The NASA Science Missions Directorate seeks technology for cost-effective high-performance advanced space telescopes for astrophysics and Earth science. Astrophysics applications require large aperture light-weight highly reflecting mirrors, deployable large structures and innovative metrology, control of unwanted radiation for high-contrast optics, precision formation flying for synthetic aperture telescopes, and cryogenic optics to enable far infrared telescopes. A few of the new astrophysics telescopes and their subsystems will require operation at cryogenic temperatures as cold as 4-degrees Kelvin. This topic will consider technologies necessary to enable future telescopes and observatories collecting electromagnetic bands, ranging from UV to millimeter waves, and also include gravity waves. The subtopics will consider all technologies associated with the collection and combination of observables. Earth science requires modest apertures in the 2 to 4 meter size category that are cost effective. New technologies in innovative mirror materials, such as silicon, silicon carbide and nanolaminates, innovative structures, including nano-technology, and wavefront sensing and control are needed to build telescope for Earth science that have the potential to cost between $50 to $150M.

Subtopics

S3.01 Precision Spacecraft Formations for Advanced Telescope Systems

Lead Center: JPL
Participating Center(s): GSFC

This subtopic seeks hardware and software technologies necessary to establish, maintain, and operate hyper-precision spacecraft formations to a level that enables cost effective large aperture and separated spacecraft optical telescopes and interferometers. Also sought are technologies (analysis, algorithms, testbeds) to enable detailed analysis, synthesis, modeling, and visualization of such constellations.

In a formation for large effective telescope apertures, multiple, collaborative spacecraft in a precision formation collectively form a variable-baseline interferometer. Large effective apertures can also be achieved by tiling curved segments to form an aperture larger than can be achieved in a single launch, for deep-space high resolution imaging of faint astrophysical sources. These formations require the capability for autonomous precision alignment and synchronized maneuvers, reconfigurations, and collision avoidance. It is important that, in order to enable precision spacecraft formation keeping from coarse requirements (relative position control of any two spacecraft to less than 1 cm, and relative bearing of 1 arcmin over target range of separations from a few meters to tens of kilometers) to fine requirements (micron relative position control and relative bearing control of 0.1 arcsec), the...
interferometer payload would still need to provide at least 1 - 3 orders of magnitude improvement on top of the S/C control requirements. The spacecraft also require onboard capability for optimal path planning and time optimal maneuver design and execution.

Development of combined nanometer-level precision formation flying control of numerous spacecraft and their optics is required to enable large baseline (1 to 10's of km), sparse aperture UV/optical (and perhaps X-ray) telescopes and interferometers needed for ultra-high angular resolution imagery.

Proposals addressing staged-control experiments that combine coarse formation control with fine-level wavefront sensing based control are particularly encouraged. Innovations that address the above precision requirements are solicited for formation systems in the following areas:

- Integrated optical/formation/control simulation tools;
- Distributed, multi-timing, high fidelity simulations;
- Formation modeling techniques;
- Precision guidance and control architectures and design methodologies;
- Centralized and decentralized formation estimation;
- Distributed sensor fusion;
- RF and optical precision metrology systems;
- Formation sensors;
- Precision microthrusters/actuators;
- Autonomous reconfigurable formation techniques;
- Optimal, synchronized, maneuver design methodologies;
- Collision avoidance mechanisms;
- Formation management and station keeping; and
- Six degrees of freedom precision formation test beds.

S3.02 Proximity Glare Suppression for Characterization of Faint Astrophysical Objects
Lead Center: JPL
This subtopic addresses the unique problem of imaging and spectroscopic characterization of faint astrophysical objects that are located within the obscuring glare of much brighter stellar sources and innovative advanced wavefront sensing and control for cost-effective space telescopes. Examples include: planetary systems beyond our own, the detailed inner structure of galaxies with very bright nuclei, binary star formation, and stellar evolution. Contrast ratios of one million to ten billion over an angular spatial scale of 0.05-1.5 arcsec are typical of these objects. Achieving a very low background requires control of both scattered and diffracted light. The failure to control either amplitude or phase fluctuations in the optical train severely reduces the effectiveness of starlight cancellation schemes.

This innovative research focuses on advances in coronagraphic instruments, starlight cancellation instruments, and potential occulting technologies that operate at visible and infrared wavelengths. The ultimate application of these instruments is to operate in space as part of a future observatory mission. Much of the scientific instrumentation used in future NASA observatories for the astrophysical sciences will require control of unwanted radiation (thermal and scattered) across a modest field of view. The performance and observing efficiency of astrophysics instruments, however, must be greatly enhanced. The instrument components are expected to offer much higher optical throughput, larger fields of view, and better detector performance. The wavelengths of primary interest extend from the visible to the thermal infrared. Measurement techniques include imaging, photometry, spectroscopy, and polarimetry. There is interest in component development, and innovative instrument design, as well as in the fabrication of subsystem devices to include, but are not limited to, the following areas:

**Starlight Suppression Technologies**

- Advanced starlight canceling coronagraphic instrument concepts;
- Advanced aperture apodization and aperture shaping techniques;
- Pupil plane masks for interferometry;
- Advanced apodization mask or occulting spot fabrication technology controlling smooth density gradients to $10^{-4}$ with spatial resolutions $\sim 1$ µm;
- Metrology for detailed evaluation of compact, deep density apodizing masks, Lyot stops, and other types of graded and binary mask elements. Development of a system to measure spatial optical density, phase inhomogeneity, scattering, spectral dispersion, thermal variations, and to otherwise estimate the accuracy of masks and stops is needed;
- Interferometric starlight cancellation instruments and techniques to include aperture synthesis and single input beam combination strategies;
- Fiber optic spatial filter development for visible coronagraph wavelengths;
- Single mode fiber filtering from visible to 20 µm wavelength;
- Methods of polarization control and polarization apodization; and
- Components and methods to insure amplitude uniformity in both coronagraphs and interferometers, specifically materials, processes, and metrology to insure coating uniformity.

