NASA SBIR 2020 Phase I Solicitation

Science

S1.01 Lidar Remote Sensing Technologies

Lead Center: GSFC

Participating Center(s): GSFC

Technology Area: TA15 Aeronautics

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 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 topography 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 balloons, 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 to retrieve the opacity of a gas.
- Ranging - Measures the return beam’s time-of-flight to retrieve distance.
- Doppler - Measures wavelength changes in the return beam to retrieve relative velocity.
- Differential absorption - Measures attenuation of two different return beams (one centered on a spectral line of interest) to retrieve concentration of a trace gas.

References

NASA missions are aligned with the National Research Council's decadal surveys, with the latest survey 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 [1]).


Conference proceedings on NASA lidar interests in earth science, exploration, and aeronautics can be found at the Technical Interchange Meeting on Active Optical Systems (https://www.nasa.gov/nesc/tim-active-optical-systems [3])

Expected TRL or TRL range at completion of the project 3 to 6
Desired Deliverables of 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. 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.

State of the Art and Critical Gaps

- Compact and rugged single-frequency continuous-wave and pulsed lasers operating between 290-nm and 2050-nm wavelengths suitable for lidar. Specific wavelengths are of interest to match absorption lines or atmospheric transmission: 290 to 320-nm (ozone absorption), 450 to 490-nm (ocean sensing), 532-nm, 817-nm (water line), 935-nm (water line), 1064-nm, 1570-nm (CO2 line), 1650-nm (methane line), and 2050-nm (Doppler wind). Architectures involving new developments in diode laser, quantum cascade laser, and fiber laser technology are especially encouraged. For pulsed lasers two different regimes of repetition rate and pulse energies are desired: from 1-kHz to 10-kHz with pulse energy greater than 1-mJ and from 20-Hz to 100-Hz with pulse energy greater than 100-mJ. Laser sources of wavelength at or around 780-nm are not sought this year.

- Novel approaches and components for lidar receivers such as: integrated optical/photonic circuitry, compact and lightweight Cassegrain telescopes compatible with existing differential absorption lidar (DIAL) and HSRL lidar systems, frequency agile solar blocking filters at 817-nm and/or 935-nm, and scanners for large apertures of telescope of at least 10-cm diameter and scalable to 50-cm diameter.

- New space lidar technologies that use small and high-efficiency diode or 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 fit into a 4U CubeSat or smaller. New lidar technologies 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.

- Transformative technologies and architectures are sought to vastly reduce the cost, size, and complexity of lidar instruments. Advances are needed in generation of high pulse energy (>> 1-mJ) from compact (CubeSat size) packages, avoiding the long cavity lengths associated with current solid-state laser transmitter designs. Mass-producible laser designs, perhaps by a hybrid diode/fiber/crystal architecture, are desirable for affordable sensor solutions and reducing parts count. Heat removal from lasers is a persistent problem, requiring new technologies for thermal management of laser transmitters. New materials concepts could be of interest for the reduction of weight for optical benches and telescopes. Distributed transmitter/receiver apertures may offer another option for weight reduction.

Relevance / Science Traceability

The proposed subtopic address many missions, programs, and projects identified by the Science Mission Directorate including:

Aerosols--ongoing and planned missions include ACE (Aerosols/Clouds/Ecosystems), PACE (Plankton, Aerosol, Cloud, ocean Ecosystems), and MESCAL (Monitoring the Evolving State of Clouds and Aerosols).

Greenhouse Gases--planned missions include sensing of carbon dioxide and methane. The ASCENDS (Active Sensing of CO2 Emissions over Nights, Days, and Seasons) mission was recommended by the Decadal Survey.

Ice Elevation--ongoing and planned missions include ICESat (Ice, Cloud, and land Elevation Satellite), as well as aircraft-based projects such as IceBridge.

Atmospheric Winds--planned missions include 3D-Winds, as recommended by the Decadal Survey. Lidar wind measurements in the Mars atmosphere are also under study in the MARLI (Mars Lidar for Global Climate Measurements from Orbit) program.
Planetary Topography--altimetry similar to Earth applications is being planned for planetary bodies such as Titan and Europa.

Gases related to Air Quality--planned missions include sensing of tropospheric ozone, nitrogen dioxide, or formaldehyde to support NASA projects such as TOLNet (Tropospheric Ozone Lidar Network) and the Pandora Global Network.

Automated Landing, Hazard Avoidance, and Docking--technology development is called for under programs and missions such as ALHAT (Autonomous Landing and Hazard Avoidance Technology), SPLICE (Safe and Precise Landing Integrated Capabilities Evolution), and NPLP (NASA Provided Lunar Payloads).

S1.02 Technologies for Active Microwave Remote Sensing

Lead Center: GSFC
Participating Center(s): GSFC
Technology Area: TA15 Aeronautics

This subtopic supports technologies to aid NASA in its active microwave sensing missions. Specifically, we are seeking:

1 Watt G-band (167-175 GHz) Solid State Power Amplifier for Remote Sensing Radars - Future cloud, water, and precipitation missions require higher frequency electronics, with small form factors and high Power Added Efficiencies (PAE) in order to measure smaller particles and enable compact instruments. Solid state amplifiers that meet high efficiency (>20% 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 2-4 at the completion of the project.

GPS (Global Positioning System) Denied Timing Synchronization - This would enable multi-platform instruments to share timing, which is enabling for GPS-denied environments (e.g., planetary exploration or GPS-hostile locations on Earth such as the subsurface). Multi-static radar has many applications for planetary science, but is impractical due to the lack of universal timing systems, such as what GPS provides on Earth. A low SWaP (size, weight, and power) system would be enabling for small, multi-static radars to perform in non-terrestrial environments. We desire to wirelessly distribute a synchronized PPS and/or 10 MHz clock in a GPS-denied environment between multiple radar units with <0.5 ns accuracy. The system should perform at distances of up to 5 km; synchronization hardware should be low mass (<1 kg), low power (<1 W), and small size (<5x5x10 cm). Ideally, the system should have a path to flight qualification to be used for lunar and planetary science. Deliverables include design and analysis of potential solutions, for which realizable hardware exists or is plausibly able to be developed with current technology. We expect a system with TRL 2-4 at the completion of the project.

V Band SSPA (65-71 GHz) – We seek highly efficient solid-state power amplifier (SSPA) for pressure sensing. No commercial solutions exist that satisfy high power added efficiency and bandwidth in a form factor suitable for CubeSat/SmallSat platforms. The desired capability is for smallsats doing surface pressure sensing absorption radar using V-band. The total SSPA bandwidth desired is 65-71 GHz with a maximum power of 10+ Watts at 65 GHz and 1+ Watt at 70 GHz. The package should be suitable for CubeSat/SmallSat platforms with high power added efficiency. SSPA should be pulsed with a minimum duty cycle of 25% and be suitable for a spaceflight environment. Desired deliverables are V-band SSPA prototype. We expect TRL 4-5 at the completion of the project.

Extreme environments Digital-to-Analog Converter (DAC) – We seek a single chip (or single package) DAC, capable of surviving and maintaining performance in high radiation environments (~100's krad), including ELDRS (enhanced low dose rate sensitivity) in the range of approximately 0.5-10 mrad (Si)/s. This capability is relevant to planetary remote sensing. The DAC should support a sampling rate of 500Ms/s or higher, with an effective number of bits >6. The desired deliverable is a DAC prototype.
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 [4]. 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 2020 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


Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

S1.03 Technologies for Passive Microwave Remote Sensing

Lead Center: GSFC

Participating Center(s): JPL

Technology Area: TA15 Aeronautics

Scope Title

Components for addressing gain instability in Low Noise Amplifier (LNA) based radiometers from 100 and 600 GHz

Scope Description

NASA requires low insertion loss solutions to the challenges of developing stable radiometers and spectrometers operating above 100 GHz that employ LNA based receiver front ends. This includes noise diodes with Excess Noise Ratio (ENR) > 10dBm with better than ? 0.01 dB/°C thermal stability, Dicke switches with better than 30 dB isolation, phase modulators, and low loss isolators along with fully integrated state-of-art receiver systems operating at room and cryogenic temperatures.

Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype, Hardware

Desired Deliverables Description

Hardware to enable low-loss radiometer gain calibration above 100 GHz.

State of the Art and Critical Gaps

Traditional internal microwave radiometer gain instability calibration electronics become prohibitively lossy as the
frequency increases above 100 GHz. As such, radiometers at this frequency are most commonly calibrated with external references. These are larger and more massive than internal calibration electronics.

Relevance / Science Traceability

Critical need: Immediate for 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.

Scope Title
Ultra Compact Radiometer

Scope Description

An ultra-compact radiometer of either a switching or pseudo-correlation architecture with internal calibration sources is needed. Designs with operating frequencies at the conventional passive microwave bands of 36.6 GHz (priority), 18.65 GHz, and 23.8 GHz enabling dual-polarization inputs. Interfaces include waveguide input, control, and digital data output. Ideal design features enable subsystems of multiple (10's of) integrated units to be efficiently realized.

Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype, Hardware

Desired Deliverables Description

Ultra-compact radiometer prototype.

State of the Art and Critical Gaps

Current microwave radiometers at this frequency are bulky with significant waveguide and coaxial interconnects. Dramatically smaller systems are desired for small SmallSat and CubeSat payloads, or for arrays of radiometer receivers.

Relevance / Science Traceability

This technology, in conjunction with deployable antenna technology, would enable traditional Earth land and ocean radiometry with significantly reduced instrument size, making it suitable for CubeSat or SmallSat platforms.

Scope Title
Correlating radiometer front-ends and low 1/f-noise detectors for 100-700 GHz

Scope Description

Low DC power correlating radiometer front-ends and low 1/f-noise detectors are required for 100-700 GHz. Deliverables should provide improved calibration stability, sensitivity, or 1/f noise performance compared to conventional total-power or Dicke / noise-injection radiometers at these frequencies.

Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype, Hardware
Desired Deliverables Description

Low DC power correlating radiometer front-ends and low 1/f-noise detectors for 100-700 GHz.

State of the Art and Critical Gaps

The low DC power consumption is critical for small missions, such as CubeSats. Low 1/f-noise of the detectors and correlating radiometers needed for radiometer stability across the scan for measurements at above 100 GHz for atmospheric humidity and cloud measurements as well as atmospheric chemistry.

Relevance / Science Traceability

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.

Scope Title
Photonic Integrated Circuits for Microwave Remote Sensing

Scope Description

Photonic Integrated Circuits are an emerging technology for passive microwave remote sensing. NASA is looking for photonic integrated circuits for processing microwave signals in spectrometers, beam forming arrays, correlation arrays and other active or passive microwave instruments.

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

PIC designs to enable increased capability in passive microwave remote sensing instruments. This is a low-TRL emerging technology, so vendors are encouraged to identify and propose designs where PIC technology would be most beneficial.

State of the Art and Critical Gaps

Photonic Integrated Circuits (PIC) are an emerging technology not used in current NASA microwave missions, but may enable significant increases in bandwidth.

Relevance / Science Traceability

PICs may enable significantly increased bandwidth of Earth viewing, astrophysics, and planetary science missions. In particular, this may allow for increased bandwidth or resolution receivers, with applications such as hyperspectral radiometry.

Scope Title
Spectrometer back ends for microwave radiometers

Scope Description

Technology for low-power, rad-tolerant broad band spectrometer back ends for microwave radiometers.
Possible Implementations Include:

- Digitizers starting at 20 Gsps, 20 GHz bandwidth, 4 or more bit and simple interface to FPGA;
- ASIC implementations of polyphase spectrometer digital signal processing with ~1 Watt/GHz.
- 5-GHz bandwidth polarimetric-spectrometer with 512 channels. Two simultaneously sampled ADC inputs. Spectrometer filter banks and either polarization combiners or cross correlators for computing all four Stokes parameters (any Stokes vector basis is acceptable: e.g., IQUV, vhUV, vhpmlr). Kurtosis detectors on at least the two principal channels. Rad-hard and minimized power dissipation.
- Combined radar/radiometer receiver with radiometer spectral processing (polyphase filter bank or FFT) synchronized with radar matched filtering and moment processing.

**Expected TRL or TRL range at completion of the project:** 4 to 5

**Desired Deliverables of Phase II**

Prototype, Analysis, Hardware

**Desired Deliverables Description**

The desired deliverable of this Subtopic Scope is a low-power Spectrometer ASIC or other component that can be incorporated into multiple NASA radiometers.

**State of the Art and Critical Gaps**

Current FPGA based spectrometers require ~10 W/GHz and are not flight qualifiable. High speed digitizers exist but have poorly designed output interfaces. Specifically designed ASICs could reduce this power by a factor of 10.

**Relevance / Science Traceability**

Broadband spectrometers are required for Earth observing, planetary, and astrophysics missions. Improved digital spectrometer capability is directly applicable to planetary science, and enables Radio Frequency Interference (RFI) mitigation for Earth science.

**S1.04 Sensor and Detector Technologies for Visible, IR, Far-IR, and Submillimeter**

**Lead Center:** GSFC

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

**Technology Area:** TA15 Aeronautics

**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:

- Earth Science and Applications from Space: [http://www.nap.edu/catalog/11820.html](http://www.nap.edu/catalog/11820.html) [8]

**Technologies for visible detectors are not being solicited this year.**

**LOW-POWER & LOW-COST READOUT INTEGRATED ELECTRONICS**

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

**MKID/TES Detectors:** A radiation tolerant, digital readout system is needed for the readout of low temperature detectors such as Microwave Kinetic Inductance Detector (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 1500 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 an RF System on a Chip or ASIC with combined digitizer and channelizer functionality.

**Bolometric Arrays:** Low power, low noise, cryogenic multiplexed readout for large format two-dimensional bolometer arrays with 1000 or more pixels, operating at 65-350 mK. We require a superconducting readout capable of reading two Transition Edge Sensors (TESs) per pixel within a 1 mm-square spacing. The wafer-scale readout of interest will be capable of being indium-bump bonded directly to two-dimensional arrays of membrane bolometers. We require row and column readout with very low crosstalk, low read noise, and low detector Noise Equivalent Power degradation.

**Thermopile Detector Arrays:** Mars Climate Sounder (MCS), the Diviner Lunar Radiometer Experiment (DLRE), and the Polar Radiant Energy in the Far Infrared Experiment (PREFIRE) are NASA space-borne radiometers that utilize custom thermopile detector arrays. Next-generation radiometers will use larger format thermopile detector arrays, indium bump bonding to hybridize the detector arrays to the Readout Integrated Circuits (ROICs), low input-referred noise, and low power consumption. ROICs compatible with 128x64 element Bi-Sb-Te thermopile arrays with low 1/f noise, an operating temperature between 200-300 K, radiation hardness to 300 krad and on-ROIC analog-to-digital converter (ADC) will be desirable.

**LIDAR DETECTORS**

Development of single-mode fiber-coupled extended-wavelength integrated InGaAs detectors/preamplifiers for heterodyne detection lidar at 2-2.1 um wavelengths with near shot-noise-limited performance for less than 3 mW local oscillator power, quantum efficiency > 90% over 2-2.1 um wavelengths, and bandwidth > 5 GHz. Specifications should be demonstrated in heterodyne detection experiments.

**IR & 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 (YBCO, MgB2) or engineered semiconductor materials, especially 2-Dimensional 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.

**Receiver Components:** Local Oscillators capable of spectral coverage 2-5 THz; Output power up to > 2 mW; Frequency agility with > 1 GHz near chosen THz frequency; Continuous phase-locking ability over the THz tunable range with < 100 kHz line width. Both solid-state (low parasitic Schottky diodes) as well as Quantum Cascade Lasers (for f > 2 THz) will be needed. Components and devices such as mixers, isolators, and orthomode transducers, working in the THz range, that enable future heterodyne array receivers are also desired. GaN based power amplifiers at frequencies above 100 GHz and with PAE > 25% are also needed. ASIC based SoC (System on Chip) solutions are needed for heterodyne receiver backends. ASICs capable of binning > 6 GHz intermediate frequency bandwidth into 0.1-0.5 MHz channels with low power dissipation < 0.5 W would be needed for array receivers.
References

and


Desired Deliverables of Phase II

Prototypes and analysis

Desired Deliverables Description

- All of the detectors and associated readout and other technologies can be built as prototypes to advance TRL. Detailed analysis of the operation and tradeoff space would also be very helpful.

State of the Art and Critical Gaps

Efficient multi-pixel readout electronics are needed both for room temperature operation as well as cryogenic temperatures. We can produce millions-of-pixel detector arrays at infrared wavelengths up to about 14 microns, only because there are readout circuits (ROIC) available on the market. Without these, high-density, large-format infrared arrays such as Quantum Well Infrared Photodiode, HgCdTe, and Strained Layer Superlattice 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 readout integrated circuits (ROICs) typically have well depths of less than 10 million electrons.

6-9bit, ROACH-2 board solutions with 2000 bands, <10kHz bandwidth in each are SOA.

IR detector systems are needed for Earth imaging based on the recently release Earth Decadal Survey.

Direct detectors with D~10^9 cm-rtHz/W achieved in this range. Technologies with new materials that take advantage of cooling to the 30-100K range are capable of D~10^12 cm-rtHz/W. Broadband (>15%) heterodyne detectors that can provide sensitivities of 5 to 10 times the quantum limit in the submillimeter-wave range while operating at 30-77 K are an improvement in the state or art due to higher operating temperature.

Detector array detection efficiency < 20% at 532nm (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 3dB gain bandwidth of around 3 GHz. Novel superconducting material such a MgB2 can provide significant enhancement of up to 9 GHz IF bandwidth.

Cryogenic Low Noise Amplifiers (LNAs) in the 4-8 GHz bandwidth with thermal stability are needed for Focal Plane Arrays, Origins Space Telescope (OST) instruments, Origins Survey Spectrometers (OSS), microwave kinetic inductance detectors (MKIDs), Far-infrared Imager and Polarimeters (FIP), Heterodyne Instrument on OST (HERO), and the Lynx Telescope. DC power dissipation should be only a few mW.

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

15-20 dB Gain and <5 Kelvin Noise over the 4-8 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 State of the Art readout circuit is capable of reading one TES per pixel in a 1 mm square area. 2D arrays developed by NIST have been a boon for current NASA programs. However, NIST has declined to continue to produce two-dimensional circuits, or to develop one capable of two TES-per-pixel readout. This work is extremely important to NASA’s filled, kilopixel bolometer array program.

Two dimensional cryogenic readout circuits are analogous to semiconductor Readout Integrated Circuits operating at much higher temperatures. We can produce millions-of-pixel detector arrays at infrared wavelengths up to about 14 microns, only because there are readout circuits (ROIC) available on the market. Without these, high-density, large-format infrared arrays such as Quantum Well Infrared Photodiode, HgCdTe, and Strained Layer Superlattice would not exist.

