NASA SBIR 2021 Phase I Solicitation

S2.03 Advanced Optical Systems and Fabrication/Testing/Control Technologies for Extended-Ultraviolet/Optical and Infrared Telescope

Lead Center: MSFC

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

Scope Title:

Optical Components and Systems for Large Telescope Missions

Scope Description:

Accomplishing NASA's high-priority science at all levels (flagship, probe, Medium-Class Explorers (MIDEX), Small Explorers (SMEX), rocket, and balloon) requires low-cost, ultrastable, normal-incidence mirror systems with low mass-to-collecting area ratios. Here, a mirror system is defined as the mirror substrate, supporting structure, and associated actuation and thermal management systems. After performance, 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×, to between \$100K/m^2 and \$1M/m^2.

Specific metrics are defined for each wavelength application region:

1. Aperture diameter for all wavelengths, except far-infrared (IR):

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

2. For ultraviolet (UV)/optical:

- Areal cost: <$500K/m^2
- 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 pathlength stability: <1 pm/10,000 sec for precision metrology
- Areal density: <15 kg/m^2 (<35 kg/m^2 with backplane)
- Operating temperature range: 250 to 300 K

3. For far-IR:

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

4. For extreme ultraviolet (EUV):

- Surface slope: <0.1 µrad

Also needed is the 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: suborbital rocket or balloon; competed SMEX or MIDEX; or Decadal-class mission. Successful proposals will demonstrate an ability to manufacture, test, and control ultra-low-cost optical systems that can meet science performance requirements and mission requirements (including processing and infrastructure issues). Material behavior, process control, active and/or passive optical performance, and mounting/deploying issues should be resolved and demonstrated.

Expected TRL or TRL Range at completion of the Project: 3 to 5
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories
Desired Deliverables of Phase I and Phase II:

- Research
- Prototype
- Hardware

Desired Deliverables Description:

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

State of the Art and Critical Gaps:

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×, to between $100K/m^2$ and $1M/m^2$.

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 Laser Interferometer Space Antenna (LISA), Habitable Exoplanet Observatory (HabEx), Large UV/Optical/Near-IR Surveyor (LUVOIR) and the Origins Space Telescope (OST).

References:

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

- The HabEx Interim Report 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 is a single-aperture telescope concept for the Far-Infrared Surveyor mission described in the NASA Astrophysics Roadmap, "Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades": https://smd-prod.s3.amazonaws.com/science-pink/s3fs-public/atoms/files/secure-Astrophysics_Roadmap_2013_0.pdf
- The OST mission is described on the website: https://origins.ipac.caltech.edu
- The Space Infrared Interferometric Telescope (SPIRIT) and its optical system requirements description: https://asd.gsfc.nasa.gov/cosmology/spirit/
- LISA mission description: https://lisa.nasa.gov/

Scope Title:

Balloon Planetary Telescope

Scope Description:

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

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

- UVO science missions require a 1-m-class telescope diffraction limited at 500 nm or a primary mirror system that can maintain <10 nm rms surface figure error for elevation angles ranging from 0° to 60° over a temperature range of 220 to 280 K.
- IR science missions require 1.5-m-class telescopes diffraction limited at 5 µm.
- FIR missions require 2-m-class (or larger) telescopes diffraction limited at 50 µm.

In all cases, the telescopes need to achieve:

- Mass: <300 kg
- Shock: 10G without damage
- Elevation: 0° to 60°
- Temperature: 220 to 280 K

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

Expected TRL or TRL Range at completion of the Project: 3 to 5
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories
Desired Deliverables of Phase I and Phase II:

- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

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

State of the Art and Critical Gaps:

Current SOA (state-of-the-art) mirrors made from Zerodur(C) or ULE(C), for example, require lightweighting 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:

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

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

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

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

References:

- For additional discussion of the advantages of observations from stratosphere platforms, refer to:
  Dankanich et. al.: "Planetary Balloon-Based Science Platform Evaluation and Program Implementation - Final Report," available from: https://ntrs.nasa.gov/ (search for "NASA/TM-2016-218870").
- Additional information about scientific balloons can be found at: https://www.csbf.nasa.gov/docs.html

Scope Title:

Large Ultraviolet/Optical/near-IR (LUVOIR) Surveyor and Habitable Exoplanet (HabEx) Missions

Scope Description:

Potential ultraviolet/optical (UVO) missions require 4- to 16-m 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, a potential exoplanet mission, using an internal coronagraph, requires total telescope wavefront stability on the order of 10 pm rms per 10 min. This stability specification places severe constraints on the dynamic mechanical and thermal performance of 4-m and larger telescope. Potential enabling technologies include: active thermal control systems, ultrastable mirror support structures, athermal telescope structures, athermal mirror struts, ultrastable joints with low coefficient of thermal expansion (CTE) and high stability, and vibration compensation.

