NASA SBIR 2022 Phase I Solicitation

S12.03 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

INTRODUCTION

Scope Description

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

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

Scopes are defined based on specific applications, technology gap needs, or operating wavelength regime. Each scope has its own defined performance metrics.

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

Expected TRL or TRL Range at completion of the Project

3 to 5

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments
Level 2

TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II

- Research
- Prototype
- Hardware

Desired Deliverables Description

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

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

State of the Art and Critical Gaps

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

Relevance / Science Traceability

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

References


Scope Title

Telescopes for Balloon Missions

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

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

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

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

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

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

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

3 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 08 Sensors and Instruments

**Level 2**

TX 08.2 Observatories

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

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

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

Relevance / Science Traceability

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

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

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

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

References

- For additional information about scientific balloons, refer to: https://www.csbf.nasa.gov/docs.html

Scope Title

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

Scope Description

Potential ultraviolet/optical (UVO) space missions require telescopes with apertures ranging from 1 to 8 m monolithic or 3 to 16 m segmented with better than 500 nm diffraction-limited performance or 40 nm rms transmitted wavefront (achieved either passively or via active control). Optical components need to have <5 nm rms surface figures. Additionally, a potential exoplanet mission, using an internal coronagraph, requires total telescope wavefront stability on order of 10 pm rms per 10 min. This stability specification places severe constraints on the dynamic mechanical and thermal performance of a 4-m or larger telescope. Potential enabling technologies include active thermal control systems, ultrastable mirror support structures, athermal telescope structures, athermal mirror struts, ultrastable joints with low coefficients of thermal expansion (CTE), and vibration compensation. Analysis indicates that the first mode for structure and optical components needs to be in the range of 60 to 500 Hz. Also, operating temperatures should range from 250 to 300 K.
Mirror areal density depends upon available launch vehicle capacities to Sun-Earth L2 (i.e., 15 kg/m^2 for a 5-m-fairing Evolved Expendable Launch Vehicle (EELV) versus 150 kg/m^2 for a 10-m-fairing Space Launch System (SLS)). Regarding areal cost, a good goal is to keep the total cost of the primary mirror at or below $100M. Thus, an 8-m-class mirror (with 50 m^2 of collecting area) should have an areal cost of less than $2M/m^2. Also, a 16-m-class mirror (with 200 m^2 of collecting area) should have an areal cost of less than $0.5M/m^2.

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

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

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

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

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

2 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 08 Sensors and Instruments

**Level 2**

TX 08.2 Observatories

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

- Research
- Analysis
- Hardware
- Software
- Prototype

**Desired Deliverables Description**

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

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

State of the Art and Critical Gaps

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

Relevance / Science Traceability

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

References

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

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

Scope Title

Two Special Topics: LISA Epoxy Study and Ultra-Stable Structures

Scope Description

Topic #1: LISA Epoxy Study

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

For many years the bonding technique of choice has been hydroxide catalysis bonding, originally developed for the Gravity Probe B mission, but used more recently for the optical bench in the LISA Pathfinder mission. This bonding technique easily supports the small 20-mm steering mirrors and optics on an optical bench, but it does not so easily support the expected launch loads of a telescope structure.
Proposals are solicited to develop high-strength, high-glass-transition-temperature, low-viscosity adhesives that can be cured near room temperature and maintain full performance with low cure shrinkage. The near-room-temperature cure is necessary to avoid damaging low-CTE ceramics such as Zerodur<sup>(R)</sup>. The adhesive should cure rapidly so that it can be used during alignment of a telescope without requiring extremely stable alignment support equipment over long durations of time. A cure process that involves an initial ultraviolet (UV) exposure to set the adhesive rapidly and then is followed by a thermal cure at only slightly elevated above room temperature might be one way to accomplish this.

Specific metrics:

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

Topic #2: Ultrastable Structures

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

Expected TRL or TRL Range at completion of the Project

2 to 3

Primary Technology Taxonomy

Level 1
TX 08 Sensors and Instruments

Level 2
TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description

For Topic #1:

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

For Topic #2:

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

State of the Art and Critical Gaps

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

Relevance / Science Traceability

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

References


Scope Title

Fabrication, Test, and Control of Optical Components and Telescopes

Scope Description

The ability to fabricate, test, and control optical components is enabling for future missions of all spectral bands (ultraviolet (UV), optical, infrared (IR), and far-IR). This scope solicits technology advances that enable the manufacture of optical components (of all diffraction limits, sizes, and operating temperatures) for a lower cost. Achieving this goal requires technologies that enable/enhance the deterministic manufacture of optical components to their desired optical prescription or technologies that enable/enhance the control of the shape of optical components "in flight."

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

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

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

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

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

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

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

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

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

2 to 4

**Primary Technology Taxonomy**

**Level 1**

TX 08 Sensors and Instruments

**Level 2**

TX 08.2 Observatories

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

- Research
- Analysis
- Hardware
- Software
- Prototype

**Desired Deliverables Description**

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

State of the Art and Critical Gaps

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

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

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

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

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

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

Relevance / Science Traceability

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

References

- HabEx: https://www.jpl.nasa.gov/habex/
- LUVOIR: https://asd.gsfc.nasa.gov/luvoir/reports/
- OST: https://asd.gsfc.nasa.gov/firs/docs/

Scope Title

Optical Components and Telescopes for Infrared/Far-Infrared Missions

Scope Description

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

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

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

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

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

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

2 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 08 Sensors and Instruments

**Level 2**

TX 08.2 Observatories

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

- Research
- Prototype
- Hardware

**Desired Deliverables Description**

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

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

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

Relevance / Science Traceability

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

References

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

Scope Title

Telescopes for CubeSAT Missions

Scope Description

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

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

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

Expected TRL or TRL Range at completion of the Project

2 to 4

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2
Desired Deliverables of Phase I and Phase II

- Prototype
- Hardware
- Analysis

**Desired Deliverables Description**

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

**State of the Art and Critical Gaps**

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

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

**Relevance / Science Traceability**

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

**References**

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