The NASA Science Mission Directorate (SMD) seeks technology for cost-effective high-performance advanced space telescopes for astrophysics and Earth science. Astrophysics applications require large aperture light-weight highly reflecting mirrors, deployable large structures and innovative metrology, control of unwanted radiation for high-contrast optics, precision formation flying for synthetic aperture telescopes, and cryogenic optics to enable far infrared telescopes. A few of the new astrophysics telescopes and their subsystems will require operation at cryogenic temperatures as cold a 4 K. This topic will consider technologies necessary to enable future telescopes and observatories collecting electromagnetic bands, ranging from UV to millimeter waves, and also include gravity waves. The subtopics will consider all technologies associated with the collection and combination of observable signals. Earth science requires modest apertures in the 2 to 4 meter size category that are cost effective. New technologies in innovative mirror materials, such as silicon, silicon carbide and nanolaminates, innovative structures, including nanotechnology, and wavefront sensing and control are needed to build telescopes for Earth science.

Subtopics

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

Lead Center: JPL
Participating Center(s): GSFC
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
- Exoplanet Exploration Program: https://exoplanets.nasa.gov/exep/
- Goddard Space Flight Center: https://www.nasa.gov/goddard

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.

S2.02 Precision Deployable Optical Structures and Metrology

Lead Center: JPL
Participating Center(s): GSFC

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/

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

What is an Exoplanet? https://exoplanets.nasa.gov/what-is-an-exoplanet/technology/

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

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

**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 m2 per month
- Areal density < 15 kg/m2 (< 40 kg/m2 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 MIDEX; or, Decadal class mission. Successful proposals will demonstrate an ability to manufacture, test and control ultra-low-cost optical systems that can meet science performance requirements and mission requirements (including processing and infrastructure issues). Material behavior, process control, active and/or passive optical performance, and mounting/deploying issues should be resolved and demonstrated.

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.ipl.nasa.gov/habex/documents/. The LUVOIR Interim Report is available at: https://asd.gsfc.nasa.gov/luvoir/.


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

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

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

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/, 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.

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/, 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. 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.\textsuperscript{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/m\textsuperscript{2} for a 5 m fairing EELV vs. 150 kg/m\textsuperscript{2} 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 m\textsuperscript{2} of collecting area) should have an areal cost of less than $2M/m\textsuperscript{2}. And, a 16-m class mirror (with 200 m\textsuperscript{2} of collecting area) should have an areal cost of less than $0.5M/m\textsuperscript{2}.

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

- Mirror substrate materials and/or architectural designs
- Processes to rapidly fabricate and test UVO quality mirrors
- Mirror support structures, joints and mechanisms that are athermal or 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. The LUVOIR Interim Report is available at: https://asd.gsfc.nasa.gov/luvoir/.


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

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

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.
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/).

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 off 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](https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10563/105630X/NASAs-current-activities-in-free-space-optical-communications/10.1117/12.2304175.full?SSO=1)

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

**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:

1) On-axis or axisymmetric designs are typically used for (space) optical comm and imaging, which inherently are problematic due to the central obscuration.

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

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

Scope Description

The National Academy Astro2010 Decadal Report identifies studies of optical components and ability to manufacture, coat, and perform metrology needed to enable future X-Ray observatory missions 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/
LUVOIR: https://asd.gsfc.nasa.gov/luvoir/
Origins Space Telescope: https://asd.gsfc.nasa.gov/firs/
The LYNX Mission Concept: https://wwwastro.msfc.nasa.gov/lynx/

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/.

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

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. MgF2 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](https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/concepts.html).

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)

**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-obscured 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 coronagraphy 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

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: JPL
Participating Center(s): GSFC

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:

- Gris-Sanchez et al. (2018) Multicore fibre photonic lanterns for precision radial velocity Science:

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.