SBIR/STTR

Small Business Innovation Research / Small Business Technology Transfer

NASA SBIR 2020 Phase I Solicitation

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

Lead Center: MSFC

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

Technology Area: TA8 Science Instruments, Observatories & Sensor Systems

Scope Title

Optical Components and Systems for Large Telescope Missions

Scope Description

To accomplish NASA's high-priority science at all levels (flagship, probe, Medium-Class Explorers (MIDEX), Small Explorers (SMEX), rocket and balloon) requires low-cost, ultra-stable, normal incidence mirror systems with low mass-to-collecting area ratios. Where a mirror system is defined as the mirror substrate, supporting structure, and associated actuation and thermal management systems. After performance, the most important metric for an advanced optical system is affordability or areal cost (cost per square meter of collecting aperture). Current normal incidence space mirrors cost \$4 million to \$6 million per square meter of optical surface area. This research effort seeks to improve the performance of advanced precision optical components while reducing their cost by 5 to 50 times, to between \$100K/m2 to \$1M/m2.

Specific metrics are defined for each wavelength application region:

Aperture Diameter for all wavelengths, except Far-IR

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

For UV/Optical

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

For Far-IR

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

For EUV

- Surface Slope < 0.1 micro-radian

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

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

References

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

The Origins Space Telescope (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 are described on the website: https://asd.gsfc.nasa.gov/cosmology/spirit/.

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

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

Desired Deliverables of Phase II

Prototype, Hardware, Research

Desired Deliverables Description

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

An ideal Phase 2 project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 meters or relevant sub-component (with a TRL in the 4 to 5 range); or a working fabrication, test or control system. Phase 1 and Phase 2 mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission oriented Phase 2 would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly which can be integrated into the potential mission; and, demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analysis).

State of the Art and Critical Gaps

Current normal incidence space mirrors cost $4 million to $6 million per square meter of optical surface area. This research effort seeks a cost reduction for precision optical components by 5 to 50 times, to between $100K/m2 to $1M/m2.

Relevance / Science Traceability

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

Scope Title
Balloon Planetary Telescope

Scope Description

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

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

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

Phase I will produce a preliminary design and report including initial design requirements such as wave-front error budget, mass allocation budget, structural stiffness requirements, etc., trade studies performed and analysis that compares the design to the expected performance over the specified operating range. Development challenges shall be identified during phase I including trade studies and challenges to be addressed during Phase II with subsystem proof of concept demonstration hardware. If Phase II can only produce a sub-scale component, then it should also produce a detailed final design, including final requirements (wave-front error budget, mass allocation, etc) and performance assessment over the specified operating range.

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

Telescope Specifications:

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

Primary Mirror Assembly Specifications:

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

References

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

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

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

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

State of the Art and Critical Gaps

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

Relevance / Science Traceability

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

- Page 22, Last Paragraph of NASA Telescope Facilities within the Summary Section:
  Balloon- and rocket-borne telescopes offer a cost-effective means of studying planetary bodies at wavelengths inaccessible from the ground.6 Because of their modest costs and development times, they also provide training opportunities for would-be developers of future spacecraft instruments. Although NASA’s Science Mission Directorate regularly flies balloon missions into the stratosphere, there are few funding opportunities to take advantage of this resource for planetary science, because typical planetary grants are too small to support these missions. A funding line to promote further use of these suborbital

observing platforms for planetary observations would complement and reduce the load on the already oversubscribed planetary astronomy program.

- Page 203, 5th paragraph, Section titled Earth and Space-Based Telescopes:
  Significant planetary work can be done from balloon-based missions flying higher than 45,000 ft. This altitude provides access to electromagnetic radiation that would otherwise be absorbed by Earth's atmosphere and permits high-spatial-resolution imaging unaffected by atmospheric turbulence. These facilities offer a combination of cost, flexibility, risk tolerance, and support for innovative solutions that is ideal for the pursuit of certain scientific opportunities, the development of new instrumentation, and infrastructure support. Given the rarity of giant-planet missions, these types of observing platforms (high-altitude telescopes on balloons and sounding rockets) can be used to fill an important data gap.154, 155,156.

