SBIR/STTR

Small Business Innovation Research / Small Business Technology Transfer

NASA SBIR 2021 Phase I Solicitation

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.

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

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

This subtopic solicits proposals in the following three focus areas:

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

Expected TRL or TRL Range at completion of the Project: 3 to 6
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories
Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Typical deliverables based on sub-elements of this subtopic:

Phase I:

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

Phase II:

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

State of the Art and Critical Gaps:

This subtopic focuses on three areas of technology development:

- This work is a very costly and time consuming. Most of SOA (state of the art) requiring improvement is ~10 arcsec 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 2× such that the larger collecting area can be produced for the same cost or half the cost.
- Coating technology for wide range of wavelengths from x-ray to IR (x-ray, EUV, LUV, VUV, visible, and IR). The current x-ray coating is defined by NuSTAR. Current EV is defined by Heliophysics (80% reflectivity from 60 to 200 nm). Current UVOIR is defined by Hubble. MgFI2 over coated aluminum on 2.4-m mirror. This coating has birefringence concerns and marginally acceptable reflectivity between 100 to 200 nm.
- Free-form optics design, fabrication, and metrology for package constrained imaging systems. This field is in early stages of development. Improving the optical surfaces with large field of view and fast F/#s is highly desirable.

Relevance / Science Traceability:

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 free-form optics in preparation for Decadal missions such as HabEx, LUVOIR, and OST.

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

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

References:

The 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, multiwavelength space observatory with ambitious science goals. This mission would enable great leaps forward in a broad range of science, from the epoch of re-ionization, through galaxy formation and evolution, star and planet formation, to solar system remote sensing. LUVOIR also has the major goal of characterizing a wide range of exoplanets, including those that might be habitable—or even inhabited. The LUVOIR Interim Report 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 3-order-of-magnitude gain in sensitivity, angular resolution sufficient to overcome spatial confusion in deep cosmic surveys or to resolve protoplanetary disks, and new spectroscopic capability. The community report is available at: https://science.nasa.gov/science-committee/subcommittees/nac-astrophysics-subcommittee/astrophysics-roadmap

Scope Title:

X-Ray Mirror Systems Technology

Scope Description:

NASA large x-ray observatory requires low-cost, ultrastable, lightweight mirrors with high-reflectance optical coatings and effective stray-light suppression. The current state of the art of mirror fabrication technology for x-ray missions is very expensive and time consuming. Additionally, a number of improvements such as 10 arcsec angular resolutions and 1 to 5 m^2 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 infrared (IR) radiation (with wavelengths between 1.5 and 6 µm 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 $100K per square meter.

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

Expected TRL or TRL Range at completion of the Project: 3 to 6
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories
Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

Typical deliverable based on sub-elements of this subtopic:
X-ray optical mirror system—Demonstration, analysis, reports, software, and hardware prototype:

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

State of the Art and Critical Gaps:

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

The gaps to be covered in this track are:

- Lightweight, low-cost, ultrastable mirrors for large x-ray observatory.
- Stray-light suppression systems (baffles) for large advanced x-ray observatories.
- Ultrastable, inexpensive lightweight x-ray telescope using grazing-incidence optics for high-altitude balloon-borne and rocket-borne 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 National Research Council NASA Technology Roadmap Assessment ranked advanced mirror technology for new x-ray telescopes as the #1 Object C technology requiring NASA investment.

References:

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

- https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/concepts.html

Scope Title:

Coating Technology for X-Ray-UV-OIR

Scope Description:

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

The current coating technology of optical components 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 K 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 carbon nanotube (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 a highly absorbing coating such as CNT. Ideally, the application of CNT coating needs to:

- Achieve broadband (visible plus near infrared (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 as vibration, acoustics, etc.
- Tolerate both high continuous-wave (CW) and pulsed power and power densities without damage: ~10 W for CW and ~0.1 GW/cm^2 density, and 1-kW/nsec pulses.
- Adhere to the multilayer 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 bidirectional reflectance distribution function (BRDF) ultralow specular reflectance of 1×10^{-7} in the range of 500 to 1,064 nm. The advancement of this technology is desired to obtain ultralow reflectivity.

- Improve the specular reflectance to 1×10^{-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.

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

Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories
Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

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

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

State of the Art and Critical Gaps:

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

- The current x-ray coating is defined by Nuclear Spectroscopic Telescope Array (NuSTAR).
- Current EUV is defined by Heliophysics (80% reflectivity from 60 to 200 nm).
- Current UVOIR is defined by Hubble. MgFI2 overcoated aluminum on 2.4-m mirror. This coating has birefringence concerns and marginally acceptable reflectivity between 100 and 200 nm.

Metrics for X-Ray:

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

Metrics for EUV:

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

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

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

Metrics for LISA:

- HR: Reflectivity >99% at 1,064+/-2 nm with very low scattered light and polarization-independent performance over apertures of ~0.5 m.
- AR: Reflectivity <0.005% at 1,064+/-2 nm.
  - Low-absorption, low-scatter, laser-line optical coatings at 1,064 nm.
  - High reflectivity, R > 0.9995.
  - Performance in a space environment without significant degradation over time, due for example to

    radiation exposure or outgassing.
    - High polarization purity, low optical birefringence over a range of incident angles from ~5° to ~20°.
    - Low coating noise (thermal, photothermal, etc.) for high-precision interferometric measurements.
    - Ability to endure applied temperature gradients (without destructive effects, such as delamination from the substrate).
    - Ability to clean and protect the coatings and optical surfaces during mission integration and testing. Cleaning should not degrade the coating performance.

Nonstationary Optical Coatings:

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

CNT Coatings:

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

Black-Silicon Cryogenic Etching (new):

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

Software tools to simulate and assist the anisotropic etching by employing 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), and Solar-C.
- LISA requires low-scatter HR coatings and low reflectivity coatings for scatter suppression near 1064 nm. Polarization-independent performance is important.
- Nulling polarimetry/coronagraphy for exoplanets imaging and characterization, dust and debris disks, extra-galactic studies, and relativistic and nonrelativistic jet studies.

References:

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

- More information can be found at: https://lisa.nasa.gov

Scope Title:

Free-Form Optics

Scope Description:

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

Specific metrics are:

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

Expected TRL or TRL Range at completion of the Project: 3 to 6
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories
Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description:

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

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

State of the Art and Critical Gaps:

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

Relevance / Science Traceability:

NASA missions with alternative low-cost science and small-size payload are increasing. However, the traditional interferometric testing as a means of metrology is unsuited to 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 Origins Space Telescope (OST) and Large UV/Optical/IR Surveyor (LUVOIR, currently being proposed for the 2020 Astrophysics Decadal Survey) have demonstrated improved optical performance over a larger field-of-view afforded by free-form optics.

Such programs will require advances in free-form metrology to be successful.

References:

A presentation on application of Freeform Optics at NASA is available at:

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