Further research into fault detection and diagnosis, prognosis, fault recovery, and mitigation of
unrecoverable faults is needed to realize greater system autonomy.

2. Fault management design and implementation tools: Also sought are methods to formalize and optimize onboard FM, such as model-based system engineering (MBSE). New technologies to improve or guarantee fault coverage, manage and streamline complex FM, and improve system modeling and analysis significantly contribute to the quality of FM design and may prove decisive in trades of new versus traditional FM approaches. Automated test case development, false positive/false negative test tools, model V&V tools, and test coverage risk assessments are examples of contributing technologies.

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

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

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

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

Expected TRL or TRL Range at completion of the Project

3 to 4

Primary Technology Taxonomy

Level 1

TX 10 Autonomous Systems

Level 2

TX 10.2 Reasoning and Acting

Desired Deliverables of Phase I and Phase II

- Analysis
Desired Deliverables Description

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

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

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

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

- For innovations that are algorithmic in nature, this could include development code or prototype applications, demonstrations of capability, and results of algorithm stress-testing.
- For innovations that are procedural in nature, this may include sample artifacts such as workflows, model prototypes and schema, functional diagrams, examples, or tutorial applications.
- Where a suitable test problem can be found, documentation of the test problem and a report on test results should illustrate the nature of the innovation in a quantifiable and reproducible way. Test reports should discuss maturation of the technology, implementation difficulties encountered and overcome, and results and interpretation.

Phase II proposals require 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 provision of trial or evaluation materials to future customers.
- Technical manuals, such as functional descriptions, specifications, and users guides.
- Conference papers or other publications.
- Establishment of a preliminary performance model describing technology metrics and requirements.

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

State of the Art and Critical Gaps

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

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

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

Relevance / Science Traceability

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

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

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


- Additional information is included in the talks presented at the 2012 FM Workshop:
  - [https://www.nasa.gov/offices/oce/documents/2012_fm_workshop.html](https://www.nasa.gov/offices/oce/documents/2012_fm_workshop.html) [168]
  - particularly [https://www.nasa.gov/sites/default/files/637595main_day_1-brian_muirhead.pdf](https://www.nasa.gov/sites/default/files/637595main_day_1-brian_muirhead.pdf) [169]

- 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](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060003929.pdf) [170]

- FM technologies are strongly associated with autonomous systems as a key component of situational awareness and system resilience. A useful overview was presented at the 2018 SMD Autonomy Workshop, archiving a number of talks on mission challenges and design concepts: [https://science.nasa.gov/technology/2018-autonomy-workshop](https://science.nasa.gov/technology/2018-autonomy-workshop) [172]
natural system.

Proposals MUST specify and be in alignment with existing and/or future NASA/NOAA programs. Research proposed to this subtopic should demonstrate technical feasibility during Phase I, and in partnership with scientists and/or engineers, show a path toward a Phase II prototype demonstration, with significant communication with missions and programs to later plan a potential Phase III infusion. It is highly desirable that the proposed projects lead to solutions that will be infused into government programs and projects.

Expected TRL or TRL Range at completion of the Project

4 to 6

Primary Technology Taxonomy

Level 1

TX 11 Software, Modeling, Simulation, and Information Processing

Level 2

TX 11.2 Modeling

Desired Deliverables of Phase I and Phase II

- Prototype
- Software
- Research

Desired Deliverables Description

Data products developed under this subtopic may be developed for broad public dissemination or used within a narrow scientific community. It is expected that the labeled training data sets, models, and resulting data assimilation products will be publicly accessible.

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

- New methods and approaches for science data assimilation.
- New/improved data assimilation products that can be used and infused into NASA science projects.
- Labeled training data sets and trained models specific to a given problem but that can also be used as a basis for furthering other science and engineering research and development.

More specifically:

- Phase I should be used to establish a proof of concept with deliverables including a final report, any software developed, training sets, etc.
- Phase II will expand on this proof of concept to a full prototype with a very similar set of deliverables, including a final report, software, training sets, etc.

State of the Art and Critical Gaps

NASA, along with other Federal Agencies and commercial and foreign research organizations that perform science and engineering, is making large strides in the use of artificial intelligence (AI) technologies (which includes computer vision, machine learning, and deep learning). This subtopic is looking to improve this by providing trained models that have the possibility of creating a better initial state of the physical system (i.e., Earth, solar wind, etc.) prior to being used as input for scientific data analysis and as input into physics-based simulations to improve forecasts.
In addition, emerging computational platforms now provide significant improvements in computing capabilities to enable AI to be applied to a wide variety of applications in science and engineering. These emerging computational capabilities have the potential to dramatically speed up AI calculations, and these systems are even being used as the reference architecture for exascale high-performance computing systems.

**Relevance / Science Traceability**

Broad applicability across throughout the decadal surveys and satellite development requirements to improve the quality and granularity of system forecasts:

- Improved measurements of the Earth system could provide better gap analysis for future mission requirements.
- Global Modeling and Assimilation Office (GMAO) assimilation: Augment data assimilation to improve computational performance or data quality.
- Carbon Cycle Ecosystems Office (CCOE): Wide variety of applications given the diversity of data sets from sparse in-situ to global satellite measurements.
- Earth Science Technology Office/Advanced Information Systems Technology (ESTO/AIST): New technology and services to exploit NASA and non-NASA data leading to digital twins of physical systems.
- Computational and Information Sciences and Technology Office (CISTO - Code 606): Computational, analytic, and visualization technologies used for new data science.
- NASA Center for Climate Simulation (NCCS - Code 606.2): Building applications toward exascale computing.

**References**

- 2013-2022 Decadal Survey in Solar and Space Physics
- NASA Goddard Institute for Space Studies: [https://www.giss.nasa.gov/](https://www.giss.nasa.gov/) [176]
- NASA Earth Science Data: [https://earthdata.nasa.gov/](https://earthdata.nasa.gov/) [45]
- NASA Center for Climate Simulation: [https://www.nccs.nasa.gov/](https://www.nccs.nasa.gov/) [177]
- NASA High-End Computing (HEC) Program: [https://www.hec.nasa.gov/](https://www.hec.nasa.gov/) [178]
- 2019 OSTP/OMB memo: Fiscal Year 2021 Administration Research and Development Budget Priorities

In addition, proposers are encouraged to search the NASA Technical Report Server (NTRS) for additional information to help guide potential solutions: [https://ntrs.nasa.gov/](https://ntrs.nasa.gov/) [69]