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

Potential Projects Gondola for High Altitude Planetary Science (GHAPS).

Scope Title

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

Scope Description

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

Mirror areal density depends upon available launch vehicle capacities to Sun-Earth L2 (i.e. 15 kg/m2 for a 5 m fairing EELV vs. 150 kg/m2 for a 10 m fairing SLS). Regarding areal cost, a good goal is to keep the total cost of the primary mirror at or below $100M. Thus, an 8-m class mirror (with 50 m2 of collecting area) should have an areal cost of less than $2M/m2. And, a 16-m class mirror (with 200 m2 of collecting area) should have an areal cost of less than $0.5M/m2.

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

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

Also needed is ability to fully characterize surface errors and predict optical performance via integrated opto-mechanical modeling.

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

References

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

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

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

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

Desired Deliverables of Phase II

Analysis, Hardware, Software, Research

Desired Deliverables Description

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

An ideal Phase 2 project would further advance the technology to produce a flight-qualifiable optical system greater than 0.5 meters or relevant sub-component (with a TRL in the 4 to 5 range); or a working fabrication, test or control system. Phase 1 and Phase 2 mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission oriented Phase 2 would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly which can be integrated into the potential mission; and, demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analysis).

State of the Art and Critical Gaps

Hubble at 2.4m is the SOA.

Relevance / Science Traceability

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

Scope Title
NIR LIDAR Beam Expander Telescope

Scope Description

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

References

NRC Decadal Surveys at: http://sites.nationalacademies.org/DEPS/ESAS2017/index.htm.

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, 2017, "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: 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

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

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

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

State of the Art and Critical Gaps

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

Relevance / Science Traceability

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

Scope Title
Fabrication, Test and Control of Advanced Optical Systems

Scope Description

Future UV/Optical/NIR telescopes require mirror systems that are very precise and ultra-stable.

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

One area of current emphasis is the ability to non-destructively characterize CTE homogeneity in 4-m class Zerodur and 2-m class ULE mirror substrates to an uncertainty of 1 ppb/K and a spatial sampling of 100 x 100. This characterization capability is needed to select mirror substrates before they undergo the expense of turning them into a light-weight space mirror.

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

Current methods of wavefront sensing include image-based techniques such as phase retrieval, focal-plane contrast techniques such as electric field conjugation and speckle nulling, and low-order and out-of-band wavefront sensing that use non-science light rejected by the coronagraph to estimate drifts in the system wavefront during observations. These techniques are limited by the low stellar photon rates of the dim objects being observed (~5 - 11 Vmag), leading to 10s of minutes between wavefront control updates.

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

Current methods of metrology include edge sensors (capacitive, inductive, or optical) for maintaining segment cophasing, and laser distance interferometers for absolute measurement of system rigid body alignment. Development of these techniques to improve sensitivity, speed, and component reliability is desired. Low power, high-reliability electronics are also needed.

Finally, metrology techniques for system verification and validation at the picometer level during integration and test (I&T) are needed. High speed spatial and speckle interferometers are currently capable of measuring single-digit picometer displacements and deformations on small components in controlled environments. Extension of these techniques to large-scale optics and structures in typical I&T environments is needed.

References

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

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

Desired Deliverables of Phase II

Analysis, Hardware, Software, Research

Desired Deliverables Description

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

An ideal Phase 2 project would further advance the technology to produce a flight-qualifiable relevant sub-component (with a TRL in the 4 to 5 range); or a working fabrication, test or control system. Phase 1 and Phase 2 mirror system or component deliverables would be accompanied by all necessary documentation, including the optical performance assessment and all data on processing and properties of its substrate materials. A successful mission oriented Phase 2 would have a credible plan to deliver for the allocated budget a fully assembled and tested telescope assembly which can be integrated into the potential mission; and, demonstrate an understanding of how the engineering specifications of their system meets the performance requirements and operational constraints of the mission (including mechanical and thermal stability analysis).