For Lidar detectors, extended wavelength InGaAs detector/preamplifier packages operating at 2-2.1 micron wavelengths with high quantum efficiency (> 90%) operating up to about 1 GHz bandwidth are available as are packages operating up to about 10 GHz with lower quantum efficiency. Detectors that have > 90% quantum efficiency over the full bandwidth from near DC to > 5 GHz and capable of achieving near-shot-noise limited operation are not currently available.

Relevance / Science Traceability

- Future short-wave, mid-wave, and long-wave infrared 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 super-sensitive and broadband and provide imaging capability (multi-pixel).
- Aerosol spaceborne lidar as identified by 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 Origins Space Telescope (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 infrared earth observing missions.
- Current Science missions utilizing two-dimensional, large-format cryogenic readout circuits:
  1. HAWC + (High Resolution Airborne Wideband Camera Upgrade) for SOFIA (Stratospheric Observatory for Infrared Astronomy) Future missions:
1) PIPER (Primordial Inflation Polarization Experiment), Balloon-borne
2) PICO (Probe of Inflation and Cosmic Origins, a Probe-class Cosmic Microwave Background mission concept

- Lidar detectors are needed for 3D wind measurements from space.

S1.05 Detector Technologies for UV, X-Ray, Gamma-Ray Instruments

Lead Center: GSFC
Participating Center(s): GSFC, MSFC
Technology Area: TA15 Aeronautics

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 Earth Science 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
- Solid-state detectors with polarization sensitivity relevant to astrophysics as well as planetary and Earth science applications for example in spectropolarimetry
- 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 > 10E6 at a breakdown reverse voltage between 80 and 100 V; detection capability of better than 6 photons/pixel/s down to 135 nm wavelength. See needs of National Research Council's Earth Science Decadal Survey (NRC, 2007): Tropospheric ozone.
- Solar-blind (visible-blind) UV, far-UV (80-200 nm), EUV sensor technology with high pixel resolution, large format, high sensitivity and high dynamic range, low voltage and power requirements; with or without photon counting.
- UV detectors suitable for upcoming Ultrahigh-Energy Cosmic Ray (UHECR) mission concepts
- Solar X-ray detectors with small independent pixels (<250 µm) and fast read-out (>10,000 count/s/pixel) over an energy range from <5 keV to 300 keV.
- Supporting technologies that would help enable X-ray Surveyor mission that requires the development of X-ray microcalorimeter arrays with much larger field of view, ~10^5-10^6 pixels, of pitch ~25-100 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. Filters with supporting grids are sought that, in addition to increasing filter strength, also enhance EMI shielding (1 - 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 ultraviolet transmission of less than 5% per filter. Means of producing filter diameters as large as 10 cm should be considered.

- Detectors with fast readout that can support high count rates and large incident flux from the extreme UV (EUV) and X-Rays for heliophysics applications, especially solar-flare measurements.

References

- Planetary Missions Program Office: https://planetarymissions.nasa.gov/ [16]

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

Results of tests and analysis of designs and/or prototype hardware. Hardware for further testing and evaluation.

State of the Art and Critical Gaps

This subtopic aims to develop and advance detector technologies focused on ultraviolet, x-ray, gamma ray spectral range. The science needs in this range spans a number of fields with main focus 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 while more complex material 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

Flagship missions under study: Large Ultraviolet Optical Infrared Surveyor (LUVOIR), Habitable Exoplanet Observatory (HabEx), Lynx, New Frontier-IO,

- Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/ [22]
- The LYNX Mission Concept: https://wwwastro.msfc.nasa.gov/lynx/ [23]
- NASA Astrophysics: https://science.nasa.gov/astrophysics/ [24]
- The Explorers Program: https://explorers.gsfc.nasa.gov/ [25]

S1.06 Particles and Fields Sensors & Instrument Enabling Technologies

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

Technology Area: TA15 Aeronautics

Scope Description:

The 2013 National Research Council’s, Solar and Space Physics: A Science for a Technological Society (http://nap.edu/13060 [26]) 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 elementary particles (atoms, molecules and their ions) and electric and magnetic fields in space and 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 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 particles and fields 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 subtopic solicits instrument development that provides significant advances in the following areas:

- Mini scalar-only temperature insensitive absolute magnetometer for CubeSats
- Magnetically clean >2 meter compact deployable booms for CubeSats
- Complementary metal-oxide-semiconductor (CMOS) active pixel type or charge-coupled device (CCD) type electron detectors in the energy range ~0.1-20KeV
- Fast visible light CMOS or CCD imaging detectors for high sensitivity (10 photons per pixel) read out of scintillator crystal light tracks caused by incident neutrons or protons
- Wide energy fast particle detectors resistant to very high radiation of >100Mrads, for instance diamond detectors.
- Grids, collimators and other components that enable the rejection of stray UV or visible light
- Innovative high efficiency neutral particle ionizers based on thermionic, cold electron emission or UV ionization
- Direct neutral particle detectors to energies <1eV
- High-resolution and high-efficiency UV-blind ENA detectors
- High voltage space qualified optocoupler components for >20KV power supplies
- Innovative miniature nested electrostatic analyzers for scan-less energy analysis
- Detectors/sensors for interplanetary/interstellar dust detection
  - Electronics technologies (e.g., field programmable gate array (FPGA) and application-specific integrated circuit (ASIC) implementations, advanced array readouts, miniature high voltage power supplies)

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 [4]. 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 2020 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:

For example missions, see http://science.nasa.gov/missions [27]. (E.g. NASA Magnetospheric Multiscale (MMS) mission, Fast Plasma Instrument)

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 [26]).

Expected TRL or TRL range at completion of the project: 3-6

Desired Deliverables of Phase II (Check all that apply):

Prototype, Hardware

Desired Deliverables Description:

A prototype component that can be tested in engineering model instruments.

State of the Art and Critical Gaps:

In situ particles and fields instruments and technologies are essential bases to achieve the Science Mission Directorate’s (SMD) Heliophysics goals summarized in the National Research Council’s, Solar and Space Physics: A Science for a Technological Society. These 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 particles and fields instrumentation 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, 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 mass, power and volume.

Relevance / Science Traceability:

Particles and fields instruments and technologies are essential bases to achieve 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 particles and fields 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. 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. Further opportunities through SMD include Explorer Missions, New Frontiers Missions, and the upcoming Geospace Dynamic Constellation.
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 & innovative scientific measurements are solicited. For examples of NASA science missions, see https://science.nasa.gov/missions-page [28]. 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/ [20]), 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** - Sub-systems 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, 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 elemental, mineralogical, and organic composition of planetary materials are sought. 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 are sought. 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.

- **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 depth in a comet nucleus, 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 towards 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** - 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.

- **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 be comprised of multiple free-standing seismic stations which 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.

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.

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 [4]. 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 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

**Expected TRL or TRL range at completion of the project:** 3 to 5

**Desired Deliverables of Phase II**

Prototype, Analysis, Hardware, Software

**Desired Deliverables Description**

*In-situ* instruments in TRL 3 - 5 for planetary science purpose

**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 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 requirement and challenges for diverse planetary bodies. For example, there is urgent need for exploring RSL (recurring slope lineae) on Mars, 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 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 additional 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, and the Maturation of Instruments for Solar System Exploration (MatISSE) Program, which invests in mid-TRL technologies and enables timely and efficient infusion of technology into planetary science missions.

**S1.08 Suborbital Instruments and Sensor Systems for Earth Science Measurements**

Lead Center: GSFC

Participating Center(s): ARC, GSFC, JPL

Technology Area: TA15 Aeronautics

**Scope Description**
NASA seeks measurement capabilities that support current satellite and model validation, advancement of surface-based remote sensing networks, and targeted Airborne Science Program and ship-based field campaign activities as discussed in the Research Opportunities in Space and Earth Science (ROSES) solicitation. Data from such sensors also inform process studies to improve our scientific understanding of the Earth System. In-situ sensor systems (airborne, land, and water-based) can comprise stand-alone instrument and data packages; instrument systems configured for integration on ship-based (or alternate surface-based platform) and in-water deployments, NASA’s Airborne Science aircraft fleet or commercial providers, Unmanned Aircraft Systems (UAS), or balloons, ground networks; or end-to-end solutions providing needed data products from mated sensor and airborne/surface/subsurface platforms. An important goal is to create sustainable measurement capabilities to support NASA’s Earth science objectives, with infusion of new technologies and systems into current/future NASA research programs. Instrument prototypes as a deliverable in Phase II proposals and/or field demonstrations are highly encouraged.

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

Specific desired sensors or mated platform/sensors include:

- A hyperspectral radiometry system with polarization capability covering the UV-Vis-NIR wavelength range (350-865 with a minimum resolution of 5 nm; 2.5-nm desired). The instrument shall measure hyperspectral above water upwelling radiance, sky radiance, downwelling irradiance and polarization state of the atmosphere and ocean, and be capable of autonomously positioning itself with respect to the sun for optimized measurement geometry.
- An in situ hyperspectral ocean water absorption instrument (ocean submersible to 300 m) covering the UV-Vis wavelength range (resolution of 2nm for 350-750 nm and 5nm for 300-350nm) with an accuracy better than 0.005 m$^{-1}$ or 5% of the signal and precision better than 0.001 m$^{-1}$. Instrument design must mitigate/correct for the confounding effects of scattering and fluorescence.
- In-situ measurements of ocean particulate backscatter, depolarization, beam attenuation, and diffuse attenuation coefficients relevant for combined ocean-atmosphere lidar remote sensing (355, 473, 486, 532, 1064 nm wavelengths and 170-180° scattering angle with 2 degree angular resolution).
- In situ polarized hyperspectral UV-Vis volume scattering function (VSF) instrument (ocean submersible to 300 m) covering the angular range close to 0 degrees and, more importantly so, as far as 180 degrees (with 2 degree angular resolution). Instrument should have ability to measure (at least) horizontal and vertical aspects of linear polarization. Degree of resolution in angles and wavelength can be decreased for instrument portability and robustness (such as for autonomous underwater vehicle (AUV) deployments).
- Portable hyperspectral UV-Vis-NIR radiometric calibration system with a stabilized optical light source for verification of field radiometer stability by traceable NIST standards with variable flux levels. System must include thermal stabilization for the instrument to be independent of ambient temperature for evaluation of radiometric stability as function of time.
- Innovative, high-value sensors directly targeting a stated NASA need (including aerosols and trace gases) may also be considered. Proposals must identify a specific, relevant NASA subject matter expert.

Expected TRL or TRL range at completion of the project is: 4 to 7

**Desired Deliverables of Phase II**: Prototype, Hardware, and/or Software

**Desired Deliverables Description**: 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 S1.08 subtopic is and remains highly relevant to NASA Science Mission Directorate (SMD) and Earth Science research programs, in particular the Earth Science Atmospheric Composition, Climate Variability & Change, and Carbon Cycle and Ecosystems focus areas. In situ and ground-based sensors inform NASA ship and airborne
science campaigns led by these programs and provide important validation of the current and next-generation of satellite-based sensors (e.g., PACE, OCO-2, TEMPO, SGB, and 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., NAAMES, EXPORTS, CAMP2EX, FIREX-AQ, KORUS-AQ, DISCOVER-AQ (see links in references).

References:

Relevant current and past satellite missions and field campaigns include:

PACE Satellite Mission, scheduled to launch in 2022 that focuses on observations of ocean biology, aerosols, and clouds (https://pace.gsfc.nasa.gov/ [29])

Decadal Survey Recommended ACCP Mission focusing on aerosols, clouds, convection, and precipitation/Aerosols and Clouds, Convection and Precipitation (ACCP) (combined) (https://science.nasa.gov/earth-science/decadal-surveys [30])

Decadal Survey Recommended SGB Mission focusing on surface biology and geology/ Surface Biology and Geology (https://science.nasa.gov/earth-science/decadal-surveys [30])

OCO-2 Satellite Mission that targets spaceborne observations of carbon dioxide and the Earth’s carbon cycle (https://www.nasa.gov/mission_pages/oco2/index.html [31])

TEMPO Satellite Mission focusing on geostationary observations of air quality over North America (http://tempo.si.edu/overview.html [32])

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 [33])

EXPORTS field campaign targeting the export and fate of upper ocean net primary production using satellite observations and surface-based measurements (https://oceanexports.org [34])

CAMP2Ex airborne field campaign focusing on tropical meteorology and aerosol science (https://espo.nasa.gov/camp2ex [35])

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/ [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])

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 [38])

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/ [39])

S1.09 Cryogenic Systems for Sensors and Detectors

Lead Center: GSFC

Participating Center(s): JPL

Technology Area: TA15 Aeronautics

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 high efficiency. The desired cooling power is application specific, but two examples are 0.3 Watts at 10 K and 0.2 Watts at 4 K. Devices that produce extremely low vibration, particularly at frequencies below a few hundred Hz, are of special interest. System or component level improvements that improve efficiency and reduce complexity and cost are desirable.

Expected TRL or TRL range at completion of the project: 2 to 5

Desired Deliverables of Phase II:

Prototype Hardware

Desired Deliverables Description

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 point 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: Goal 1 and Objective 1.6 of 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.


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
- Lynx microcalorimeter instrument

References

For more information on the Origins Space Telescope, see: https://asd.gsfc.nasa.gov/firs/ [40]
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.

Expected TRL or TRL range at completion of the project: 3 to 4

Desired Deliverables of Phase II:

Prototype Hardware

Desired Deliverables Description

Working prototypes ready for testing in the relevant environments are desired.

State of the Art and Critical Gaps

Motors and actuators: Instruments often have motors and actuators, typically for optical elements. In current cryogenic instruments, these devices often dissipate relatively large powers and are a significant design drivers.

Cryogenic heat pipes: Currently, heat transport in cryogenic instruments are handled with solid thermal straps. These do not scale well for larger heat loads.

Relevance / Science Traceability

Science traceability:
NASA Strategic plan 2018, Objective 1.1: Understand The Sun, Earth, Solar System, And Universe

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

References

For more information on earlier low temperature heat pipes, see


Scope Title
Ultra-Lightweight Dewars

Scope Description

NASA seeks extremely lightweight thermal isolation systems for scientific instruments. An important example is a large cylindrical, open top dewar to enable large, cold balloon telescopes. In one scenario, such a dewar would be
launched warm, and so would not need to function at ambient pressure, but at altitude, under ~4 millibar external pressure, it would need to contain cold helium vapor. The ability to rapidly pump and hold a vacuum at altitude is necessary. An alternative concept is that the dewar would be launched at operating temperature, with some or all of the needed liquid helium. In both cases, heat flux through the walls should be less than 0.5 Watts per square meter, and the internal surfaces must be leak tight against superfluid helium. Initial demonstration units of greater than 1 meter diameter and height are desired, but the technology must be scalable to an inner diameter of 3 – 4 meters with a mass that is a small fraction of the net lift capability of a scientific balloon (~2000 kg).

**Expected TRL or TRL range at completion of the project:** 3 to 4

**Desired Deliverables of Phase II:**

Prototype Hardware

**Desired Deliverables Description**

A working prototype of the scale described is desired.

**State of the Art and Critical Gaps**

Currently available liquid helium dewars have heavy vacuum shells that allow them to be operated in ambient pressure. Such dewars have been used for balloon-based astronomy, as in the Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission (ARCADE) experiment. However, the current dewars are already near the limit of balloon lift capacity, and cannot be scaled up to the required size for future astrophysics measurements.

**Relevance / Science Traceability**


The potential for ground-based infrared astronomy is extremely limited. Even in airborne observatories, such as SOFIA, observations are limited by the brightness of the atmosphere and the warm telescope itself. However, high altitude scientific balloons are above enough of the atmosphere that, with a telescope large enough and cold enough, background-limited observations are possible. The ARCADE project demonstrated that at high altitudes, it is possible to cool instruments in helium vapor. Development of ultra-lightweight dewars that could be scaled up to large size, yet still be liftable by a balloon would enable ground-breaking observational capability.

**References**

For a description of a state-of-the art balloon cryostat, see

**Scope Title**

Miniaturized/Efficient Cryocooler Systems

**Scope Description**

NASA seeks miniature, highly efficient cryocoolers for instruments on earth and planetary missions. A range of cooling capabilities sought. Two examples include 0.2 Watt at 30 K with heat rejection at 300 K, and 0.3 W at 35K with heat reject of 150 K. For both examples, an input power of ? 5 Watt and a total mass of ? 400 grams is desired. The ability to fit within the volume and power limitations of a SMALLSAT platform would be highly advantageous. Components, such as low-cost cryocooler electronics that are sufficiently rad hard for lunar or planetary missions, are also sought.

**Expected TRL or TRL range at completion of the project:** 2 to 4
Desired Deliverables of Phase II:

Prototype Hardware

Desired Deliverables Description

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 grams.

Cryocoolers enable the use of highly sensitive detectors, but current coolers cannot operate within the tight power constraints of outer planetary missions. 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 is given at: https://www.jpl.nasa.gov/cubesat/missions/ciras.php [44]

Scope Title

Sub-Kelvin Cooling Systems

Scope Description

Future NASA missions will require requiring sub-Kelvin coolers for extremely low temperature detectors. Systems are sought that will provide continuous cooling with high cooling power (> 5 microWatts at 50 mK), low operating temperature (<35 mK), and higher heat rejection temperature (preferably > 10K), 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 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 Amp/mm².
   - A field/current ratio of >0.33 Tesla/Amp, and preferably >0.66 Tesla/Amp.
2) Lightweight Active/Passive magnetic shielding (for use with 4 Tesla magnets) with low hysteresis and eddy current losses, and low remanence. Also needed are lightweight, highly effective outer shields that reduce the field outside an entire multi-stage device to < 5 microTesla. Outer shields must operate at 4 - 10 K, and must have penetrations for low temperature, non-contacting heat straps.

3) Heat switches with on/off conductance ratio > 30,000 and actuation time of <10 s. Materials are also sought for gas gap heat switch shells: these are tubes with extremely low thermal conductance below 1 K; they must be impermeable to helium gas, have high strength, including stability against buckling, and have an inner diameter > 20 mm.

4) High cooling power density magnetocaloric materials, especially single crystals with volume > 20 cc. Examples of desired single crystals include GdF3, GdLiF4, and Gd elpasolite.

5) 10 mK- 300 mK high resolution thermometry.

6) Suspensions with the strength and stiffness of Kevlar, but lower thermal conductance from 4 K to 0.050 K.

References


For articles describing magnetic subKelvin coolers and their components, see the July 2014 special issue of Cryogenics: Cryogenics 62 (2014) 129–220.

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 [4]. 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 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II:

Prototype Hardware

Desired Deliverables Description

For components, functioning hardware that is directly usable in NASA systems is desired.