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

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

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

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

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

Expected TRL or TRL Range at completion of the Project: 2 to 4
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories
Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Hardware
- Software

Desired Deliverables Description:

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

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

State of the Art and Critical Gaps:

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

Relevance / Science Traceability:

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 Laser Interferometer Space Antenna (LISA), Habitable Exoplanet Observatory (HabEx), Large UV/Optical/Near-IR Surveyor (LUVOIR) and the Origins Space Telescope (OST).

References:

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

- The HabEx Interim Report is available at: https://www.jpl.nasa.gov/habex/
- The LUVOIR Interim Report is available at: https://asd.gsfc.nasa.gov/luvoir/

The OST is a single-aperture far-infrared telescope concept.

- The OST mission is described at: https://asd.gsfc.nasa.gov/firs/
- The Space Infrared Interferometric Telescope (SPIRIT) and its optical system requirements are described at: https://asd.gsfc.nasa.gov/cosmology/spirit/

Scope Title:

Near-Infrared Lidar Beam Expander Telescope

Scope Description:

Potential airborne coherent lidar missions need compact 15-cm diameter 20× magnification beam expander telescopes. Potential space-based coherent lidar missions need at least 50-cm 65× magnification beam expander telescopes. Candidate coherent lidar systems (operating with a pulsed 2-µm 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 Dall-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 nonmoving scanning of the beam expander output is needed.

Expected TRL or TRL Range at completion of the Project: 3 to 4
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories
Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:

- An ideal Phase I deliverable would be a precision optical system of at least 0.15 m or a relevant subcomponent of a system. While detailed analysis will be conducted in Phase II, the preliminary design should address how optical, mechanical (static and dynamic), and thermal designs and performance analysis will be done to show compliance with all requirements. Past experience or technology demonstrations that support the design and manufacturing plans will be given appropriate weight in the evaluation.
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State of the Art and Critical Gaps:

The current state of the art (SOA) is a commercial off-the-shelf (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 -to 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 versus 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 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, Doppler Aerosol Wind (DAWN), was included in three proposals that are under review. Furthermore, SMD is baselining DAWN for a second Convective Processes Experiment (CPEX-) type airborne science campaign and for providing calibration/validation assistance to the European Space Agency (ESA) Aeolus space mission. DAWN flies on the DC-8, and it is highly desired to fit DAWN on other NASA and National Oceanic and Atmospheric Administration (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.

References:

- NRC Decadal Surveys at: http://sites.nationalacademies.org/DEPS/ESAS2017/index.htm
- "Workshop Report on Scientific Challenges and Opportunities in the NASA Weather Focus Area," https://smd-prod.s3.amazonaws.com/science-pink/s3fs-public/atoms/files/Weather_Focus_Area_Workshop_Report_2015_0.pdf
- A. K. DuVivier, J. J. Cassano, S. Greco and G. D. Emmitt: “A Case Study of Observed and Modeled Barrier Flow in the Denmark Strait in May 2015,” *Monthly Weather Review*, 145, 2385–2404 (2017), https://doi.org/10.1175/MWR-D-16-0386.1
    - See also supplemental material at: http://dx.doi.org/10.1175/MWR-D-16-0386.s1
- M. J. Kavaya, J. Y. Beyon, G. J. Koch, M. Petros, P. J. Petzar, U. N. Singh, B. C. Trieu, and J. Yu: “The Doppler Aerosol Wind Lidar (DAWN) Airborne, Wind-Profiling, Coherent-Detection Lidar System: Overview and Preliminary Flight Results,” *J. of Atmospheric and Oceanic Technology* 34 (4), 826-842 (2014), https://doi.org/10.1175/JTECH-D-12-00274.1
- Scott A. Braun, Ramesh Kakar, Edward Zipser, Gerald Heymsfield, Cerese Albers, Shannon Brown, Stephen L. Durden, Stephen Guimond, Jeffery Halverson, Andrew Heymsfield, Syed Ismail, Bjorn Lambrigtsen, Timothy Miller, Simone

Tanelli, Janel Thomas, and Jon Zawislak: “NASA’s Genesis and Rapid Intensification Processes (GRIP) Field Experiment,” *Bull. Amer. Meteor. Soc. (BAMS)* 94(3), 345-363 (2013), https://doi.org/10.1175/BAMS-D-11-00232.1

Scope Title:

Fabrication, Test, and Control of Advanced Optical Systems

Scope Description:

Future ultraviolet (UV)/optical/near-infrared (NIR) telescopes require mirror systems that are very precise and ultrastable.