State of the Art and Critical Gaps

Wavefront sensing using star images, including dispersed-fringe and phase retrieval methods, is at TRL 6, qualified for space by JWST. Wavefront sensing and control for coronagraphs, including electric field conjugation and Low-Order WF Sensing (LOWFS) is at TRL4, and is being developed and demonstrated by WFIRST/CGI.

Laser distance interferometers for point-to-point measurements with accuracies from nanometers to picometers have been demonstrated on the ground by the Space Interferometry Mission and other projects, and on orbit by the Lisa Pathfinder and Grace Follow-On mission. Application to telescope alignment metrology has been demonstrated on testbeds, to TRL4 for nanometer accuracy. Picometer accuracy for telescopes awaits demonstration.

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

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

Relevance / Science Traceability

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

Scope Title

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

Scope Description

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

In the context of subtopic S2.03, the challenge is to take advantage of relaxed tolerances stemming from a requirement for long wavelength (30 micron) diffraction-limited performance in the fully-integrated optical telescope assembly to minimize the total mission cost through innovative design and material choices and novel approaches to fabrication, integration, and performance verification.

The Far-IR Surveyor is a cryogenic far-infrared mission, which could be either a large single-aperture telescope or an interferometer. There are many common and a few divergent optical system requirements between the two architectures.

Common requirements:

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

Divergent requirements:

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

Success metrics:

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

References

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.

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

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

Desired Deliverables of Phase II

Prototype, Hardware, Research

Desired Deliverables Description

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

State of the Art and Critical Gaps

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

Relevance / Science Traceability

The technology is relevant to the Far-IR Surveyor mission described in NASA's Astrophysics Roadmap and prioritized in NASA's Program Annual Technology Reports for Cosmic Origins and Physics of the Cosmos. A future NASA far-infrared astrophysics mission will answer compelling questions, such as: How common are life-bearing planets?; How do the conditions for habitability develop during the process of planet formation?; and How did the universe evolve in response to its changing ingredients (build-up of heavy elements and dust over time)? To answer these questions, NASA will need telescopes and interferometers that reach fundamental sensitivity limits imposed by astrophysical background photon noise. Only telescopes cooled to a cryogenic temperature can provide such sensitivity.

Novel approaches to fabrication and test developed for a far-infrared astrophysics mission may be applicable to far-infrared optical systems employed in other divisions of the NASA Science Mission Directorate, or to optical systems designed to operate at wavelengths shorter than the far-infrared.

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

Scope Description

The need exists for a low cost methodology to produce compact (for ex., cubesat-class), scalable, diffraction limited, athermalized, off-axis reflective-type, optics for NIR/SWIR-band communication applications. Typically, specialty optical aperture systems are designed and built as “one-offs” which are inherently high in cost and often out of scope for smaller projects. A Phase I would investigate current compact off-axis reflective designs and develop a trade space to identify the most effective path forward. The work would include a strategy for aperture diameter scalability, athermalization, and low cost fabrication. Detailed optical designs would be developed along with detailed structural, thermal, optical performances (STOP) analyses confirming diffraction limited operation across a wide range of operational disturbances, both structural dynamic and thermal. Commercial of the shelf (COTS) NIR/SWIR optical communication support hardware should be assumed towards an integrated approach, including fiber optics, fast steering mirrors, and applicable detectors. Phase II may follow up with development of prototypes, built at multiple aperture diameters and fidelities.

References

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

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

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

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

Prototype unobscured telescope with the required scale size

State of the Art and Critical Gaps

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

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

2) Off-axis designs provide superior optical performance due to the clear aperture, however, are rarely considered due to complex design, manufacturing, and metrology procedures needed.

Relevance / Science Traceability

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