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 hour 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 two of the large missions under study for the 2020 Astrophysics Decadal Survey:

- Origins Space Telescope
- Lynx (microcalorimeter instrument)

Also: Probe of Inflation and Cosmic Origins

S1.10 Atomic Interferometry

Lead Center: GSFC

Participating Center(s): JPL

Technology Area: TA15 Aeronautics

Scope Description

Recent developments of laser control and manipulation of atoms have led to new types of precision inertial force and gravity sensors based on atom interferometry. Atom interferometers exploit the quantum mechanical wave nature of atomic particles and quantum gases for sensitive interferometric measurements. Ground-based laboratory experiments and instruments have already demonstrated beyond the state-of-the-art performances of accelerometer, gyroscope, and gravity measurements. The microgravity environment in space provides opportunities for further drastic improvements in sensitivity and precision. Such inertial sensors will have great potential to provide new capabilities for NASA Earth and planetary gravity measurements, for spacecraft inertial navigation and guidance, and for gravitational wave detection and test of properties of gravity in space.

Currently the most mature development of atom interferometers as measurement instruments are those based on light pulsed atom interferometers with freefall cold atoms. There remain a number of technical challenges to infuse this technology in space applications. Some of the identified key challenges are (but not limited to):

- Compact high flux ultra-cold atom sources for free space atom interferometers (Example: >1e+06 total useful free-space atoms, <1 nK, Rb, K, Cs, Yb, Sr, and Hg. Performance and species can be defined by offeror. Other related innovative methods and components for cold atom sources are of great interest, such as a highly compact and regulatable atomic vapor cell.
- Ultra-high vacuum technologies that allow completely sealed, non-magnetic enclosures with high quality optical access and the base pressure maintained
- <1e-09 Torr. Consideration should be given to the inclusion of cold atom sources of interest.
- Beyond the state-of-the-art photonic components at wavelengths for atomic species of interest, particularly at Near Infrared (NIR) and visible: efficient acousto-optic modulators (low RF power ~200 mW, low thermal distortion, ~80% or greater diffraction efficiency); efficient electro-optic modulators (low bias drift, residual AM, and return loss, fiber- coupled preferred), miniature optical isolators (~30 dB isolation or greater, ~ -2 dB loss or less), robust high-speed high-extinction shutters (switching time < 1 ms, extinction > 60 dB are highly desired).
• Flight qualifiable lasers or laser systems of narrow linewidth, high tunability, and/or higher power for clock and cooling transitions of atomic species of interest. Cooling and trapping lasers: 10 kHz linewidth and ~ 1 W or greater total optical power.
• Compact clock lasers: 5e-15 Hz/tau^{½} near 1 s (wavelengths for Yb+, Yb, Sr clock transitions are of special interest).

All proposed system performances can be defined by offeror with sufficient justification. Subsystem technology development proposals should clearly state the relevance, define requirements, relevant atomic species and working laser wavelengths, and indicate its path to a space-borne instrument.

References

• 2017 NASA Strategic Technology Investment Plan: [https://go.usa.gov/xU7sE](https://go.usa.gov/xU7sE) [45]
• 2015 NASA Technology Roadmaps: [https://go.usa.gov/xU7sy](https://go.usa.gov/xU7sy) [46]
• NOTE: The 2015 NASA Technology Roadmaps will be replaced beginning early fall of 2019 with the 2020 NASA Technology Taxonomy and the NASA Strategic Technology Integration Framework. The 2015 NASA Technology Roadmaps will be archived and remain accessible via their current Internet address as well as via the new 2020 NASA Technology Taxonomy Internet page.

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Hardware

Desired Deliverables Description

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

State of the Art and Critical Gaps

This technology reduces gravitational sensors from two satellites to a single, table-top instrument and enhances the sensitivity of the state-of-the-art, including time measurement accuracy by factor of 100+.

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:

• TA-7.1.1: Destination Reconnaissance, Prospecting, and Mapping (gravimetry)
• TA-8.1.2: Electronics (reliable control electronics for laser systems)
• TA-8.1.3: Optical Components (reliable laser systems)
• TA-8.1.4: Microwave, Millimeter, and Submillimeter-Waves (ultra-low noise microwave output when coupled w/ optical frequency comb)
• TA-8.1.5: Lasers (reliable laser system w/ long lifetime)

See note in References section regarding the status of the 2015 NASA Technology Roadmaps.

S1.11 In Situ Instruments/Technologies and Plume Sampling Systems for Ocean Worlds Life Detection

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

Technology Area: TA15 Aeronautics

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) velocity 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 S4.02, 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, 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.
  - 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. 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 (microg to mg) 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 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 (microg to mg) 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** - 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. 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. Balloon instruments, such as IR spectrometers, imagers, meteorological instruments, radar sounders, solid, liquid, air sampling mechanisms for mass analyzers, and aerosol detectors are also solicited. Low mass and power sensors, mechanisms and concepts for converting 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).

- Other Ocean Worlds targets may include Ganymede, Callisto, Ceres, etc.

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 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.

**References**

For the NASA Roadmap for Ocean World Exploration see: http://www.lpi.usra.edu/opag/ROW [47]

In situ instruments and technologies for NASA's Ocean Worlds exploration goals see: https://www.nasa.gov/specials/ocean-worlds/ [48]


**Expected TRL or TRL range at completion of the project:** 3 to 5

**Desired Deliverables of Phase II**
Prototype, Analysis, Hardware, Software

Desired Deliverables Description

In-situ instruments in TRL 3 - 5 for Ocean Worlds exploration

State of the Art and Critical Gaps

In situ instruments and technologies are essential bases 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 surface 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 bases to achieve Science Mission Directorate's (SMD) planetary science goals summarized in Decadal Study (National Research Council's Vision and Voyages for Planetary Science in the Decade 2013-2022.) In situ instruments and technologies play indispensable role 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.

S1.12 Remote Sensing Instrument Technologies for Heliophysics

Lead Center: GSFC

Participating Center(s): HQ, MSFC

Technology Area: TA15 Aeronautics

Scope Description

The 2013 National Research Council’s, Solar and Space Physics: A Science for a Technological Society (http://nap.edu/13060 [26]) 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 deployment on 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. 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. For example missions, see https://science.nasa.gov/missions-page?field_division_tid=5&field_phase_tid=All [51]. For details of the specific requirements see the Heliophysics Decadal Survey. 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 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 in the visible, far-ultraviolet and soft x-ray (e.g., mirrors and gratings with high-reflectance coatings, multi-layer coatings, narrow-band filters, and blazed gratings with high ruling densities)
- Technologies that enable the development of dedicated solar flare sensors with intrinsic ion suppression and sufficient angular resolution in the extreme UV (EUV) to soft x-ray wavelength range such as fast cadence charge-coupled devices, complementary metal-oxide semiconductor devices
- Technologies that enable x-ray detectors to observe bright solar flares in x-ray from 1 to hundreds of keV without saturation
- Technologies that attenuate solar x-ray fluences by flattening the observed spectrum by a factor of 100 to 1000 across the energy range encompassing both low and high energy x-rays – preferably flight programmable
- X-ray optics technologies to reduce the size, complexity, or mass or to improve the point spread function of solar telescopes used for imaging solar x-rays in the ~1 to 300 keV range
- Technologies that allow polarization and wavelength filtering without mechanical moving parts

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

**References**

For example missions, see [https://science.nasa.gov/missions](https://science.nasa.gov/missions) [52]

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) [26]).


**Expected TRL or TRL range at completion of the project**: 3 to 5

**Desired Deliverables of Phase II**

Prototype, Analysis, Hardware, Software

**Desired Deliverables Description**

Remote sensing instruments in TRL 3 - 5 for heliophysics science purpose

**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 LWS and STP.
mission programs, as well as a host of smaller spacecraft in the Explorers Program. In addition, there is growing demand for remote sensing technologies amenable to CubeSats and SmallSats. To narrow the critical gaps between the current state of art and the technology needed for the ever increasing science/exploration requirements, remote sensing technologies are being sought to achieve much higher resolution and sensitivity with significant improvements over existing capabilities, and at the same time with lower mass, power and volume.

Relevance / Science Traceability

Remote sensing instruments and technologies are essential bases to achieve SMD's Heliophysics goals summarized in National Research Council's, Solar and Space Physics: A Science for a Technological Society. These instruments and technologies play indispensable roles for NASA's 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. 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. 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.

S2.01 Proximity Glare Suppression for Astronomical Direct Detection of Exoplanets

Lead Center: MSFC

Participating Center(s): GSFC

Technology Area: TA15 Aeronautics

Scope Title
Control of Scattered Starlight with Coronagraphs and Starshades

Scope Description

This subtopic 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 - 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, starlight cancellation instruments, and potential occulting technologies 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 concepts 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 to include, but not limited to, the following areas:

Starlight Suppression Technologies:

- Hybrid metal/dielectric and polarization apodization masks for diffraction control of phase and amplitude for coronagraph scaled starshade experiments.
- Low-scatter, low-reflectivity, sharp, flexible edges for control of solar scatter in starshades.
- Low-reflectivity coatings for flexible starshade optical shields.
• 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 Measurement and Control Technologies:

• Small stroke, high precision, deformable mirrors and associated driving electronics 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, and performance precision of current devices.
• Multiplexers with ultra-low power dissipation for electrical connection to deformable mirrors
• Low-order wavefront sensors for measuring wavefront instabilities to enable real-time control and post-processing of aberrations.
• Thermally and mechanically insensitive optical benches and systems.

Optical Coating and Measurement Technologies:

• Instruments capable of measuring polarization cross-talk and birefringence to parts per million.
• Polarization-insensitive coatings for large optics.
• Methods to measure the spectral reflectivity and polarization uniformity across large optics.
• Methods to apply carbon nanotube coatings on the surfaces of the coronagraphs for broadband suppression from visible to near infrared (NIR).

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.

Websites:
• Exoplanet Exploration - Planets Beyond Our Solar System: https://exoplanets.jpl.nasa.gov [53]
• Exoplanet Exploration Program: https://exoplanets.nasa.gov/exep/ [54]
• Goddard Space Flight Center: https://www.nasa.gov/goddard [55]

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

This subtopic solicits proposals to develop components that improve the footprint, robustness, power consumption, reliability, and wavefront quality of high-contrast, low-temporal bandwidth, adaptive optics systems. These include ASIC drivers that easily integrate with the deformable mirrors, improved connectivity technologies, as well as high-actuator count deformable mirrors with high-quality, ultrastable wavefronts.

It also seeks coronagraph masks that can be tested in ground-based high-contrast testbeds in place at a number of institutions, as well as devices to measure the masks to inform optical models. The masks include transmissive scalar, polarization-dependent, and spatial apodizing masks including those with extremely low reflectivity regions that allow them to be used in reflection.

The subtopic seeks samples of optical coatings that reduce polarization and can be applied to large optics, and methods and instruments to characterize them over large optical surfaces.
Finally, for starshades, the subtopic seeks low reflectivity and potentially diffraction-controlling edges that minimize scattered sunlight while also remaining robust to handling and cleaning. Low-reflectivity optical coatings that can be applied to the surfaces for the large (hundreds of square meters) optical shield are also desired.

**State of the Art and Critical Gaps**

Coronagraphs have been demonstrated to achieve high contrast in moderate bandwidth in laboratory environments. Starshades will enable even deeper contrast over broader bands but to date have demonstrated deep contrast in narrow band light. 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. Neither of these technologies is well characterized at levels required for 1e10 contrast. 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 1e10, but they require thousands of wires, and overall wavefront quality and stroke remain concerns.

**Relevance / Science Traceability**

These technologies are directly applicable to the Wide Field Infrared Survey Telescope (WFIRST), coronagraph instrument (CGI), and the HabEx and LUVOIR concept studies.

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**S2.02 Precision Deployable Optical Structures and Metrology**

Lead Center: MSFC

Participating Center(s): GSFC

**Technology Area:** TA15 Aeronautics

**Scope Title**

Precision Deployable Optical Structures and Metrology

**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, 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 30-70 m class space structures.

This subtopic addresses the need to mature technologies that can be used to fabricate 10-20 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 Thermal Expansion (CTE)/Coefficient of Moisture Expansion (CME) materials/structures to enable highly dimensionally stable optics, optical benches, 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 sub-micron level repeatability
• Mechanical connections providing micro-dynamic 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 (20-50 m class)
• Packaging techniques to enable more efficient deployable structures

Metrology:

• Techniques to verify dimensional stability requirements at sub-nanometer level precisions (10 – 100 picometers)
• 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-meter 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 to transition into future NASA program(s).

References

Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/ [22]
Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/ [40]
What is an Exoplanet? https://exoplanets.nasa.gov/what-is-an-exoplanet/technology/ [56]
NASA in-Space Assembled Telescope (iSAT) Study: https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/ [57]

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Research

Desired Deliverables Description

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. 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, currently set to launch in 2021, represents the state of the art in large deployable telescopes. The Wide Field Infrared Survey Telescope’s (WFIRST) 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 WFIRST CGI and the HabEx, LUVOIR, and OST mission concepts.

S2.03 Advanced Optical Systems and Fabrication/Testing/Control Technologies for EUV/Optical and IR Telescope

Lead Center: MSFC

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

Technology Area: TA15 Aeronautics

Scope Title

Optical Components and Systems for Large Telescope Missions

Scope Description

To accomplish 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. Where a mirror system is defined as the mirror substrate, supporting structure, and associated actuation and thermal management systems. After performance, the most important metric for an advanced optical system is affordability or areal cost (cost per square meter of collecting aperture). 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 times, to between $100K/m2 to $1M/m2.

Specific metrics are defined for each wavelength application region:

Aperture Diameter for all wavelengths, except Far-IR

- Monolithic: 1 to 8 meters
- Segmented: 3 to 20 meters

For UV/Optical

- Areal Cost < $500K/m2
- Wavefront Figure < 5 nm RMS (via passive design or active deformation control)
- Wavefront Stability < 10 pm/10 min
- First Mode Frequency 60 to 500 Hz
- Actuator Resolution < 1 nm RMS
- Optical Path-length Stability < 1 pm/10,000 seconds for precision metrology
- Areal density < 15 kg/m2 (< 35 kg/m2 with backplane)
- Operating Temperature Range of 250 to 300K

For Far-IR

- Aperture diameter 1 to 4 m (monolithic), or 5 to 10 m (segmented)
- Telescope diffraction-limited at <30 microns at operating temperature 4 K
- Cryo-Deformation < 100 nm RMS
- Areal cost < $500K/m2
- Production rate $> 2$ m$^2$ per month
- Areal density $< 15$ kg/m$^2$ ($< 40$ kg/m$^2$ with backplane)
- Thermal conductivity at 4 K $> 2$ W/m$^*$K
- Survivability at temperatures ranging from 315 K to 4 K

For EUV

- Surface Slope $< 0.1$ micro-radian

Also needed is ability to fully characterize surface errors and predict optical performance.

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: sub-orbital rocket or balloon; competed SMEX or MIDE; 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.

References

The Habitable Exoplanet Imager (HabEx) and Large UVOIR (LUVOIR) space telescope studies are developing concepts for UVOIR space telescopes for exoEarth discovery and characterization, exoplanet science, general astrophysics and solar system astronomy. The HabEx Interim Report is available at: https://www.jpl.nasa.gov/habex/documents/ [58]. The LUVOIR Interim Report is available at: https://asd.gsfc.nasa.gov/luvoir/ [21].


The OST mission is described on the website: https://origins.ipac.caltech.edu [60].

The Space Infrared Interferometric Telescope (SPIRIT) and its optical system requirements are described on the website: https://asd.gsfc.nasa.gov/cosmology/spirit/ [61].

LISA (Laser Interferometer Space Antenna) mission description: https://lisa.nasa.gov/ [62].

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Hardware, Research

Desired Deliverables Description

An ideal Phase 1 deliverable would be a precision optical system of at least 0.25 meters; or a relevant sub-component of a system; or a prototype demonstration of a fabrication, test or control technology leading to a successful Phase 2 delivery; or a reviewed preliminary design and manufacturing plan which demonstrates feasibility. While detailed analysis will be conducted in Phase 2, the preliminary design should address how optical, mechanical (static and dynamic) and thermal designs and performance analysis will be done to show compliance with all requirements. Past experience or technology demonstrations which support the design and manufacturing plans will be given appropriate weight in the evaluation.

An ideal Phase 2 project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 meters or relevant sub-component (with a TRL in the 4 to 5 range); or a working fabrication, test or control system. Phase 1 and Phase 2 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 2 would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly which can be integrated into the potential mission; and, 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 analysis).

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 a cost reduction for precision optical components by 5 to 50 times, to between $100K/m² to $1M/m².

Relevance / Science Traceability

S2.03 primary supports potential Astrophysics Division missions. S2.03 has made optical systems in the past for potential balloon experiments. Future potential Decadal missions include LISA, Habitable Exoplanet Observatory (HabEx), Large UV/Optical/Near-IR Surveyor (LUVOIR) and the Origins Space Telescope (OST).

Scope Title
Balloon Planetary Telescope

Scope Description

Astronomy from a stratospheric balloon platform offers numerous advantages for planetary science. At typical balloon cruise altitudes (100,000 to 130,000 ft.), 99%+ of the atmospheric is below the balloon and the attenuation due to the remaining atmosphere is small, especially in the near ultraviolet band and in the infrared 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.

For additional discussion of the advantages of observations from stratosphere platforms, refer to “Planetary Balloon-Based Science Platform Evaluation and Program Implementation - Final Report,” Dankanich et.al. (Available from https://ntrs.nasa.gov/ [63], search for "NASA/TM-2016-218870")

To perform Planetary Science requires a 1-meter class telescope 500 nm diffraction limited performance or Primary Mirror System that can maintain < 10 nm rms surface figure error for elevation angles ranging from 0 to 60 degrees over a temperature range from 220K to 280K.

Phase I will produce a preliminary design and report including initial design requirements such as wave-front error budget, mass allocation budget, structural stiffness requirements, etc., trade studies performed and 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 sub-scale component, then it should also produce a detailed final design, including final requirements (wave-front error budget, mass allocation, etc) and performance assessment over the specified operating range.

Additional information about Scientific Balloons can be found at https://www.csbf.nasa.gov/docs.html [64].