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

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

Regarding stability, to achieve high-contrast imaging for exoplanet science using a coronagraph instrument, systems must maintain wavefront stability to <10 pm rms over intervals of ~10 min during critical observations. The ~10-min time 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 nonscience light rejected by the coronagraph to estimate drifts in the system wavefront during observations. These techniques are limited by the low stellar photon rates of the dim objects being observed (~5 to 11 Vmag), leading to 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
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories
Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Hardware
- Software

Desired Deliverables Description:

- An ideal Phase I deliverable would be a prototype demonstration of a fabrication, test or control technology leading to a successful Phase II delivery, or a reviewed preliminary design and manufacturing plan that demonstrates feasibility.
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State of the Art and Critical Gaps:

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

Laser-distance interferometers for point-to-point measurements with accuracies from nanometers to picometers have been demonstrated on the ground by the Space Interferometry Mission and other projects, and 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 are not yet on space telescopes. New designs are needed to provide picometer sensitivity and millimeter range in a space-qualified package.

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

Relevance / Science Traceability:

These technologies are enabling for coronagraph-equipped space telescopes, segmented space telescopes, and others that utilize actively controlled optics. The Large UV/Optical/IR Surveyor (LUVOIR) and Habitable Exoplanet Observatory (HabEx) mission concepts currently under study provide good examples.

References:

- The HabEx interim report is available at: https://www.jpl.nasa.gov/habex/
- The LUVOIR interim report is available at: https://asd.gsfc.nasa.gov/luvoir/reports/

Scope Title:

Optical Components and Systems for Potential Infrared/Far-Infrared Missions

Scope Description:

Far-infrared 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 µm) 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.

A far-infrared surveyor is a cryogenic far-infrared (IR) 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 of ~4 K.
- Telescope diffraction-limited at 30 µm at the operating temperature.
- Mirror survivability at temperatures ranging from 315 to 4 K.
- Mirror substrate thermal conductivity at 4 K of >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 degree-of-freedom (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/m^2.
- Areal density <15 kg/m^2 (<40 kg/m^2 with backplane).
- Production rate >2 m^2 per month.
- Short time span for optical system integration and test.

Expected TRL or TRL Range at completion of the Project: 3 to 5
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories
Desired Deliverables of Phase I and Phase II:

- Research
- Prototype
- Hardware

Desired Deliverables Description:

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

State of the Art and Critical Gaps:

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

Relevance / Science Traceability:

The technology is relevant to the Far-Infrared 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-IR 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?
- How did the universe evolve in response to its changing ingredients (buildup 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-IR astrophysics mission may be applicable to far-IR optical systems employed in other divisions of the NASA Science Mission Directorate (SMD), or to optical systems designed to operate at wavelengths shorter than the far-IR.

References:

- The Far-Infrared Surveyor is described in NASA's Astrophysics Roadmap, "Enduring Quests, Daring Visions," which can be downloaded from: https://smd-prod.s3.amazonaws.com/science-pink/s3fs-public/atoms/files/secure- Astrophysics_Roadmap_2013_0.pdf
- The Origins Space Telescope (OST) final report is at: https://asd.gsfc.nasa.gov/firs/
- Program Annual Technology Reports (PATR) can be downloaded from the NASA Physics of the Cosmos and Cosmic Origins (PCOS/COR) Technology Development website at: https://apd440.gsfc.nasa.gov/technology/

Scope Title:

Low-Cost Compact Reflective Telescope for CubeSAT Missions

Scope Description:

The need exists for a low-cost, compact (e.g., CubeSAT-class), scalable, diffraction-limited, athermalized, off-axis reflective telescopes. 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. Phase II may follow up with development of prototypes, built at multiple aperture diameters and fidelities.

This Scope topic solicits solutions for two applications: near-infrared- and short-wave-infrared- (NIR/SWIR-) band communication and the Lightning Imaging Sensor.

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

The Lightning Imaging Sensor application requires a telescope that will fit inside a 6U or smaller CubeSAT with an 80° field-of-view, is diffraction limited at 500 nm (nominal), and has high spectral transmission at both 337 and 777 nm.

Expected TRL or TRL Range at completion of the Project: 2 to 4
Primary Technology Taxonomy:
Level 1: TX 08 Sensors and Instruments
Level 2: TX 08.2 Observatories
Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Analysis

Desired Deliverables Description:

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

State of the Art and Critical Gaps:

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

1. On-axis or axisymmetric designs are typically used for (space) optical communications and imaging, which inherently are problematic 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.
3. Currently flying Lightning Imaging Sensor is a large refractive lens optimized for single-wavelength operation. A reflective system is required for dual-wavelength operation. Also, a compact design is required to fit inside a CubeSAT.

Relevance / Science Traceability:

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

References:

- An example of an on-axis design has been utilized in the Lunar Laser Communications Demonstration (LLCD): https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10563/105630X/NASAs-current-activities-in-free-space-optical-communications/10.1117/12.2304175.full?SSO=1
- An example of an off-axis design is being developed by the Jet Propulsion Laboratory (JPL) for Deep Space Optical Communications (DSOC): https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10096/100960V/Discovery-deep-space-optical-communications-DSOC-transceiver/10.1117/12.2256001.full
- Information about NASA's current (large-scale) Lightning Imaging Sensor can be found at: https://gpm.nasa.gov/missions/TRMM/satellite/LIS