# NASA SBIR 2019 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**

### Optical Components and Systems for Large Telescope Missions

To accomplish NASA’s high-priority science requires low-cost, ultra-stable, large-aperture, 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 $100K/m$^2$ to $1M/m$^2$.

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 < $500K/m$^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 Path-length Stability < 1 pm/10,000 seconds for precision metrology
- Areal density < 15 kg/m$^2$ (< 35 kg/m$^2$ 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 < $500K/m$^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 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 Small Explorers (SMEX) or Medium-Class Explorers (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.

An ideal Phase I 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 II delivery; or a reviewed preliminary design and manufacturing plan which 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 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 II 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 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 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).

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).

Phase I deliverable should be a precision optical system of at least 0.25 meters; a relevant sub-component; or a prototype demonstration of a fabrication, test or control technology; or a reviewed preliminary design and manufacturing plan which demonstrates feasibility. The preliminary design should address how optical, mechanical (static/dynamic) and thermal designs and performance analysis will be done. Past experience which supports the design and manufacturing plans will be given appropriate weight. Phase II 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. Deliverables should be accompanied by all necessary documentation, including optical performance assessment and all data on processing and properties of its substrate materials. Phase II should 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.

Expected TRL for this project is 3 to 5.

**Balloon Planetary Telescope**

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. (NASA/TM-2016-

218870, available from https://ntrs.nasa.gov/)

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° 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°
- 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°
- Temperature 220 to 280 K

The relevance to NASA can be found in “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.

And 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 Goddard Space Flight Center (GSFC), APL, and Southwest Research Institute, etc., the NASA Balloon Workshop

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

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.

Expected TRL for this project is 3 to 5.

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

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. To meet this requirement requires active thermal control systems, ultra-stable mirror support structures, and vibration compensation.

Mirror areal density depends upon available launch vehicle capacities to Sun-Earth $L_2$ (i.e., 15 kg/$m^2$ for a 5 m fairing EELV vs. 150 kg/$m^2$ for a 10 m fairing SLS). Regarding areal cost, a good goal is to keep the total cost of the primary mirror at or below $100M. Thus, an 8-m class mirror (with 50 $m^2$ 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 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, nano-particle 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.

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, HabEx, LUVOIR and OST.

Phase I deliverable should be a precision optical system of at least 0.25 meters; a relevant sub-component; or a prototype demonstration of a fabrication, test or control technology; or a reviewed preliminary design and manufacturing plan which demonstrates feasibility. The preliminary design should address how optical, mechanical (static/dynamic) and thermal designs and performance analysis will be done. Past experience which supports the design and manufacturing plans will be given appropriate weight. Phase II 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. Deliverables should be accompanied by all necessary documentation, including optical performance assessment and all data on processing and properties of its substrate materials. Phase II should 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.

Expected TRL for this project is 2 to 4.

### NIR LIDAR Beam Expander Telescope

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.

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, Doppler Aerosol WiNd lidar (DAWN), was included in three proposals which are under review. Furthermore, SMD is baselining DAWN for a second Convective Processes Experiment (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.

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

Expected TRL for this project is 3 to 4.

### Fabrication, Test and Control of Advanced Optical Systems

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 in the ability to fabricate and test an optical system.

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 co-phasing, 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.

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.

Phase I deliverable should be a prototype demonstration of a fabrication, test or control technology; or a reviewed preliminary design and manufacturing plan which demonstrates feasibility. 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. Phase II 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. Deliverables should be accompanied by all necessary documentation, including optical performance assessment and all data on processing and properties of its substrate materials. Phase II should 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.

Expected TRL for this project is 2 to 4.

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

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 < $\$500K/m^2$
- 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

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 SMD, or to optical systems designed to operate at wavelengths shorter than the far-infrared.

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.

Expected TRL for this project is 3 to 5.

**Ultra-Stable Telescopes and Telescope Structures**

Multiple potential balloon and space missions to perform Astrophysics, Exoplanet and Planetary science investigations require a complete optical telescope system with 0.5 meter or larger of collecting aperture. 1-m class balloon-borne telescopes have flown successfully, however, the cost for design and construction of such telescopes can exceed $6M, and the weight of these telescopes limits the scientific payload and duration of the balloon mission. A 4X reduction in cost and mass would enable missions which today are not feasible. Space-based gravitational wave observatories (LISA) need a 0.5-meter class ultra-stable telescope with an optical path length stability of a picometer over periods of roughly one hour at temperatures near 300K in the presence of large applied static thermal gradients, but a stable thermal environment with expected thermal fluctuations of only ~ 10 microK/?Hz. The telescope will be operated in simultaneous transmit and receive mode, so an unobstructed design is required to achieve extremely low coherent backscatter light performance.

LISA Mission: Space-based gravitational wave observatories require precision displacement measurements between widely spaced proof masses. Displacements of ~ 10 pm over 1,000 seconds between masses spaced at 2.5 million km are required. Telescope systems must contribute at most ~ 1/10th of this displacement budget, or ~ 1 pm over 1,000 seconds.

Prototype unobscured telescope with the required scale size (0.3 m primary, ~ 700 mm length) that can demonstrate the required dimensional stability at room temperature. Very low coherent backscatter.

Expected TRL for this project is 3 to 5.

**References:**

**????Optical Components and Systems for Large Telescope Missions**

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

**Balloon Planetary Telescope**

- 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. (NASA/TM-2016-218870, available from https://ntrs.nasa.gov/)

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

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

### NIR LIDAR Beam Expander Telescope

- 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). See also Supplemental Material
- 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, Flight Results, and Plans,” J. of Atmospheric and Oceanic Technology 34 (4), 826-842 (2014)
- 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)

### Fabrication, Test and Control of Advanced Optical Systems

- 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_Final.pdf.

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

- 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/

### Ultra-Stable Telescopes and Telescope Structures

- LISA mission description: https://lisa.nasa.gov/
- Sanjuan, et al. Note: Silicon carbide telescope dimensional stability for space-based gravitational wave detectors, Rev.Sci. Instrum. 83, 116107 (2012) URL: http://link.aip.org/link/?RSI/83/116107
- DOI: 10.1063/1.4767247