Telescope Specifications:

- Diameter > 1 meter
- System Focal Length 14 meter (nominal)
- Diffraction Limit < 500 nm
- Mass < 300 kg
- Shock 10G without damage
- Elevation 0 to 60 degrees
- Temperature 220 to 280 K
Primary Mirror Assembly Specifications:

- Diameter > 1 meter
- Radius of Curvature 3 meters (nominal)
- Surface Figure Error < 10 nm rms
- Mass < 150 kg
- Shock 10G without damage
- Elevation 0 to 60 degrees
- Temperature 220 to 280 K

References

For additional discussion of the advantages of observations from stratosphere platforms, refer to “Planetary Balloon-Based Science Platform Evaluation and Program Implementation - Final Report,” Dankanich et.al. (Available from https://ntrs.nasa.gov/ [63], search for "NASA/TM-2016-218870")

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

If Phase II can only produce a sub-scale component, then it should also produce a detailed final design, including final requirements (wave-front error budget, mass allocation, etc.) and performance assessment over the specified operating range.

State of the Art and Critical Gaps

To perform Planetary Science requires a 1-meter class telescope 500 nm diffraction limited performance or Primary Mirror System that can maintain < 10 nm rms surface figure error for elevation angles ranging from 0 to 60 degrees over a temperature range from 220K to 280K. Significant science returns may be realized through observations in the 300 nm to 5 ?m range. Current SOA (State of the Art) mirrors made from Zerodur or ULE for example require light weighting to meet balloon mass limitations, and cannot meet diffraction limited performance over the wide temperature range due to the coefficient of thermal expansion limitations.

Relevance / Science Traceability

From “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.6 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, 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.154, 155,156.

Potential Advocates include Planetary Scientists at GSFC, APL, and Southwest Research Institute, etc. The NASA Balloon Workshop.


**Scope Title**
Large UV/Optical (LUVOIR) and Habitable Exoplanet (HabEx) Missions

**Scope Description**
Potential UV/Optical missions require 4 to 16 meter monolithic or segmented primary mirrors with < 5 nm RMS surface figures. Active or passive alignment and control is required to achieve system level diffraction limited performance at wavelengths less than 500 nm (< 40 nm RMS wavefront error, WFE). Additionally, potential Exoplanet mission, using an internal coronagraph, requires total telescope wavefront stability on order of 10 picometers RMS per 10 minutes. This stability specification places severe constraints on the dynamic mechanical and thermal performance of 4 meter and larger telescope. Potential enabling technologies include: active thermal control systems, ultra-stable mirror support structures, athermal telescope structures, athermal mirror struts, ultra-stable low CTE/high-stability joints, and vibration compensation.

Mirror areal density depends upon available launch vehicle capacities to Sun-Earth L2 (i.e. 15 kg/m2 for a 5 m fairing EELV vs. 150 kg/m2 for a 10 m fairing 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 m2 of collecting area) should have an areal cost of less than $2M/m2. And, a 16-m class mirror (with 200 m2 of collecting area) should have an areal cost of less than $0.5M/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 UVO quality mirrors
- Mirror support structures, joints and mechanisms that are athermal or zero CTE at the desired scale
- Mirror support structures, joints and mechanisms that are ultra-stable 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 ability to fully characterize surface errors and predict optical performance via integrated opto-mechanical 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, 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 meter (or larger) precision quality components. Potential solutions for achieving the 10 pico-meter wavefront stability include, but are not limited to: metrology, passive, and active control for optical alignment and mirror phasing; active vibration isolation; metrology, passive, and active thermal control.

**References**
The Habitable Exoplanet Imager (HabEx) and Large UVOIR (LUVOIR) space telescope studies are developing
concepts for UVOIR space telescopes for exoEarth discovery and characterization, exoplanet science, general astrophysics and solar system astronomy. The HabEx Interim Report is available at: https://www.jpl.nasa.gov/habex/pdf/interim_report.pdf [65]. The LUVOIR Interim Report is available at: https://asd.gsfc.nasa.gov/luvoir/ [21].


The OST mission is described on the website https://origins.ipac.caltech.edu [60].

The Space Infrared Interferometric Telescope (SPIRIT) and its optical system requirements are described on the website https://asd.gsfc.nasa.gov/cosmology/spirit/ [61].

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Analysis, Hardware, Software, Research

Desired Deliverables Description

An ideal Phase 1 deliverable would be a precision optical system of at least 0.25 meters; or a relevant sub-component of a system; or a prototype demonstration of a fabrication, test or control technology leading to a successful Phase 2 delivery; or a reviewed preliminary design and manufacturing plan which demonstrates feasibility. While detailed analysis will be conducted in Phase 2, the preliminary design should address how optical, mechanical (static and dynamic) and thermal designs and performance analysis will be done to show compliance with all requirements. Past experience or technology demonstrations which support the design and manufacturing plans will be given appropriate weight in the evaluation.

An ideal Phase 2 project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 meters or relevant sub-component (with a TRL in the 4 to 5 range); or a working fabrication, test or control system. Phase 1 and Phase 2 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 2 would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly which can be integrated into the potential mission; and, 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 analysis).

State of the Art and Critical Gaps

Hubble at 2.4m is the SOA.

Relevance / Science Traceability

S2.03 primary supports potential Astrophysics Division missions. S2.03 has made optical systems in the past for potential balloon experiments. Future potential Decadal missions include LISA, Habitable Exoplanet Observatory (HabEx), Large UV/Optical/Near-IR Surveyor (LUVOIR) and the Origins Space Telescope (OST).

Scope Title
NIR LIDAR Beam Expander Telescope

Scope Description
Potential airborne coherent LIDAR missions need compact 15-cm diameter 20X magnification beam expander
telescopes. Potential space based coherent LIDAR missions need at least 50-cm 65X magnification beam expander telescopes. Candidate coherent LIDAR systems (operating with a pulsed 2-micrometer laser) have a narrow, almost diffraction limited field of view, close to 0.8 lambda/D half angle. Aberrations, especially spherical aberration, in the optical telescope can decrease the signal. Additionally, the telescope beam expander should maintain the laser beam’s circular polarization. The incumbent telescope technology is a Dahl-Kirkham beam expander. Technology advance is needed to make the beam expander more compact with less mass while retaining optical performance, and to demonstrate the larger diameter. Additionally, technology for non-moving scanning of the beam expander output is needed.

References


Expected TRL or TRL range at completion of the project: 3 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

A detailed design or a small prototype or a full-sized beam expander.

State of the Art and Critical Gaps

The current SOA is a COTS beam expander with a 15-cm diameter primary mirror, a heavy aluminum structure, an Invar rod providing thermally insensitive primary-to-secondary mirror separation, and a manually adjustable and lockable variable focus setting by changing the mirror separation. Critical gaps include 1) a 50-70 cm diameter primary mirror beam expander that features near-diffraction limited performance, low mass design, minimal aberrations with an emphasis on spherical, characterization of the polarization changes vs. beam cross section assuming input circular polarization, a lockable electronic focus adjustment, both built-in and removable fiducial aids for aligning the input laser beam to the optical axis, and a path to space qualification; and 2) a 15-cm diameter primary mirror beam expander with the same features for airborne coherent lidar systems.

Relevance / Science Traceability

Science Mission Directorate (SMD) desires both an airborne coherent-detection wind-profiling lidar systems and a space-based wind measurement. The space mission has been recommended to SMD by both the 2007 and 2017 earth science Decadal Surveys. SMD has incorporated the wind lidar mission in its planning and has named it “3-D Winds”. SMD recently held the Earth Venture Suborbital competition for 5-years of airborne science campaigns.
The existing coherent wind lidar at Langley, DAWN, was included in three proposals which are under review. Furthermore, SMD is baselining DAWN for a second CPEX-type airborne science campaign, and for providing cal/val assistance to the ESA AEOLUS space mission. DAWN flies on the DC-8 and it is highly desired to fit DAWN on other NASA and NOAA aircraft. DAWN needs to lower its mass for several of the aircraft, and a low-mass telescope retaining the required performance is needed. Additionally, an electronic remote control of telescope focus is needed to adapt to aircraft cruise altitude and weather conditions during science flights.

Scope Title
Fabrication, Test and Control of Advanced Optical Systems

Scope Description
Future UV/Optical/NIR telescopes require mirror systems that are very precise and ultra-stable. Regarding precision, this subtopic encourages proposals to develop technology which makes a significant advance the ability to fabricate and test an optical system.

One area of current emphasis is the ability to non-destructively characterize CTE homogeneity in 4-m class Zerodur and 2-m class ULE mirror substrates to an uncertainty of 1 ppb/K and a spatial sampling of 100 x 100. This characterization capability is needed to select mirror substrates before they undergo the expense of turning them into a light-weight 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 minutes during critical observations. The ~10-minute time period of this stability is driven by current wavefront sensing and control techniques that rely on stellar photons from the target object to generate estimates of the system wavefront. This subtopic aims to develop new technologies and techniques for wavefront sensing, metrology, and verification and validation of optical system wavefront stability.

Current methods of wavefront sensing include image-based techniques such as phase retrieval, focal-plane contrast techniques such as electric field conjugation and speckle nulling, and low-order and out-of-band wavefront sensing that use non-science 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 - 11 Vmag), leading to 10s 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.

Finally, metrology techniques for system verification and validation at the picometer level during integration and test (I&T) are 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.

References
The HabEx Interim Report is available at: https://www.jpl.nasa.gov/habex/pdf/interim_report.pdf [65]. The LUVOIR Interim Report is available at: https://asd.gsfc.nasa.gov/luvoir/resources/docs/LUVOIR_Interim_Report_Fi... [72].

Expected TRL or TRL range at completion of the project: 2 to 4
Desired Deliverables of Phase II

Analysis, Hardware, Software, Research

Desired Deliverables Description

An ideal Phase 1 deliverable would be a prototype demonstration of a fabrication, test or control technology leading to a successful Phase 2 delivery; or a reviewed preliminary design and manufacturing plan which demonstrates feasibility. While detailed analysis will be conducted in Phase 2, the preliminary design should address how optical, mechanical (static and dynamic) and thermal designs and performance analysis will be done to show compliance with all requirements. Past experience or technology demonstrations which support the design and manufacturing plans will be given appropriate weight in the evaluation.

An ideal Phase 2 project would further advance the technology to produce a flight-qualifiable relevant sub-component (with a TRL in the 4 to 5 range); or a working fabrication, test or control system. Phase 1 and Phase 2 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 2 would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly which can be integrated into the potential mission; and, 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 analysis).

State of the Art and Critical Gaps

Wavefront sensing using star images, including dispersed-fringe and phase retrieval methods, is at TRL 6, qualified for space by JWST. Wavefront 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 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 on orbit by the Lisa Pathfinder and Grace Follow-On mission. Application to telescope alignment metrology has been demonstrated on testbeds, to TRL4 for nanometer accuracy. Picometer accuracy for telescopes awaits demonstration.

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

Higher-order WFS for coronagraphs using out-of-band light is beginning development, with data limited to computer simulations. Such techniques are best used

Relevance / Science Traceability

These technologies are enabling for coronagraph-equipped space telescopes, segmented space telescopes, and others that utilize actively controlled optics. The LUVOIR and HabEx mission concepts currently under study provide good examples.

Scope Title
Optical Components and Systems for potential Infrared/Far-IR missions

Scope Description

The Far-IR Surveyor Mission described in NASA's Astrophysics Roadmap, "Enduring Quests, Daring Visions":

In the context of subtopic S2.03, the challenge is to take advantage of relaxed tolerances stemming from a requirement for long wavelength (30 micron) diffraction-limited performance in the fully-integrated optical telescope assembly to minimize the total mission cost through innovative design and material choices and novel approaches to fabrication, integration, and performance verification.
The Far-IR Surveyor is a cryogenic far-infrared mission, which could be either a large single-aperture telescope or an interferometer. There are many common and a few divergent optical system requirements between the two architectures.

**Common requirements:**

- Telescope operating temperature ~4 K
- Telescope diffraction-limited at 30 microns at the operating temperature
- Mirror survivability at temperatures ranging from 315 K to 4 K
- Mirror substrate thermal conductivity at 4 K > 2 W/m*K
- Zero or low CTE mismatch between mirror substrate and backplane

**Divergent requirements:**

- Large single-aperture telescope:
  - Segmented primary mirror, circular or hexagonal
  - Primary mirror diameter 5 to 10 m
  - Possible 3 dof (tip, tilt and piston) control of mirror segments on orbit
  - Interferometer:
    - Monolithic primary mirrors
    - Afocal, off-axis telescope design
    - Primary mirror diameter 1 to 4 m

**Success metrics:**

- Areal cost < $500K/m2
- Areal density < 15 kg/m2 (< 40 kg/m2 with backplane)
- Production rate > 2 m2 per month
- Short time span for optical system integration and test

**References**


Program Annual Technology Reports (PATR) can be downloaded from the NASA PCOS/COR Technology Development website at [https://apd440.gsfc.nasa.gov/technology/](https://apd440.gsfc.nasa.gov/technology/) [73].

**Expected TRL or TRL range at completion of the project:** 3 to 5

**Desired Deliverables of Phase II**

Prototype, Hardware, Research

**Desired Deliverables Description**

Mirrors or optical systems that demonstrably advance TRL to address the overall challenge described under Scope Description while meeting requirements for a single-aperture or interferometric version of the notional Far-IR Surveyor mission.

**State of the Art and Critical Gaps**

Current SOA is represented by the Herschel Space Observatory (3.5 m monolith; SiC) and James Webb Space Telescope (6.5 m segmented primary mirror; beryllium).
Relevance / Science Traceability

The technology is relevant to the Far-IR Surveyor mission described in NASA's Astrophysics Roadmap and prioritized in NASA's Program Annual Technology Reports for Cosmic Origins and Physics of the Cosmos. A future NASA far-infrared astrophysics mission will answer compelling questions, such as: How common are life-bearing planets?; How do the conditions for habitability develop during the process of planet formation?; and How did the universe evolve in response to its changing ingredients (build-up of heavy elements and dust over time)? To answer these questions, NASA will need 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-infrared astrophysics mission may be applicable to far-infrared optical systems employed in other divisions of the NASA Science Mission Directorate, or to optical systems designed to operate at wavelengths shorter than the far-infrared.

Scope Title
Low-Cost Compact Reflective Telescope for NIR/SWIR Optical Communication

Scope Description

The need exists for a low cost methodology to produce compact (for ex., cubesat-class), scalable, diffraction limited, athermalized, off-axis reflective-type, optics for NIR/SWIR-band communication applications. 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 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 performances (STOP) analyses confirming diffraction limited operation across a wide range of operational disturbances, both structural dynamic and thermal. Commercial of the shelf (COTS) NIR/SWIR optical communication support hardware should be assumed towards an integrated approach, including fiber optics, fast steering mirrors, and applicable detectors. Phase II may follow up with development of prototypes, built at multiple aperture diameters and fidelities.

References

An example of an on-axis design has been utilized in LLCD: https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10563/105630X/NASAs-current-activities-in-free-space-optical-communications/10.1117/12.2304175.full?SSO=1 [74]

An example of an off-axis design is being developed by JPL for deep space optical comm (DSOC): https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10096/100960V/Discovery-deep-space-optical-communications-DSOC-transceiver/10.1117/12.2256001.full [75]

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

Prototype unobscured telescope with the required scale size

State of the Art and Critical Gaps

Currently, the state of the art for reflective optical system for communications applications are:
On-axis or axisymmetric designs are typically used for (space) optical communication and imaging, which inherently are problematic due to the central obscuration. Off-axis designs provide superior optical performance due to the clear aperture, however, are rarely considered due to complex design, manufacturing, and metrology procedures needed.

Relevance / Science Traceability

Optical Communication 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 applications. 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.

S2.04 X-Ray Mirror Systems Technology, Coating Technology for X-Ray-UV-OIR, and Free-Form Optics

Lead Center: MSFC

Participating Center(s): JPL, MSFC

Technology Area: TA15 Aeronautics

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 such as Next Generation of X-Ray Observatories (NGXO).

The Astrophysics Decadal specifically calls for optical coating technology investment for future UV, Optical, Exoplanet, and IR missions while Heliophysics 2009 Roadmap identifies the coating technology for space missions to enhance rejection of undesirable spectral lines, improve space/solar-flux durability of Extreme Ultraviolet (EUV) optical coatings, and coating deposition to increase the maximum spatial resolution.

Future optical systems for NASAs low-cost missions, CubeSat and other small-scale payloads, are moving away from traditional spherical optics to non-rotationally symmetric surfaces with anticipated benefits of freeform 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 (CNT) for wide range of wavelengths from X-Ray to IR (X-Ray, EUV, LUV, VUV, Visible, and IR).
- Free-form Optics design, fabrication, and metrology for CubeSat, SmallSat and various coronagraphic instruments.

References

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.
The study pages are available at:

Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/ [22]

LUVOIR: https://asd.gsfc.nasa.gov/luvoir/ [21]

Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/ [40]

The LYNX Mission Concept: https://wwwastro.msfc.nasa.gov/lynx/ [23]

The Large UV/Optical/IR Surveyor (LUVOIR) is a concept for a highly capable, multi-wavelength 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 is available at: https://asd.gsfc.nasa.gov/luvoir/ [21].

The Origins Space Telescope (OST) is the mission concept for the Far-IR Surveyor study. NASA's Astrophysics Roadmap, Enduring Quests, Daring Visions, recognized the need for an Origins Space Telescope mission with enhanced measurement capabilities relative to those of the Herschel Space Observatory, such as a three 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 community report is available at: https://science.nasa.gov/science-committee/subcommittees/nac-astrophysics-subcommittee/astrophysics-roadmap [76]

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Typical deliverables based on sub-elements of this subtopic:

- X-ray optical mirror system: Analysis, reports, and prototype
- Coating: Analysis, reports, software, demonstration of the concept and prototype
- Freeform 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:

- X-Ray manufacturing, coating, testing, and assembling complete mirror systems in addition to maturing the current technology. This work is a very costly and time consuming. Most of SOA (State of the Art) requiring improvement is ~10 arc-seconds angular resolution. SOA straylight 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 2x 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 EV is defined by Heliophysics (80% reflectivity from 60-200 nm). Current UVOIR is defined by Hubble. MgFl2 over coated aluminum on 2.4 m mirror. This coating has birefringence concerns and marginally acceptable reflectivity between 100-200 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

S2.04 supports variety of Astrophysics Division missions. The technologies in this subtopic encompasses fields of X-Ray, coating technologies ranging from UV to IR, and Freeform 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 (NGXO). The NRC NASA Technology Roadmap Assessment ranked advanced mirror technology for new x-ray telescopes as the #1 Object C technology requiring NASA investment.

Freeform 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 freeform 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 is highly desirable specifically if they could enable cost-effective manufacturing of these surfaces. (CubeSat, SmallSat, NanoSat, various coronagraphic instruments)

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 (Habitable Exoplanet Observatory (HabEx) or Large Ultraviolet Optical Infrared Surveyor (LUVOIR)). 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); & Solar-C Nulling polarimetry/coronagraph for exoplanet imaging and characterization, dust and debris disks, extra-galactic studies and relativistic and non-relativistic jet studies (VNC).

Scope Title
X-Ray Mirror Systems Technology

Scope Description

NASA large X-Ray observatory requires low-cost, ultra-stable, light-weight mirrors with high-reflectance optical coatings and effective stray light suppression. The current state-of-art of mirror fabrication technology for X-Ray missions is very expensive and time consuming. Additionally, a number of improvements such as 10 arc-second 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 to bond mirrors that are made of silicon. The epoxies should absorb IR radiation with wavelengths between 1.5 um and 6 um that traverses silicon with little or no absorption, and therefore can 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 $100 K/m2.

Additionally, proposals are solicited to develop new advanced-technology Computer-Numerical-Control (CNC) machines to polish inside and/or outside surfaces of full-shell (between 100-1000mm in height, 100-2800mm in diameter, varying radial prescription along azimuth, and approximately 2mm in thickness), grazing-incidence optics to x-ray quality surface tolerances (with surface figure error < 1 arcsecond Half-Power Diameter (HPD), radial slope error < 1 microradian, and out of round < 2 microns). Current state-of-the-art technology in CNC polishing of full-shell, grazing-incidence optics yields 2.5 arcseconds 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.

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 [77].

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Typical deliverable based on sub-elements of this subtopic:
X-ray optical mirror system: Demonstration, analysis, reports, software and hardware 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 SOA (State of the Art) requiring improvement is ~10 arc-seconds angular resolution. SOA straylight 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 2x 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:

- Light-weight, low-cost, ultra-stable mirrors for large X-ray observatory
- Stray light suppression systems (baffles) for large advanced X-Ray observatories
- Ultra-stable inexpensive light-weight X-Ray telescope using grazing-incidence optics for high altitude balloon-borne and rocket-borne mission

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

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 anti-reflective (AR) coating and high reflective coating.

The current coating technology of optical components needed to support the 2020 Astrophysics Decadal process. Historically, it takes 10 years to mature mirror technology from TRL-3 to 6.
To achieve these objectives requires sustained systematic investment.
The telescope optical coating needs to meet low temperature operation requirement. It’s desirable to achieve 35 degrees Kelvin in future.

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

- Broadband (visible plus Near IR), reflectivity of 0.1% or less
- Resist bleaching of significant albedo changes over a mission life of at least 10 years
- Withstand launch conditions such vibe, acoustics, etc.
- Tolerate both high continuous wave (CW) and pulsed power and power densities without damage. ~10 W for CE and ~ 0.1 GW/cm2 density, and 1 kW/nanosecond pulses
- Adhere to the multi-layer dielectric or protected metal coating including Ion Beam Sputtering (IBS) coating

NASA’s Laser Interferometer Space Antenna (LISA) mission on-axis design telescope operates both in transmission and reception simultaneously where the secondary mirror sends the transmitted beam directly back at the receiver. The apodized petal-shaped mask inherently suppress the diffraction once patterned at the center of the secondary mirror. The emerging cryogenic etching of black-silicon has demonstrated BRDF ultralow specular reflectance of 1e-7 in the range of 500-1064 nm. The advancement of this technology is desired to obtain ultralow reflectivity.

- Improve the specular reflectance to 1e-10 and hemispherical reflectance 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 grass
- Explore etching process and duration

References

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

More information could be found at [https://lisa.nasa.gov](https://lisa.nasa.gov) [78]

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

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

State of the Art and Critical Gaps

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 60-200 nm).
- Current UVOIR is defined by Hubble. MgF2 over coated aluminum on 2.4 m mirror. This coating has birefringence concerns and marginally acceptable reflectivity between 100-200 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 nm to 90 nm onto a < 2 meter mirror substrate.

Metrics for LUVOIR:

- Broadband Reflectivity > 70% from 90nm-120nm (LUV) and > 90% from 120nm-2.5um (VUV/Visible/IR). Reflectivity Non-uniformity < 1% 90nm-2.5um
- Induced polarization aberration < 1% 400nm-2.5um spectral range from mirror coating applicable to a 1-8m 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 1064nm
  - 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 degrees to ~20 degrees
  - Low coating noise (thermal, photothermal, etc.) for high precision interferometric measurements
  - Ability to endure applied temperature gradients (without destructive effects, such as de-lamination 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.

Non-stationary Optical Coatings:

- Used in reflection & transmission that vary with location on the optical surface.

Carbon Nanotube (CNT) Coatings

- Broadband Visible to NIR, Total Hemispherical Reflectivity of 0.01% or less, adhere to the multi-layer dielectric or protected metal coating

Black-Silicon Cryogenic Etching (New)

- Broadband UV+Visible+NIR+IR, Reflectivity of 0.01% or less, adhere to the multi-layer dielectric (silicon) or protected metal

Software tools to simulate, and assist the anisotropic etching by employing 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 (ETM).
Relevance / Science Traceability

Coating for X-ray, EUV, LUV, UV, Visible, and IR telescopes: Astrophysics Decadal specifically calls for optical coating technology investment for: Future UV/Optical and Exoplanet missions. Heliophysics 2009 Roadmap identifies optical coating technology investments for: Origins of Near-Earth Plasma (ONEP); Ion-Neutral Coupling in the Atmosphere (INCA); Dynamic Geospace Coupling (DGC); Fine-scale Advanced Coronal Transition-Region Spectrograph (FACTS); Reconnection and Micro-scale (RAM); & 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/coronagraph for Exoplanets imaging and characterization, dust and debris disks, extra-galactic studies and relativistic and non-relativistic jet studies (VNC).

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 freeform optics as they provide non-rotationally symmetric optics which allow for better packaging while maintaining desired image quality. Currently, the design and fabrication of freeform 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 un-obscurable systems. In addition to the freeform fabrication, the metrology of freeform optical components is difficult and challenging due to 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 reflective optical designs with large fields of view (> 5 degrees) and fast F/#s
- **Fabrication:** 10 cm diameter optical surfaces (mirrors) with free form optical prescriptions with surface figure tolerances are 1-2 nm rms, and roughness < 5 Angstroms. Larger mirrors are also desired for flagship missions for UV and coronography applications, with 10cm-1m diameter surfaces having figure tolerances <5nm RMS, and roughness <1 Angstroms RMS
- **Metrology:** Accurate metrology of ‘freeform’ optical components with large spherical departures (>1 mm), independent of requiring prescription specific null lenses or holograms.

References

A presentation on application of Freeform Optics at NASA is available at: [https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170010419.pdf](https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170010419.pdf) [79]

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Demonstration, analysis, design, software and hardware prototype of optical components

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 freeform 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 OST and LUVOIR (currently being proposed for the 2020 Astrophysics Decadal Survey) have demonstrated improved optical performance over a larger field of view afforded by freeform optics. Such programs will require advances in freeform metrology to be successful.

S2.05 Technology for the Precision Radial Velocity Measurement Technique

Lead Center: MSFC

Participating Center(s): GSFC

Technology Area: TA15 Aeronautics

Scope Title
Components, assemblies, and subsystems for Extreme Precision Radial Velocity Measurements and Detection of Extrasolar Planets

Scope Description

Astronomical spectrographs have proven to be powerful tools for exoplanet searches. When a star experiences periodic motion due to the gravitational pull of an orbiting planet, its spectrum is Doppler-modulated in time. This is the basis for the Precision Radial Velocity (PRV) method, one of the first and most efficient techniques for detecting and characterizing exoplanets. Since 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 instrument precision needed for detecting and characterizing Earth-like planets in the Habitable Zone of their Sun-like host stars. While “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 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/s over multiple years of observations.

This subtopic solicits proposals to develop cost effective component and subsystem technology for low SWaP, long-lived, robust implementation of radial velocity measurement instruments both on the ground and in space. Research areas of interest include but are not limited to:

- Integrated photonic spectrographs
- PRV spectrograph calibration sources
- High efficiency photonic lanterns
- Advanced fiber scrambling techniques for modal noise reduction
- Software for advanced statistical techniques to mitigate effects of telluric absorption and stellar jitter on RV precision and accuracy

References

Precision Radial Velocity:
Photonic Lanterns:


Astrocombs:


Nonlinear Waveguides:


Spectral Flattening:


Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Hardware/software

Desired Deliverables Description

This subtopic solicits proposals to develop cost-effective component and subsystem technology for low SWaP, long-lived, robust implementation of radial velocity measurement instruments both on the ground and in space. Research areas of interest include but are not limited to:

- Integrated photonic spectrographs that meet PRV specifications (e.g. wavelength coverage, resolution, throughput, and polarization). These devices should be able to accept multiple fibers - at least two for the science light and simultaneous calibration light source. Ideally, they should be able to include on-chip cross-dispersion to eliminate bulk optics.
- PRV spectrograph calibration sources, particularly optical frequency combs (a.k.a. “astrocombs”) from the
UV through the NIR (~350 nm – ~2400 nm) with ~10-30 GHz mode spacing, potentially self-referenced, or line stabilized for Allan Deviation <1E-11 over 100 seconds to years
- Spectral flattening to provide uniform power across the spectral band covered by the instrument
- Spectral broadening to obtain wide spectral coverage, preferably octave-spanning to enable self-referencing
- Integrated photonic solutions including nonlinear waveguides, microresonators or other comb generators, pump lasers, and f-2f beat-note generation
- Low phase-noise solutions
- Tunability of comb lines to scan spectrograph detectors for pixel characterization
- Optical etalons with similar requirements for stability as the frequency combs
- High efficiency photonic lanterns
- Advanced fiber scrambling techniques for modal noise reduction
- Software for advanced statistical techniques to mitigate effects of telluric absorption and stellar jitter on RV precision and accuracy.

Proposals should show an understanding of the science needs, as well as present a feasible plan to fully develop the relevant subsystem technologies and to transition into future NASA program(s).

Phase I will emphasize research aspects for technical feasibility, infusion potential into ground or space operations, 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 3-4), and a plan for further development of the specific capabilities or products to be performed in Phase II. Early development and delivery of prototype hardware/software is encouraged.

Phase II will emphasize hardware/software development with delivery of specific hardware or software products for NASA targeting demonstration operations at a ground-based telescope in coordination with the lead NASA center. Phase II deliverables include a working prototype or engineering model of the proposed product/platform or software, along with documentation of development, capabilities, and measurements (showing specific improvement metrics), documents 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

The classical bulk optic spectrographs that are traditionally used for PRV science impose architectural constraints due to their large mass and limited optical flexibility. The spectrograph is the single element that if replaced with a photonic alternative could dramatically alter the course of astronomical instrumentation. Integrated Photonic Spectrographs (IPS) are wafer thin devices that could reduce instrument volume by up to three orders of magnitude. Furthermore, high resolving power spectrographs (R~150,000) with simultaneous UV, visible, and NIR coverage and exquisite long-term stability are required for PRV studies. 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.

As spectrograph stability imposes limits on how precisely the Radial Velocity (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 (years) stability needed for extreme PRV detection of exoplanets. While both frequency combs and etalons can deliver high precision spectrograph calibration, the former requires relatively complex and sophisticated hardware in the visible portion of the spectrum. Visible band frequency combs for astronomy (a.k.a. astrocombs) were initially based on mode-locked laser comb technology. However, the intrinsic free spectral range of these instruments, 100s of MHz to 1 GHz, is too fine to be resolved by astronomical spectrographs of R~150,000 or less. Thus, mode filtering of comb lines to create a more spectrally sparse calibration grid is necessary. The filtering step introduces complexity and additional sources of instability to the calibration process, as well as instrument assemblies too large in mass and volume for flight.

Commercial fiber laser astrocombs covering 450 - 1400 nm at 25 GHz line spacing and <3 dB intensity variations over the entire bandwidth are available for ground-based astronomical spectrographs and have been developed for HARPS-S and ESPRESSO RV instruments. However, the cost for these systems is often so prohibitive that recent
RV spectrograph projects such as CARMENES and Keck Planet Finder either do not use a frequency comb or include it only as a future upgrade, owing to the cost impact on the project.

Alternatively, frequency combs produced by Electro-Optic Modulation (EOM) of a laser source have been demonstrated at observatories for PRV studies in the near-IR. EOM combs produce modes spaced at a RF modulation frequency, typically 10-30 GHz, and are inherently suitable as ground-based astrocombs. Significantly, EOM combs avoid the line filtering step of commercial mode-locked fiber laser combs. Comb frequency stabilization can be accomplished in a variety of ways, including 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 octave bandwidth necessary for f-2f stabilization for stability traceable to the Standard International (SI) second. This is accomplished through pulse amplification followed by injection into Highly Non-Linear Fiber (HNLF) or nonlinear optical waveguides, but the broadening process is accompanied by multiplication of the optical phase noise from the EOM comb modulation signal and must be optically filtered. Also, at these challenging microwave pulse repetition rates, the pulse duty-cycle requires pulse amplification to 4-5 Watts of average optical power in order to generate the high enough peak intensity needed for nonlinear broadening. This necessitates use of high power, non-telecom amplifiers that are more prone to lifetime issues, making EOM combs not optimal for flight either. It is important to note that very little comb light is actually required on the spectrograph detectors for calibration. In fact, most of the generated comb light must be deliberately attenuated to avoid detector saturation.

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 Watts of spacecraft power. Thus, for flight applications, it is highly desirable to develop frequency comb technology with low power consumption, ~10 GHz mode spacing, compact size, broad (octave spanning) spectral grasp across both the visible and NIR, phase noise insensitivity, stability traceable to the definition of the SI second, and very importantly, long life.

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 which 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 dynamical (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/s at wavelengths longer than ~700 nm and greater than 30 cm/s at >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.
S3.01 Power Generation and Conversion

Lead Center: GSFC

Participating Center(s): ARC, JPL

Technology Area: TA15 Aeronautics

Scope Title

Photovoltaic Energy Conversion

Scope Description

Photovoltaic cell and blanket technologies that lead to significant improvements in overall solar array performance by increasing photovoltaic cell efficiency greater than 30%, increasing array mass specific power greater than 300W/kg, decreased stowed volume, reduced initial and recurring costs, long-term operation in radiation environments, high power arrays and a wide range of space environmental operating conditions are solicited.

Photovoltaic Energy Conversion: advances in, but not limited to, the following: (1) Photovoltaic cell and blanket technologies capable of low intensity, low-temperature operation applicable to outer planetary (low solar intensity) missions, (2) Photovoltaic cell, and blanket technologies that enhance and extend performance in lunar applications including orbital, surface and transfer, (3) Solar arrays to support Extreme Environments Solar Power type missions, including long-lived, radiation tolerant, cell and blanket technologies applicable to Jupiter missions, and (4) Lightweight solar array technologies applicable to science missions using solar electric propulsion.

Current missions being studied require solar arrays that provide 1 to 20 kilowatts of power at 1 AU, greater than 300 watts/kilogram specific power, operation in the range of 0.7 to 3 AU, low stowed volume, and the ability to provide operational array voltages up to 300 volts to enable direct drive electric propulsion systems for science missions.

References

300 watts/kilogram specific power, operation in the range of 0.7 to 3 AU, low stowed volume, and the ability to provide operational array voltages up to 300 volts to enable direct drive electric propulsion systems for science missions.

References


NASA Science Missions, found at: https://science.nasa.gov/missions-page?field_division_tid=All&field_phase_tid=3951 [90]

Expected TRL or TRL range at completion of the project 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

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 photovoltaic array technology consists of high efficiency, multijunction cell technology on thick honeycomb panels. Lightweight arrays are just beginning to be developed. There are very limited demonstrated technology for High Intensity High Temperature (HIHT), Low Intensity Low Temperature (LILT), Solar Electric Propulsion (SEP) missions and Lunar orbital, surface or transfer applications.

Significant improvements in overall solar array performance are needed to address the current gaps between SOA (State of the Art) and many mission requirements for photovoltaic cell efficiency greater than 30%, array mass specific power greater than 300W/kg, decreased stowed volume, reduced initial and recurring costs, long-term operation in radiation environments, high power arrays and a wide range of space, lunar, and planetary environmental operating conditions.

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 listed above, 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 (6e15 1 MeV e-cm^2), high power (>50 kW at 1 AU), low mass (3× lower than SOP), low volume (3× lower than SOP), long life (>15 years), and high reliability.

These technologies are relevant and align to 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, found at: https://science.nasa.gov/missions-page?field_division_tid=All&field_phase_tid=3951 [90]
S3.02 Dynamic Power Conversion  
Lead Center: GSFC  
Technology Area: TA15 Aeronautics  
Scope Description  

NASA is developing Dynamic Radioisotope Power Systems (DRPS) for unmanned robotic missions to the moon, and other solar system bodies of interest. This technology directly aligns with the Science Mission Directorate (SMD) strategic technology investment plan for space power and energy storage and could be infused into a highly efficient RPS for missions to dark, dusty, or distant destinations where solar power is not practical. Current work in dynamic radioisotope power systems is focused on novel Stirling, Brayton, or Rankine convertors that would be integrated with one or more 250 watt-thermal General Purpose Heat Source (GPHS) modules or 1 watt-thermal Light Weight Radioisotope heater Unit (RHU) to provide high thermal-to-electric efficiency, low mass, long life, and high reliability for planetary spacecraft, landers, and rovers. Heat is transferred from the radioisotope heat source assembly to the power convertor hot end using conductive or radiative coupling. Power convertor hot end temperatures would generally range from 300-500 °C for RHU applications and 500-800 °C for GPHS applications. Waste heat is removed from the cold end of the power convertor at temperatures ranging from 20-175 °C, depending on the application, using conductive coupling to radiator panels. The NASA projects target power systems able to produce a range of electrical power output levels based on the available form factors of space rated fuel sources. These include a very low range of 0.5-2.0 watt-electric that would utilize one or more RHU, a moderately range of 40-70 watt-electric that would utilize a single GPHS Step-2 module, and a high range of 100-500 watt-electric that would utilize multiple GPHS Step-2 modules. For these power ranges, one or more power convertors could be used to improve overall system reliability. The current solicitation is focused on innovations that enable efficient and robust power conversion systems. Areas of interest include:

1. Robust, efficient, highly reliable, and long-life thermal-to-electric power convertors that would be used to populate a generator of a prescribed electric power output range.
2. Electronic controllers applicable to Stirling, Brayton, or Rankine power convertors.
3. Multi-Layered Metal Insulation (MLMI) for minimizing environmental heat losses and maximizing heat transfer from the radioisotope heat source assembly to the power convertor.
4. Advanced dynamic power conversion components and RPS integration components, including efficient alternators able to survive extended exposure to 200 °C, robust high-temperature tolerant Stirling regenerators, robust highly effective recuperators, integrated heat pipes, and radiators that improve system performance, and improving the margin, reliability, and fault tolerance for existing components.

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](https://www.nasa.gov/content/commercial-lunar-payload-services) [4]. 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 2020 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

Radioisotope Power Systems (RPS): [https://rps.nasa.gov/about-rps/overview/](https://rps.nasa.gov/about-rps/overview/) [91]


Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

The desired deliverables include prototype hardware that has demonstrated basic functionality in a laboratory environment and the appropriate research and analysis used to develop the hardware. Deliverables also include maturation options for flight designs.

State of the Art and Critical Gaps

Radioisotope Power Systems are critical for long duration NASA missions in dark, dusty, or harsh environments. Thermoelectric systems have been used on the very successful RPS flown in the past, but are limited in efficiency. Dynamic thermal energy conversion provides significantly higher efficiency and through proper engineering of the non-contact moving components, can eliminate wear mechanisms and provide long life. While high efficiency performance of dynamic power convertors has been proven, reliable and robust systems tolerant of off-nominal operation is needed. In addition to convertors appropriate for General Purpose Heat Source (GPHS) RPS, advances in much smaller and lower power dynamic power conversion systems are sought that can utilize Radioisotope Heater Units (RHU) for applications such as distributed sensor systems, small spacecraft, and other systems that take advantage of lower power electronics for the exploration of surface phenomenon on icy moons and other bodies of interest. While the power convertor advances are essential, to develop reliable and robust systems for future flight, advances in convertor components as well as RPS integration components are also needed. These would include efficient alternators able to survive 200 C, robust high-temperature tolerant regenerators, robust high efficiency recuperators, heat pipes, radiators, and controllers applicable to Stirling flexure-bearing, Stirling gas-bearing, or Brayton convertors. Similar scope and content was previously included as part of the broader S3.01 subtopic last year. This nomination is for dynamic power conversion as a stand-alone subtopic under S3.

Relevance / Science Traceability

This technology directly aligns with the Science Mission Directorate - Planetary Science Division for space power and energy storage. Investments in more mature technologies through the Radioisotope Power System Program is ongoing. This SBIR subtopic scope provides a lower TRL technology pipeline for advances in this important power capability that improves performance, reliability, and robustness.
S3.03 Energy Storage for Extreme Environments

Lead Center: GSFC

Participating Center(s): JPL

Technology Area: TA15 Aeronautics

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 from -200° C for outer planet missions to 400 to 500° C for Venus missions, and a span of -230° C to +120° C for missions to the Lunar surface. Operational durations of 60 days for Titan and 14 days for the Moon are of interest. Advancements to battery energy storage capabilities that address operation at extreme temperatures combined with high specific energy and energy density (>200 Wh/kg and >200 Wh/l) are of interest in this solicitation.

In addition to batteries, other advanced energy storage/load leveling technologies designed to the above mission requirements, such as mechanical or magnetic energy storage devices, are of interest. These technologies have the potential to minimize the size and mass of future power systems.

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 [4]. 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 2020 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

- NASA Science: https://science.nasa.gov/ [92]
- Solar Electric Propulsion: h [93]https://www1.grc.nasa.gov/space/sep/ [93]

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype

Desired Deliverables Description

Research should be conducted to demonstrate technical feasibility during 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 max temperature range of -40 to 80 deg C but suffer from capacity loss, especially at low temperatures. At -40 deg 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 over 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. This solicitation is aimed at the development of cells that can maintain performance at extreme temperatures so as to minimize or eliminate the need for strict thermal management of the batteries, which adds complexity and mass to the spacecraft.

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, and 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.

S3.04 Guidance, Navigation, and Control

Lead Center: GSFC

Participating Center(s): JPL, MSFC

Technology Area: TA15 Aeronautics

Scope Title

Guidance, Navigation, and Control

Scope Description

NASA seeks innovative, groundbreaking, and high impact developments in spacecraft guidance, navigation, and control 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 Spacecraft Attitude Determination and Control Systems, Absolute and Relative Navigation Systems, and Pointing Control Systems, and Radiation-Hardened Guidance, Navigation, and Control (GNC) Hardware.

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

Advances in the following areas are sought:

- 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 size, weight, and power requirements.
- Absolute and Relative Navigation Systems: Autonomous onboard flight navigation sensors and algorithms incorporating both spaceborne and ground-based absolute and relative measurements. For relative navigation, machine vision technologies apply. Special considerations will be given to relative navigation sensors enabling precision formation flying, astrometric alignment of a formation of vehicles, robotic servicing and sample return capabilities, and other GNC techniques for enabling the collection of distributed
science measurements. In addition, flight sensors and algorithms that support onboard terrain relative navigation are of interest.

- **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.
- **Radiation-Hardened Hardware**: GNC sensors that could operate in a high radiation environment, such as the Jovian environment.
- **Fast-light or Exceptional-Point Enhanced Gyroscopes and Accelerometers**: In conventional ring laser gyros, precision increases with cavity size and measurement time. However, by using Fast-Light (FL) media or Exceptional Points (EPs) in coupled resonators, an increase in gyro sensitivity can be achieved without having to increase size or measurement time, thereby increasing the time for standalone spacecraft navigation. (The increased precision also opens up new science possibilities such as measurements of fundamental physical constants, improving the sensitivity-bandwidth product for gravity wave detection, and tests of general relativity.) Prototype FL- or EP-enhanced gyros are sought that can be implemented in a compact rugged design that is tolerant to variations in temperature and G-conditions, with the ultimate goal of demonstrating decreased angular random walk.

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 TRL 5–6 level consistent with NASA SBIR/STTR Technology Readiness Level (TRL) 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.

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 Guidance, Navigation, and Control technology in support of SMD missions and future mission concepts. Proposals for the development of hardware, software, and/or algorithm are all welcome. The specific applications could range from CubeSats/SmallSats, to ISS payloads, to flagship missions.

**References**

- 2017 NASA Strategic Technology Investment Plan: [https://go.usa.gov/xU7sE](https://go.usa.gov/xU7sE) [45]
- 2015 NASA Technology Roadmaps: [https://go.usa.gov/xU7sy](https://go.usa.gov/xU7sy) [46]

**Expected TRL or TRL range at completion of the project**: 4 to 6

**Desired Deliverables of Phase II**

Prototype, Analysis, Hardware, Software

**Desired Deliverables Description**

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

**State of the Art and Critical Gaps**

**Capability area gaps:**

- **Spacecraft GNC Sensors** – Highly integrated, low power, low weight, rad-hard component sensor technologies, and multifunctional components.
- **Spacecraft GNC Estimation and Control Algorithms** – autonomous proximity operations algorithm, robust distributed vehicle formation sensing and control algorithms.

**Relevance / Science Traceability**
Science areas: Heliophysics, Earth Science, Astrophysics, and Planetary missions’ capability requirement areas:

- Spacecraft GNC Sensors – optical, 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.

**S3.05 Terrestrial Balloons and Planetary Aerial Vehicles**

Lead Center: GSFC

Participating Center(s): AFRC, JPL

Technology Area: TA15 Aeronautics

**Scope Title**
Planetary Aerial Vehicles for Venus

**Scope Description**

NASA is interested in scientific investigation of the Venus atmosphere and planetary surface using aerial vehicles. Aerial vehicles are expected to carry scientific payloads at Venus that will perform in-situ investigations of its atmosphere, surface and interior structure. The 2018 Venus Aerial Platforms Study report 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. Venus features a challenging atmospheric environment that significantly impacts the design of aerial vehicles. Proposals are sought in the following areas:

**Aerial Vehicle Platforms for Venus**
- Concepts for Lighter-than-Air (e.g., balloons, airships) and Heavier-than-Air (e.g., fixed wing, rotary wing) vehicles are encouraged. The current state of the art in Venus aerial vehicles has been designed to operate within the altitude range of 50 to 60 km above the surface where the atmosphere is similar to the lower Earth atmosphere. The science objectives described in the Venus Aerial Platform study indicate that a wider range of altitudes is strongly desirable.

There are 3 areas of interest in this call:

1. Aerial systems that can maneuver throughout the range 40 to 70 km altitude for a long duration. The aerial platform should be able to operate on the sunlit side of Venus and be able to transit the night side and survive several circumnavigations around the planet. The proposal should describe how the vehicle concept would be deployed into the atmosphere and operated for its mission. The proposal does not have to address thermal design of the payload (if it is suspended under a balloon), but should include concepts for addressing the thermal requirements for the aerial platform. The atmospheric temperature ranges from 145°C at 40 km to -10°C at 60 km altitude. The aerial platform is not expected to operate extensively at the lower altitudes but should be capable of operating for short durations at high temperatures. Concepts for any of the following capabilities of aerial vehicle are encouraged:
   - Technology demonstration with science payload less than 5 kg.
   - Pathfinder mission with science payload less than 30 kg.
   - Flagship mission with science payload up to 60 kg.

Other areas of interest include low cost approaches to:

1. Solar heated balloon systems to carry small science payloads (i.e. less than 10 kg payload) from 60 to 70
km altitude which would operate only on the sunlit side. These should be relatively simple systems that could operate collectively as a swarm system.

2. Deep atmospheric probes, deployed from aerial vehicles, to measure diurnal variations in the deep atmosphere of Venus. These could be deployed at different locations around Venus to capture atmospheric differences between day and night. Concepts for vehicles or neutrally buoyant probes that perform vertical descents, or guided/gliding descents to the surface are desired.

References

The Venus Aerial Platforms Study report can be found here: https://solarsystem.nasa.gov/resources/2197/aerial-platforms-for-the-scientific-exploration-of-venus/ [94]

Information about Venus can be found here: https://solarsystem.nasa.gov/planets/venus/in-depth/ [95]


Expected TRL or TRL range at completion of the project: 2 to 3

Desired Deliverables of Phase II

Prototype, Analysis, Research

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. Deliverables shall be a final report describing the results of the concept analysis, demonstration of any key technology developed and photos of any prototypes that were built and tested.

State of the Art and Critical Gaps

Terrestrial based aerial vehicles, including lighter-than-air and heavier-than-air are mature technologies and continue making advancements in capability, reliability and autonomy. But these need adaptation for operation in the Venus environment.

A gap exists in aerial vehicle technology that allows for variable altitude investigation in the Venus atmospheric environment. Floating at a fixed altitude means the vehicle is basically collecting samples of the same atmosphere each time it performs a collection since it floats with the wind. Having variable altitude capability allows significantly better investigation into the atmospheric structure. Variable altitude balloon concepts have been developed to operate over the altitude range of 50 to 60 km. New science goals defined in the Venus Aerial Platforms Study have indicated that stretching this operating range over 40 to 60 km is needed. This is a significant challenge because of the high atmospheric temperature at the 40 km altitude.

Relevance / Science Traceability

Relevance: Applied Physics Laboratory's (APL) Dragonfly mission selection by New Frontiers shows there is significant interest in aerial vehicles for science investigations. It is in NASA's interests through the SBIR program to continue fostering innovative ideas to develop mission concepts to explore Venus using aerial vehicles.

JPL's Solar System Mission Formulation Office and the NASA Science Mission Directorate's Planetary Science Division advocate Venus aerial vehicle platform development. Furthermore, there are many enthusiastic supporters of exploring other worlds with aerial platforms throughout NASA.
Science Traceability: The 2018 Venus Aerial Platforms Study report 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.

**Scope Title**  
Satellite Communications for Balloons

**Scope Description**

Improved downlink bitrates and innovative solutions using satellite relay communications from balloon payloads are needed. Long duration balloon flights currently utilize satellite communication systems to relay science and operations data from the balloon to ground based control centers. The current maximum downlink bit rate is 150 kilobits per second operating continuously during the balloon flight. Future requirements are for bit rates of 1 megabits per second or more. Improvements in bit rate performance, reduction in size and mass of existing systems, or reductions in cost of high bit rate systems are needed. Tracking and Data Relay Satellite (TDRSS) and Iridium satellite communications are currently used for balloon payload applications. A commercial S-band TDRSS transceiver and a mechanically steered 18 dBi gain antenna provide 150 kbps continuous downlink. TDRSS K-band transceivers are available but are currently cost prohibitive. Open port Iridium service is also in use, but the operational cost is high per byte transferred.

**References**

NASA's SuperTIGER Balloon Flies Again to Study Heavy Cosmic Particles: [https://sites.wff.nasa.gov/code820/](https://sites.wff.nasa.gov/code820/) [97]

Expected TRL or TRL range at completion of the project: 1 to 3

**Desired Deliverables of Phase II**

Prototype, Analysis, Hardware, Software, Research

**Desired Deliverables Description**

Desired deliverables include results of analysis or simulation, or test results of actual prototype hardware and/or software. Phase II deliverables could include a prototype that could be test flown on a balloon mission.

**State of the Art and Critical Gaps**

Current commercially available satellite relays systems that could be used for balloon flight are either too costly, or do not provide the needed downlink data rates.

**Relevance / Science Traceability**


**Scope Title**  
Helium Replenishment System

**Scope Description**

NASA long duration Super Pressure Balloons (SPB) are large and complex structures that contain seams and
fittings. Since these balloons are hand constructed, there is potential for gas loss due to leaks through the seams or fittings, or permeation through the balloon envelope that is made of linear low-density polyethylene. In the event of a gas loss, a helium replenishment system is needed to augment the lifting gas in order to increase the likelihood of payload recovery overland, and to extend the flight duration. The desired system shall not significantly affect the overall mass of the payload and shall require limited power for efficient operation.

References

NASA's SuperTIGER Balloon Flies Again to Study Heavy Cosmic Particles: https://sites.wff.nasa.gov/code820/

Expected TRL or TRL range at completion of the project: 1 to 3

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Desired deliverables include results of analysis or simulation, or test results of actual prototype hardware and/or software. Phase II deliverables could include a prototype that could be test flown on a balloon mission.

State of the Art and Critical Gaps

No such system currently exists.

Relevance / Science Traceability

SMD - NASA HQ (Astrophysics Division). Enables multiple ROSES opportunities, Small Explorer (SMEX) Announcement of Opportunity (AO) (Astrophysics), Astrophysics Mission of Opportunity, Hands-On Project Experience (HOPE) (annually). A replenishment system can potentially prove very beneficial for avoiding payload termination over water by extending flight duration and enabling payload recovery overland in case of limited gas loss. This in turn can result in salvaging high value science data and payload recovery. Such a system can also possibly extend flight duration enabling more science data collection as well as other such potential benefits.

S3.06 Thermal Control Systems

Lead Center: GSFC

Participating Center(s): JPL, LaRC, MSFC

Technology Area: TA15 Aeronautics

Future spacecraft and instruments for NASA's Science Mission Directorate (SMD) will require increasingly sophisticated thermal control technology. Innovative proposals for the cross-cutting thermal control discipline are sought in the following areas/scopes. Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward a Phase II hardware demonstration. Phase II should deliver a demonstration unit for NASA testing at the completion of the Phase II effort.

Scope Title

Dust Mitigation Thermal Coatings

Scope Description

Thermal coatings are an integral part of a space mission and are essential to the survivability of the spacecraft and instrument. Coating of the radiator with desired emissivity and absorptivity on the radiator surface provides 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, anti-contamination 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 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.

References

The following website provides links to some references for dust mitigation coatings such as lotus thermal coatings:

https://ntrs.nasa.gov/search.jsp?R=20150020486 [98]

Expected TRL or TRL range at completion of the project: 2 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

- Successfully develop the formulations of the coating that leads to the desired dust mitigation.
- Samples of the hardware for further testing at NASA facilities.
- Results of performance characterization tests.
- Results of stability test of the coating formulations and its mechanical durability test under the influence of simulated space and lunar environmental conditions.
- Final report.

State of the Art and Critical Gaps

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

Relevance / Science Traceability

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

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 to 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 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 mid-range heat pumps that are suitable for small science rovers where internal heat dissipation may range from 20 Watts to 100 Watts.

References

Apollo Lunar Roving Vehicle Documentation: https://www.hq.nasa.gov/alsj/alsj-LRVdocs.html [99]


Expected TRL or TRL range at completion of the project: 2 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Research

Desired Deliverables Description

- Conceptual design
- Physics-based analysis or model
- Proof-of-concept hardware
- Final report

State of the Art and Critical Gaps

Specifically, heat pump systems are needed for the following:

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

Novel heat pump systems are desired. Enabling improvements over 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 NRC's Planetary Science Decadal Survey are included.

Scope Title
Software Improvements for Integrated Thermal-Structural-Optical Performance Analysis

Scope Description

Sensitive optical components and systems, as are frequently used on science missions, require structural, thermal, and optical performance (STOP) analysis in their design process to validate optical system performance in expected mission environments. This analysis often utilizes models generated in software unique to each field. The models, or their outputs, are transferred between analysts, creating iterative and time consuming design cycles. Software packages do exist that provide multiphysics analysis or coupling between analysis programs; however, the packages can be difficult to learn/implement and cost prohibitive. A new software is needed that can provide concurrent (or near concurrent) analysis using analysis programs in use by NASA, is straightforward to learn, and can be used by the growing number of low cost flight programs.

References

Nearly all spacecraft with optical components require some level of STOP analysis.

Structural-Thermal-Optical performance (STOP) Analysis:
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150017758.pdf [102]

Expected TRL or TRL range at completion of the project: 5 to 9

Desired Deliverables of Phase II

Analysis, Software

Desired Deliverables Description

A successful STOP analysis software program will be applicable to any optical system and capable of interfacing with mechanical, structural, thermal, and optical analysis software used at NASA to provide concurrent (or near concurrent) analysis capability by users of the various disciplines. Additionally, the software must be straightforward to use and easy to learn.

State of the Art and Critical Gaps

STOP analyses have traditionally required a time-consuming, iterative approach where models, or their outputs, have been transferred among the respective structural, optical, and thermal analysts. Recently, multi-physics software package have become available that can centralize the analysis into one program. However, these can be cumbersome to learn, lack heritage, and can be cost-prohibitive to use.

Relevance / Science Traceability

Any mission/project in which optical components or systems are used will require STOP analyses to be completed. As such, a general, integrated, and easy-to-use STOP software is a common desire among engineers of different disciplines.

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 spacecraft. 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 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.

References


Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

- Successfully develop advanced techniques to manufacture the LHP evaporator and reservoir assembly.
- Demonstrate the performance of the evaporator/reservoir performance in an LHP setup.
- Final report.

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 size, the higher the capillary pumping capability. On the other hand, the smaller the pore size, the higher the flow resistance which must be overcome by the capillary force. Traditional sintered metal wicks have a pore size on the order of 1 micron and porosity around 0.4-0.6. 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 microns.

Relevance / Science Traceability

Traditional LHPs are used on many NASA missions including ICESat (Ice, Cloud, and Land Elevation Satellite), 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 SMD missions, especially those using small satellites, can greatly benefit from this technology.

Scope Title

Approaches and Techniques for Lunar Surface Payload Survival

Scope Description

The lunar environment poses significant challenges to small, low power (~100W 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 400K at local solar noon or drop to below 100K during the lunar night, even colder in permanently shadowed regions. These hot and cold conditions can last several earth days due to 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.

This call seeks to solicit innovative proposals to enable lunar science in the difficult lunar environment. Some technologies may include, but are not limited to, active loops that may be turned off and are freeze tolerate, zero or low power heat generation sources, high thermal capacitance thermal storage, advanced insulation, passive
switching. Technologies should show substantial increase over the state-of-the-art. Considerations include power usage in day and night/shadow, mass, heat transport when turned on, heat leak when turned off, sensitivity to lunar topography and orientation, etc.

References


The Surveyor Program: https://www.lpi.usra.edu/lunar/missions/surveyor/ [105]

Missions - Lunokhod 01: https://solarsystem.nasa.gov/missions/lunokhod-01/in-depth/ [106]

Missions - Lunokhod 02: https://solarsystem.nasa.gov/missions/lunokhod-02/in-depth/ [107]

Expected TRL or TRL range at completion of the project: 3 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

Thermal management approaches, techniques, and hardware components to enable the accommodation of lunar temperature extremes encountered in the lunar environment.

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. ALSEP’s (Apollo Lunar Surface Experiments Package) 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.

While interest in lunar science and the development of abilities to deliver payloads to the lunar surface are resurgent, the capability to operate through the entire lunar environment is critical. In the absence of perpetual power supplies like RTG’s, thermal management approaches to accommodate the lunar extremes, extended day/night cycles, and shadowed regions are seen as enabling.

Relevance / Science Traceability

SMD lunar surface science investigations will employ small, low power payloads that will require advanced thermal control approaches and techniques to survive and operate for extended duration through extreme thermal environments on the lunar surface.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the 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 [4]. 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 2020 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.

S3.08 Command, Data Handling, and Electronics

Lead Center: GSFC

Participating Center(s): JPL, LaRC, MSFC

Technology Area: TA15 Aeronautics

Scope Description

NASA’s space based observatories, fly-by 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 2020 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), while planetary
missions can have requirements well in excess of 1 Mrad(Si).

Specific technologies sought by this subtopic include:

Fault-tolerant computing: Processor and eco-system (ASIC & Design IP) designed to mitigate single event upsets
(SEUs) – Technologies are sought that implement fault tolerant computers leveraging industry standard processor
instruction set architectures (ISPIAs) and interfaces. Although not limited to, there is particular interest in leveraging
the reduced instruction set computer (RISC) principles of RISC-V architecture. Offerors should identify coding
language of IP cores, use of architecture specific modules which would limit the ability to swap hardware chipsets,
options for scaling fault tolerance, code/gate size and features versus power and speed. Offerors working
application-specific integrated circuit (ASIC) efforts should identify possible foundries and their radiation tolerance
processes. Offerors offering processing units should identify operating system / toolchain support. Offerors
proposing design intellectual property (IP) should identify mitigation technique(s) including burdens on code
development time / hardware performance and size.

Multiple output point of load power regulator: This module, preferably implemented utilizing one or more controller
ASICs, will source a minimum of 3 settable output voltages when provided with standard spacecraft power bus
input. Output voltages shall be independently settable to any voltage between 3.3V and .9 V with efficiency of at
least 95%. Regulation, noise filtering and other operational specifications should be commensurate with industry
standards for space-based systems. Output current in the 10A range to handle field-programmable gate array
(FPGA) core requirements. The module should provide standard spacecraft power supply features, including over
voltage protection, fault tolerance, load monitoring, sequencing, synchronization, soft start and should allow control
and status monitoring by a remote power system controller. Using fewer external components is also highly
desirable. There is also interest in a capability to provide data over power line communication to the converter for
control and monitoring functions. The offeror should determine radiation tolerance levels achievable utilizing
commercially available processes and indicate, in the proposal, the radiation tolerance goals.
High density high-reliability interconnections: A high reliability connector or interconnect mechanism that can operate in space environments (vacuum, vibration) and deliver hundreds of signal/power connections while using as little physical board area as possible is desired. The design should handle everything from carrying power to high speed (10+ Gbps) impedance controlled connections. The design should be scalable in different sizes to accommodate fewer connections and save board space. Low insertion force is desirable. Right angle and stacking design options should be considered.

References

For descriptions of radiation effects in electronics, the proposer may visit [http://radhome.gsfc.nasa.gov/radhome/overview.htm](http://radhome.gsfc.nasa.gov/radhome/overview.htm) [108].

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

Desired Phase 2 deliverables for fault tolerant computing architectures are IP cores / ASIC designs implemented using an appropriate hardware design language (VHDL or Verilog) that have been demonstrated as an integrated system. Any required system software should be available, preferably as open source, to provide compilers, debuggers, and operating systems to the architecture. The fault tolerance of the architecture should be demonstrated.

Desired Phase 2 deliverable for the multiple output point of load switcher is a prototype multi-output point of load regulator. The regulator should be integrated onto a test board and be performance tested under varying resistive, capacitive, and transient load conditions.

Desired Phase 2 deliverables for the high density high-reliability interconnect are prototypes of the connection system (different size, orientations, etc.). The connector should be integrated onto a test board where its performance (speed, cross talk, etc.) can be verified.

State of the Art and Critical Gaps

There is a need for a broader range of offerings for fault tolerant computing architectures. This includes the need for viable options between performance, size (gate count) and power tradeoffs. There are currently a few sources of fault tolerant computing, and additional variety would help reduce costs for future NASA missions. Fault tolerant computing enables robust autonomous systems to be designed and implemented. Furthermore, recent commercial processor architecture developments offer improved performance and a broader array of performance options, and fault tolerant variants of these could significantly benefit NASA missions.

There are multiple output point of load converters available from commercial companies. The existing commercial parts require many external components eliminating their space savings. Commercial parts are not built on radiation tolerant processes.

Current connectors are too large, especially for small satellites and CubeSats. As the size of the printed circuit boards has shrunk, the percent of board space being used by the I/O connectors has become unacceptable. The connectors are taking away from circuitry and sensors that could be providing additional functionality and science products. High density commercial connectors also tend to be lacking in their general ruggedness, outgassing, and ability to prevent intermittent connections in high vibration environments like orbital launches.

Relevance / Science Traceability

Fault tolerant / autonomous computing 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 planets instruments, and heliophysics missions to harsh radiation environments. For these missions, the inherent fault tolerance would provide an additional level of protection on top of the radiation tolerance of the FPGA or ASIC on which the computing system is implemented. Additionally, for missions with large communication delays, the inherent fault tolerance can limit the need for ground intervention.

Multi-output point of load converters and high-density high-reliability interconnects are relevant to miniaturizing electronics. Miniaturized flight electronics allows one to fit more functionality into less volume, allowing smaller spacecraft to perform science that was previously done by larger satellites. These missions include interplanetary CubeSats and smallsats, outer planets instruments, and heliophysics missions.

**S4.02 Robotic Mobility, Manipulation and Sampling**

*Lead Center: JPL*

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

*Technology Area: TA15 Aeronautics*

**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 and acquisition and handling of samples for in-situ analysis or return to Earth from planets and small planetary bodies. The Moon and planetary moons with liquid oceans are of particular interest, as well as Mars, 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 well as 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 the harsh mission environment are important characteristics for the tools. Finally, 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, and dust, are of particular interest. Technical feasibility should be demonstrated during Phase I 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 fully develop a technology and infuse it into a NASA program. Specific areas of interest include the following:

- Surface mobility and sampling systems for planets, small bodies, and moons
- Near subsurface sampling tools such as icy surface drills to 30 cm depth deployed from a manipulator
- Subsurface ocean access such as via a deep drill system
- Sample handling technologies that minimize cross contamination and preserve mechanical integrity of samples
- Pneumatic sample transfer systems and particle flow measurement sensors
- Low mass/power vision systems and processing capabilities that enable fast surface traverse
- Active lighting stereo systems for landers and rovers
- Electro-mechanical connectors enabling tool change-out in dirty environments
- Tethers and tether play-out and retrieval systems
- Miniaturized flight motor controllers
- Cryogenic operation actuators
- Robotic arms for low gravity environments

Proposers should also note a related subtopic exists that is focused solely on lunar robotic missions (see Z5.05, Lunar Rover Technologies for In-Situ Resource Utilization and Exploration), under the Space Technology Mission Directorate). With NASA's present emphasis on lunar exploration, Z5.05 is provided to help develop innovative lunar rover technologies to support in-situ resource utilization activities and for developing ideas, subsystem components, software tools, and prototypes that contribute to more capable and/or lower cost lunar robots. In particular, cryogenic or cryo-capable actuators that are specifically for lunar rover applications should be directed towards Z5.05.

References

Mars Exploration/Programs & Missions: https://mars.nasa.gov/programmissions/ [109]

Solar System Exploration: https://solarsystem.nasa.gov/ [110]

Ocean Worlds website: https://www.nasa.gov/specials/ocean-worlds/ [48]

Ocean Worlds article: https://science.nasa.gov/news-articles/ocean-worlds [111]

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Hardware and software for component robotic systems.

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. Non-flight systems have been developed for sampling on comets, Venus, and Earth's moon. However, these have not been incorporated in a robotic mission, and the lack of a sufficient solution or technology readiness level is in some cases the reason a mission has not yet been possible. Exploration of icy ocean worlds is in the concept phase and associated sampling and sample handling systems do not exist.

Relevance / Science Traceability

The subtopic supports multiple programs within 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: surface and deep drills for Europa. 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.

S4.04 Extreme Environments Technology

Lead Center: GSFC

Participating Center(s): GRC, GSFC, LaRC

Technology Area: TA15 Aeronautics
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 surface of Titan and of other Ocean Worlds as low as -180 deg C; and in permanently shadowed craters on the Moon), or

2) Combination of low temperature and radiation environments (e.g., surface conditions at Europa of -180 deg C with very high radiation), or

3) Very high temperature, high pressure and chemically corrosive environments (e.g., Venus surface conditions having very high pressure and temperature of 486 deg 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 Venustian surface (485°C, 93 atmospheres), 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 Mega-rad total ionizing dose (TID) behind 0.1 inch 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 out-gassing 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, e.g., 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-arc-second/nanometer precision
- Long life bearings/tribological surfaces/lubricants
- High temperature energy storage systems
- High-temperature actuators and gear boxes for robotic arms and other mechanisms
- Low-power and wide-operating-temperature radiation-tolerant/ radiation hardened RF electronics
- Radiation-tolerant/radiation-hardened low-power/ultra-low power, wide-operating-temperature, low-noise mixed-signal electronics for space-borne systems such as guidance and navigation avionics and instruments
- Radiation-tolerant/radiation-hardened power electronics
- Radiation-tolerant/radiation-hardened electronic packaging (including shielding, passives, connectors, wiring harness and materials used in advanced electronics assembly)

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.

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 [4]. 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 2020 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


Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Hardware

Desired Deliverables Description

Deliverables include proof of concept working prototypes that demonstrate the innovations defined in the proposal and enable direct operation in extreme environments.

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 deg 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, 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.

Relevance / Science Traceability

Relevance to SMD (Science Mission Directorate) is high.

Low temperature survivability is required for surface missions to Titan (-180 deg C), Europa (-220 deg C), Ganymede (-200 deg C), small bodies and comets. Mars diurnal temperatures range from -120 deg C to +20 deg C. For the Europa Clipper baseline concept, with a mission life of 10 years, the radiation environment is estimated at 2.9 megarad total ionizing dose (TID) behind 100 mil thick aluminum. Lunar equatorial region temperatures swing from -180 deg C to +130 deg C during the lunar day/night cycle, and shadowed lunar pole temperatures can drop to -230 deg C.

Advanced technologies for high temperature systems (electronics, electro-mechanical 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 which operate in high temperature and high pressure environments.

S4.05 Contamination Control and Planetary Protection
Scope Description

The planetary protection and contamination control subtopic focuses on mission-enabling and capability-driven technologies to improve NASA's ability to prevent forward and backward contamination. Forward contamination is the transfer of viable organisms from Earth to another body. Backward contamination is the transfer of material posing a biological threat back to Earth's biosphere. NASA is seeking innovative technologies or applications of technologies to facilitate meeting portions of forward and backward contamination requirements to include:

- Improvements to spacecraft cleaning and sterilization that remain compatible with spacecraft materials and assemblies,
- Prevention of re-contamination and cross-contamination throughout the spacecraft lifecycle,
- Improvements to detection and verification of organic compounds and biologicals on spacecraft, to include microbial detection and assessments for viable organism and DNA-based verification technologies to encompass sampling devices, sample processing, and sample analysis pipelines, and
- 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.
- Enabling end-to-end sample return functions to assure containment and pristine preservation of materials gathered on NASA missions.

For contamination control efforts, understanding contaminants and preventing contamination supports the preservation of sample science integrity and ensures spacecraft function nominally. NASA is seeking analytical and physics-based modeling technologies and techniques to quantify and validate sub-micron particulate contamination, low energy surface material coatings to prevent contamination, and modeling and analysis of particles to ensure hardware and instrumentation meet organic contamination requirements.

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/re-contamination mitigation system that can withstand spacecraft assembly and testing operations
- In-flight spacecraft component-to-component cross contamination mitigation system
- Viable organism and/or DNA sample collection devices, sample processing (e.g. low biomass extraction), and sample analysis (e.g. bioinformatic 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
- Low surface area energy coatings
- Molecular adsorbers ("getters")
- Experimental technologies for measurement of outgassing rates lower than 1.0E-15 g/cm2/s 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 transport modeling and analysis for continuum, rarefied and molecular flow environments, with electrostatic, vibro-acoustic, particle detachment and attachment capabilities
- Modeling and analysis technologies for view-factor computation technologies for complex geometries with articulation (e.g., rotating solar arrays, articulating robotic arms)
Expected TRL or TRL range at completion of the project 2 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Technologies, approaches, techniques, models, and/or prototypes including accompanying data validation reports demonstrating how the product will enable spacecraft compliance with planetary protection and contamination control requirements.

State of the Art and Critical Gaps

Planetary protection state-of-the-art leverages the technologies resulting from the 1960s-1970s Viking spacecraft assembly and test era. The predominant means to control biological contamination on spacecraft surfaces is using some combination of heat microbial reduction processing, solvent cleaning (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 the hardware then is protected in a cleanroom environment (ISO 8 or better) using protective coverings when hardware is not being assembled or tested. Biological cleanliness is then verified through the NASA standard assay which is a culture-based method. 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 which include the total adenosine triphosphate (tATP) and limulus amoebocyte lysate (LAL) assays. 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 developed approaches for compliance environmental assessments are implemented to understand recontamination potential for cleanroom surfaces and air. While the NASA standard assay is performed on the cleanroom surfaces DNA-based methodologies have been adopted to include 16S and 18S rRNA targeted sequencing while metagenomic approaches are currently undergoing development. Thus, the critical planetary protection gaps include the assessment of DNA from low biomass surfaces (<0.1 ng/µL DNA using current technologies from 1-5m² of surface), sampling devices that are suitable for low biomass and compounds (e.g. viable organisms, DNA) but also compliant with cleanroom and electrostatic discharge limits, quantification of the widest spectrum of viable organisms, enhanced microbial reduction / sterilization modalities that are compatible with flight materials and a ground- and flight-based recontamination systems.

Contamination Control 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 Contamination Control includes:

- Testing and measurement of outgassing rates down to 3.0E-15 g/cm²/s 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 transport modeling and analysis for continuum, rarefied and molecular flow environments with electrostatic, vibro-acoustic, particle detachment and attachment capabilities.
- Modeling and analysis of molecular return flux using Direct Simulation Monte Carlo (DSMC) and the BGK formulation.

Relevance / Science Traceability

Planetary protection requirements has emerged in recent years with increased interest in investigating bodies with
the potential for life detection such as Europa, Enceladus, Mars, etc. and the potential for sample return from such bodies. The development of such technologies would enable missions to be able to be responsive to planetary protection requirements as they would be able to assess viable organisms and establish microbial reduction technologies to achieve acceptable microbial bioburden levels for sensitive life detection instruments to prevent inadvertent “false positives,” to ensure compliance sample return planetary protection and science requirements, and to provide a means to comply with probabilistic based planetary protection requirements for biologically sensitive missions (e.g. outer planets and sample return).

S5.01 Technologies for Large-Scale Numerical Simulation

Lead Center: JPL

Participating Center(s): GSFC

Technology Area: TA15 Aeronautics

Scope Title
Exascale Computing

Scope Description

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

- Decrease the barriers to entry for prospective supercomputing users
- Minimize the supercomputer user’s total time-to-solution (e.g., time to discover, understand, predict, or design)
- Increase the achievable scale and complexity of computational analysis, data ingest, and data communications
- Reduce the cost of providing a given level of supercomputing performance for NASA applications
- Enhance the efficiency and effectiveness of NASA’s supercomputing operations and services

The approach of this subtopic is to seek novel software and hardware technologies that provide notable benefits to NASA’s supercomputing users and facilities, and to infuse these technologies into NASA supercomputing operations. Successful technology development efforts under this subtopic would be considered for follow-on funding by, and infusion into, NASA’s High-End Computing (HEC) projects - the High End Computing Capability project at Ames and the Scientific Computing project at Goddard. To assure maximum relevance to NASA, funded SBIR contracts under this subtopic should engage in direct interactions with one or both HEC projects, and with key HEC users where appropriate. Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration.

Offerors should demonstrate awareness of the state-of-the-art of their proposed technology, and should leverage existing commercial capabilities and research efforts where appropriate. Open source software and open standards are strongly preferred. Note that the NASA supercomputing environment is characterized by:

- HEC systems operating behind a firewall to meet strict IT security requirements
- Communication-intensive applications
- Massive computations requiring high concurrency
- Complex computational workflows and immense datasets
- The need to support hundreds of complex application codes - many of which are frequently updated by the user/developer.

Projects need not benefit all NASA HEC users or application codes, but demonstrating applicability to an important
NASA discipline, or even a key NASA application code, could provide significant value. For instance, a GPU accelerated (or multi-core) planetary accretion code such as LIPAD (Lagrangian Integrator for Planetary Accretion and Dynamics) could be one possible project.

The three main technology areas of S5.01 are aligned with three objectives of the National Strategic Computing Initiative (NSCI) announced by the White House in July 2015. The overarching goal of NSCI is to coordinate and accelerate U.S. activities in HEC, including hardware, software, and workforce development, so that the U.S. remains the world leader in HEC technology and application. NSCI charges every agency that is a significant user of HEC to make a significant contribution to this goal. This SBIR subtopic is an important part of NASA's contribution to NSCI. See https://www.nitrd.gov/nsci/index.aspx [117] for more information about NSCI. The three main elements of S5.01 are:

- Many NASA science applications demand much faster supercomputers. This area seeks technologies to accelerate the development of an efficient and practical exascale computing system (10¹⁸ operations per second). Innovative file systems that leverage node memory and a new exascale operating system geared toward NASA applications are two possible technologies for this element. At the same time, this area calls for technology to support co-design (i.e., concurrent design) of NASA applications and exascale supercomputers, enabling application scaling to billion-fold parallelism while dramatically increasing memory access efficiency. This supports NSCI Objective 1. (Accelerating delivery of a capable exascale computing system that integrates hardware and software capability to deliver approximately 100 times the performance of current 10 petaflop systems across a range of applications representing government needs.)
- Data analytics is becoming a bigger part of the supercomputing workload, as computed and measured data expand dramatically, and the need grows to rapidly utilize and understand that data. This area calls for technologies that support convergence of computing systems optimized for modeling & simulation and those optimized for data analytics (e.g., data assimilation, data compression, image analysis, machine learning, visualization, and data mining). In situ data analytics that can run in-memory side-by-side with the model run is another possible technology for this element. This supports NSCI Objective 2. (Increasing coherence between the technology base used for modeling and simulation and that used for data analytic computing.)
- Presently it is difficult to integrate cyberinfrastructure elements (supercomputing system, data stores, distributed teams, instruments, mobile devices, etc.) into an efficient and productive science environment. This area seeks technologies to make elements of the supercomputing ecosystem much more accessible and composable, while maintaining security. This supports NSCI Objective 4. (Increasing the capacity and capability of an enduring national HPC ecosystem by employing a holistic approach that addresses relevant factors such as networking technology, workflow, downward scaling, foundational algorithms and software, accessibility, and workforce development.)

References:
Exascale Computing

https://www.nas.nasa.gov/hecc/about/hecc_project.html [118] (NASA High-End Computing Capability Project)


Expected TRL or TRL range at completion of the project: 5 to 7

Desired Deliverables of Phase II:
Prototype Software

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

State of the Art and Critical Gaps:
The SOA and the critical gaps of the three technologies areas are: 1. NASA science requires at least 100X more powerful supercomputers and 1000X higher application parallelism in 10 years, at the same power. 2. Current technologies for high-fidelity computational simulations and data analytics are distinct, and interfacing them is inefficient. 3. It is difficult to integrate cyberinfrastructure elements (supercomputing, data stores, distributed teams, instruments, mobile devices, etc.).

Relevance/Science Traceability:

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

S5.03 Accelerating NASA Science and Engineering through the Application of Artificial Intelligence

Lead Center: JPL

Participating Center(s): ARC, JPL, LaRC

Technology Area: TA15 Aeronautics

Scope Title

Accelerating NASA Science and Engineering through the Application of Artificial Intelligence

Scope Description

NASA researchers are increasingly using Artificial Intelligence (AI) technologies across science and engineering to address questions that previously could not be studied, in order to open up new insights. While many problems can be addressed with AI, the adoption of these techniques and technologies has been slow due to the large learning curve associated with the application of these technologies, the applicability of commercial tools to specific problems of interest for NASA, and the high level of effort to create training sets. The goal of this subtopic is to overcome these challenges and accelerate NASA science and engineering through the development and/or application of tools and technologies that use AI, including Machine Learning (ML), Deep Learning (DL), and more. The expected outcomes of this subtopic are tools and technologies that use AI that lead to improved science and engineering, and that lead to advancements in operational capabilities for remote sensing instruments and platforms.

The specific objectives of this subtopic include the following. Innovative proposals using AI are being sought to solve these unique problems across NASA science. Proposals MUST be in alignment with existing and/or future NASA programs and address or extend a specific need or question for those programs. Examples of AI solutions to NASA problems include:

- Mission Operations with long latency communications in deep space environments where the models of the destinations are not well known. Examples of these missions include rovers/instruments on Mars2020 and the Europa Lander.
  - Advanced autonomy with the ability for instruments to learn at the edge
  - Fault detection and recovery
  - Anomaly detection for instruments or platforms
  - Onboard/embedded machine learning for remote sensing platforms
- Data fusion and predictions across multiple data sets using AI, examples include
  - Enhanced geoeffective space-weather predictions
  - Creation of a global product from the fusion of multiple satellite inputs for areas such as carbon science or aerosols
  -Downscaling lower-resolution images to higher resolutions, either from previous missions or through combination of multiple data sets and in-situ data
- Augmenting automatic image analysis, including registration, classification, segmentation, and/or change detection. Examples include
- Identification of spatial patterns to better determine calibration factors across multiple instruments or for detecting instrument degradation
- The detection of transient events in astronomical imagery
- The detection of burned areas from Earth imagery

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 NASA programs and projects.

Tools and products developed under this subtopic may be developed for broad public dissemination or used within a narrow community. These tools can be plug-ins or enhancements to existing software, online data/computing services, or new stand-alone applications or web services, provided that they promote interoperability and use standard protocols, file formats, and Application Programming Interfaces (APIs).

References

Most Recent Decadal Surveys: https://science.nasa.gov/about-us/science-strategy/decadal-surveys [119]


Mars 2020 Mission: https://mars.nasa.gov/mars2020/ [121]


NASA Goddard Institute for Space Studies: https://www.giss.nasa.gov/ [123]

NASA Earth Science Data: https://earthdata.nasa.gov/ [124]

NASA Center for Climate Simulation: https://www.nccs.nasa.gov/ [125]

NASA High-End Computing (HEC) Program: https://www.hec.nasa.gov/ [126]

Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables of Phase II

Prototype, Software, Research

Desired Deliverables Description

Tools and products developed under this subtopic may be developed for broad public dissemination or used within a narrow scientific community. These tools can be plug-ins or enhancements to existing software, online data/computing services, or new stand-alone applications or web services, provided that they promote interoperability and use standard protocols, file formats, and Application Programming Interfaces (APIs).

The desired outcomes for this subtopic include: (1) new or accelerated science and engineering products, (2) training data sets and trained models specifically for a given problem but that can also be used as a basis for furthering other science and engineering research and development, and (3) software algorithms and capabilities developed during the SBIR work would be used and infused in NASA science projects and potentially used to develop new missions.

State of the Art and Critical Gaps

NASA science and engineering have only just begun making use of Artificial Intelligence (AI) technologies (which includes both machine learning and deep learning). 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.
computing systems.

The current applications of AI across NASA science and engineering are just beginning, and the technologies are difficult to use with significant barriers to entry. This has dramatically slowed the adoption of AI across NASA.

Relevance / Science Traceability

Broad applicability across throughout the decadal surveys

Specific missions include the Europa Lander, Mars2020, and more:

- Global Modeling and Assimilation Office (GMAO) Assimilation - Augment Earth system modeling or data assimilation
- Carbon Cycle Ecosystems Office (CCOE) - Wide variety of applications given the diversity of data sets from sparse in-situ to global satellite measurements
- Earth Observing System Data and Information System (EOSDIS)/ Distributed Active Archive Centers (DAACs) - Harnessing the potential for new discoveries across the wide array of observation data
- Earth Science Technology Office (ESTO/AIST) - New technology and services to exploit NASA and non-NASA data
- Computational and Information Sciences and Technology Office (CISTO - Code 606) - Technologies used for new data science
- NASA Center for Climate Simulation (NCCS - Code 606.2) - Building applications toward exascale computing

S5.04 Integrated Science Mission Modeling

Lead Center: JPL

Participating Center(s): GSFC

Technology Area: TA15 Aeronautics

Scope Title
Innovative System Modeling Methods and Tools

Scope Description

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

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

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

1. Conceptual phase models and tools that allow design teams to easily develop, populate, and visualize very
broad, multidimensional trade spaces; 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.

2. 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:
   1. To support emerging usage of autonomy, both in mission operations and flight software as well as in growing usage of auto-coding.
   2. 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.
   3. 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).

3. 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.

References


Habitable Exoplanet Observatory (HabEx): https://www.jpl.nasa.gov/habex/ [22]

Lynx: https://wwwastro.msfc.nasa.gov/lynx/ [23]

Laser Interferometer Space Antenna (LISA): https://lisa.gsfc.nasa.gov/ [127]


Mars Exploration/Program & Missions: https://mars.nasa.gov/programmissions/ [109]

JPL Missions: https://www.jpl.nasa.gov/missions/ [129]

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Prototype, Software

Desired Deliverables Description

At the completion of Phase 2, NASA desires a working prototype suitable for demonstrations with "real" data to make a compelling case for NASA usage. Use and development of the model - including any and all work performed to verify and validate it - should be documented.

State of the Art and Critical Gaps

There currently are 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 sub-topic 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 the fidelity/credibility. While some NASA folks 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: LUVOIR, OST, 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 requires 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.

**S5.05 Fault Management Technologies**

Lead Center: JPL

Participating Center(s): ARC, MSFC

Technology Area: TA15 Aeronautics

**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, but also must consider failure of sensors or the flow of sensor data, harmful or unexpected system interaction with the environment, and problems due to faults in software or incorrect control inputs -- including failure of autonomy components themselves. Despite a wealth of lessons learned from past missions, spacecraft failures are still not uncommon and reuse of FM approaches is very limited, illustrating deficiencies our approach to handling faults in all phases of the flight project lifecycle. While this subtopic addresses particular interest in on-board Fault Management capabilities (viz. on-board sensing approaches, computing, algorithms, and models to assess and maintain spacecraft health), the goal is to provide a system capability, and thus off-board components such as modeling techniques and tools, development environments, testbeds, and verification and validation (V&V) technologies are also relevant. Specific algorithms and sensor technologies are in scope provided their impact is not limited to a particular subsystem, mission goal, or failure mechanism. Innovations in Fault Management can be grouped into the categories below.

- Fault Management Design Tools: System modeling and analysis significantly contributes to the quality of FM design, and may prove decisive in trades of new vs. traditional FM approaches. However, the difficulty in translating system design information into system models often impacts modeling and analysis accuracy.
Examples of enabling techniques and tools are automated modeling systems, spacecraft modeling libraries, algorithm prototyping and test environments, sensor placement analyses, and system modeling that supports multiple autonomy functions including FM. System design should enable multi-disciplinary assessment of FM approaches, addressing performance metrics, standardization of data products and models, and analyses to reduce design costs and design escapes.

- **Fault Management Visualization Tools**: FM systems have impacts on hardware, software, and operations. The ability to visualize the full FM system behavior and the contribution of each component to protecting mission functions and assets is critical to assessing completeness of the approach, and to evaluate appropriateness of the FM design against mission needs. Fault trees and state transition diagrams are simple visualization products. Other examples of visualization could focus on margin management, probabilistic risk assessment, or FM impacts on scenario timelines.

- **Fault Management Operations Approaches**: This category encompasses FM "in the loop," including algorithms, computing, state estimation / classification, machine learning, and model-based reasoning. Advanced FM approaches may reduce the need for spacecraft safing and reliance on mission operations through more accurate health assessment, early detection of problems, more effective discrimination and understanding of root causes, or automated recovery. Particularly desirable are technologies and approaches that enable new mission concepts with greater autonomy, minimizing or eliminating spacecraft safing in response to faults — for example, riding out failures gracefully, or autonomously recovering and restarting system behavior to complete science objectives that require timely execution. Future spacecraft must be able to make decisions about how to recover from failures or degraded capacity and continue the mission, and also to work cooperatively with mission operations to replan mission goals apace with changes in system capability.

- **Fault Management Verification and Validation Tools**: Along with difficulties in system engineering, the challenge of V&V'ing implementations of new FM technologies has been a significant barrier to infusion in flight projects. As complexity of spacecraft and systems increases, the testing required to verify and validate FM implementations can become prohibitively resource intensive without new approaches. Automated test case development, false positive/false negative test tools, model verification and validation tools, and test coverage risk assessments are examples of contributing technologies.

- **Fault Management Design Architectures**: FM capabilities may be implemented through numerous system, hardware, and software architecture solutions. The FM architecture trade space includes options such as embedding within the flight control software or deployment as independent onboard software; on-board versus ground-based capabilities; centralized or distributed FM functions; sensor suite implications; integration of multiple FM techniques; innovative software FM architectures implemented on flight processors or on Field Programmable Gate Arrays (FPGAs); and execution in real-time or off-line analysis post-operations. Alternative architecture choices such as model-based approaches could help control FM system complexity and cost and could offer solutions to transparency, verifiability, and completeness challenges.

Expected outcomes and objectives of this subtopic are to mature the practice of Fault Management, 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:

- Improve predictability of FM system complexity and estimates of development and operations costs
- 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 extent of testing required, completeness of verification planned, and residual risk resulting from incomplete coverage
- Increase data integrity between multi-discipline tools
- Standardize metrics and calculations across FM, SE, S&MA and operations disciplines
- Increase reliability of FM systems
- **Overall, bound and improve costs and implementation risks of FM while improving capability, such that benefits demonstrably outweigh the risks, leading to mission infusion**

References: NASA's approach to Fault Management and the various needs are summarized in the NASA FM Handbook [130]. Additional information is
Fault Management 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 Science Mission Directorate (SMD) Autonomy Workshop, archiving a number of talks on mission challenges and design concepts. Expected TRL or TRL range at completion of the project: 3 to 4

**Desired Deliverables**

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 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 report that summarizes the project’s technical accomplishments. As noted above, it is intended that proposed efforts conduct an initial proof of concept, after which successful efforts would be considered for follow-on funding by SMD missions as risk-reduction and infusion activities. Research should be conducted to demonstrate technical feasibility and NASA relevance during Phase I and show a path toward a Phase II prototype demonstration. The 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, foundational concepts and operating theory, mathematical basis, and requirements for application. Results should include strengths and weaknesses found, 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. While 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, illustrating 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.

**State of the Art and Critical Gaps**

Many recent Science Mission Directorate (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 on-board systems. The SBIR program is an appropriate venue due to 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 fault management. 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**: Enable very low-cost operations and high science return from a 6U cubesat through on-board error detection and mitigation, streamlining mission operations. Provide autonomous resilience to on-board errors and disturbances that interrupt or interfere with science observations.
- **Europa Clipper**: Provide on-board 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, V&V of FM capabilities, and coordinated development with flight software.
- **Rovers and Rotorcraft (Mars Sample Return, Dragonfly)**: Provide on-board 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).
- **Search for Extrasolar Planets (Observation)**: Provide sufficient system reliability through on-board detection, reasoning, and response to enable long-period, stable observations. Provide on-board or on-ground analysis capabilities to predict system response and optimize observation schedule. Enable reliable operations while out of direct contact (e.g., deliberately occulted from Earth to reduce photon, thermal, and radio frequency background).

**S5.06 Space Weather R2O/O2R Technology Development**

**Lead Center:** JPL

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

**Technology Area:** TA15 Aeronautics

**Scope Title**

Space Weather R2O/O2R Technology Development

**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 released in March 2019.

NASA’s role under the National Space Weather Strategy and Action Plan 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 monitoring of space weather for NASA's space missions. This includes research that advances operational space weather needs.

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 Research-to-Operations/Operations-to-Research (R2O/O2R) responsibilities outlined in the Strategy and Action Plan, five areas have been identified for priority development:

(1) **Space Weather Forecasting Technologies and Techniques**: 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 GSFC, and the Short-term Prediction Research and Transition (SPoRT) Center at Marshall Space Flight Center (MSFC), is appropriate. 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 in spacecraft anomaly resolution, and end-users such as spacecraft operators;
- Approaches that potentially lead to a 2-3 days forecasting of atmospheric drag effects on satellites and improvement in the quantification of orbital uncertainties in LEO altitude ranges (up to ~2000 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 (2-3 days) forecasting of SPEs (Solar Particle Events) and an improved all-clear SPE forecasting capability.

(2) **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; and/or,
- Integrate underutilized resources (e.g. space-based radio occultation for ionospheric specification or U.S. Geological Survey (USGS) ground conductivity measurements related to geomagnetically induced currents).

(3) **Space Weather Benchmarks**: The Heliophysics System Observatory (HSO) data archives include a vast array of spacecraft observations suitable for the development of space weather benchmarks, which are the set of characteristics against which space weather events are measured. This includes refining the Phase 1 Benchmarks that were released by the National Science and Technology Council in 2018 for induced geo-electric fields, ionizing radiation, ionospheric disturbance, solar radio bursts, and upper atmospheric expansion. These benchmarks should be in a form useful to the owners and operators of systems and assets that contribute to critical national functions. Innovations to produce and/or further refine these benchmarks are solicited, as are concepts for future creative approaches utilizing new data types or models that could become available.

(4) **Space Weather Mitigation Technologies**: The 2019 National Space Weather Strategy and Action Plan specifically calls 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 effects on satellites. It also includes the development of processes to improve the transition of research approaches to operations.
(5) **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. Concepts are solicited for instrumentation 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. In order 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 (e.g. Interstellar Mapping and Acceleration Probe (IMAP), Geospace Dynamics Constellation (GDC), Medici, Explorer concepts, etc.).

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 National Space Weather Strategy and Action Plan.

**References**


The Space Weather Operations, Research, and Mitigation (SWORM) Working Group is a Federal interagency coordinating body organized under the Space Weather, Security, and Hazards (SWSH) Subcommittee. THE SWSH is a part of the 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 released in March 2019. See: [https://www.sworm.gov/](https://www.sworm.gov/) [137]


An Executive Order (EO) on Coordinating National Resilience to Electromagnetic Pulses (EMP) 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. See: [https://www.whitehouse.gov/presidential-actions/executive-order-coordinating-national-resilience-electromagnetic-pulses/](https://www.whitehouse.gov/presidential-actions/executive-order-coordinating-national-resilience-electromagnetic-pulses/) [140]

**Expected TRL or TRL range at completion of the project**: 3 to 8

**Desired Deliverables of Phase II**

Prototype, Hardware, Software

**Desired Deliverables Description**

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

**State of the Art and Critical Gaps**

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

Space weather poses a constant threat to the Nation's critical infrastructure, our satellites in orbit, and our crewed and 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 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 released in March 2019.

The Heliophysics Space Weather Science and Applications (SWxSA) Program establishes an expanded role for NASA in space weather science under single element. It is consistent with the recommendation of the NRC Decadal Survey and the OSTP/SWORM 2019 National Space Weather Strategy and Action Plan. It competes ideas and products, leverages existing agency capabilities, collaborates with other agencies, and fosters partnership with user communities. The SWxSA program is distinguishable from other heliophysics research elements in that it is specifically focused on investigations that significantly advance understanding of space weather and then apply this progress 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 the 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 are not protected by the Earth’s atmosphere and are exposed to space radiation such as galactic cosmic rays and solar energetic particles. A robust space weather program and associated forecasting capabilities is essential for NASA's future exploration success.