**Wavefront Control Technologies**
• Development of small stroke, high precision, deformable mirrors (DM) and associated driving electronics scalable to 104 or more actuators (both to further the state-of-the-art towards flight-like hardware and to explore novel concepts). Multiple DM technologies in various phases of development and processes are encouraged to ultimately improve the state-of-the-art in deformable mirror technology. Process improvements are needed to improve repeatability, yield, and performance precision of current devices;

• Adaptive optics actuators, integrated mirror/actuator programmable deformable mirror;

• Reliability and qualification of actuators and structures in deformable mirrors to eliminate or mitigate single actuator failures;

• Multiplexer development for electrical connection to deformable mirrors that has ultra-low power dissipation. The most promising DM technology may be sensitive to temperature, so developing a MUX that has very low thermal hot spots, and very uniform temperature performance will improve the control of the mirror surface;

• High precision wavefront error sensing and control techniques to improve and advance coronagraphic imaging performance; and

• Highly reflecting broadband coatings.

S3.03 Precision Deployable Structures and Metrology for Advanced Telescope Systems

Lead Center: JPL

Planned future NASA Missions in astrophysics, (such as the Single Aperture Far-IR (SAFIR) telescope, Life Finder, and Submillimeter Probe of the Evolution of Cosmic Structure (SPECS), and the UV Optical Imager (UVOIR) require 10 - 30 m class cost effective telescopes that are diffraction limited at wavelengths from the visible to the far IR, and operate at temperatures from 4 - 300 K. The desired areal density is 1 - 10 kg/m$^2$. Static and dynamic wavefront error tolerances may be achieved through passive means (e.g., via a high stiffness system) or through active control. Potential architecture implementations must package into an existing launch volume, deploy and be self-aligning to the micron level. The target space environment is expected to be L2.

This topic solicits proposals to develop enabling, cost effective component and subsystem technology for these telescopes. Research areas of particular interest include: precision deployable structures and metrology, i.e., innovative active or passive deployable primary or secondary support structures; innovative concepts for packaging fully integrated (i.e., including power distribution, sensing, and control components), distributed and localized actuation systems; deployment packaging and mechanisms; active control distributed on or within the structure (downstream corrective and adaptive optics are not included in this topic area); actuator systems for alignment of reflector panels (order of cm stroke actuators, lightweight, submicron dynamic range, nanometer stability); mechanical, inflatable, or other deployable technologies; new thermally-stable materials (CTE

Also of interest are innovative metrology systems for direct measurement of the optical elements or their supporting structure. Requirements for micron level absolute and subnanometer relative metrology for tens of points on the primary mirror. Also measurement of the metering truss. Innovative systems which minimize complexity, mass, power and cost are sought.
The goal for this effort is to mature technologies that can be used to fabricate 20 m class, lightweight, ambient or cryogenic flight-qualified telescope primary mirror systems. Proposals to fabricate demonstration components and subsystems with direct scalability to flight systems (concept described in the proposal) will be given preference. The target launch volume and expected disturbances, along with the estimate of system performance, should be included in the discussion. A successful proposal shows a path toward a Phase 2 delivery of demonstration hardware on the scale of 3 m for characterization.

S3.04 Optical Devices for Starlight Detection and Wavefront Analysis

Lead Center: MSFC

Participating Center(s): GSFC, JPL

This subtopic addresses the unique problems associated with collecting and pre-detection processing of star light for advanced optical telescopes and telescope arrays. This topic includes innovative optical subsystems, devices and components that directly collect and process optical signals and images for all regions of the electromagnetic spectrum from X-ray to UV to Visible to Far-IR/Sub-MM. Pre-detection technologies of interest include capabilities to preprocess or analyze an optical wave front or signal to extract time-dependent, spectral, polarization and spatial information from scenes or signals prior to detection. These devices can be placed anywhere within an optical system, between the entrance aperture and the focal plane. A specific technology area of interest is high reflectance UV coatings and uniform polarization coatings for all wavelengths. Collection technologies of interest include capabilities which enable large-baseline segmented-aperture telescopes and sparse aperture telescopes and interferometers that will be needed to obtain high angular resolution observations to support future science goals. This subtopic addresses problems associated with formation flying including development of high-precision, high-stability laser and phase sensors, as well as of techniques to enable the monitoring of the separations of the individual spacecraft and overall orientation of the constellation. Specifically of interest is component-level technology needed to enable the characterization and combination of wavefronts from multiple apertures. Innovative technology to fabricate and test large aperture optical substrates continues to be an interest of this subtopic. Additionally, this interest is specifically extended to include technology to fabricate and test large aperture very lightweight x-ray mirrors. The primary objective of this subtopic is to reduce the mass and volume of advanced telescopes and observatories - either the primary mirror or the relay and science instrument optics. The proposed effort must address the technical need of a recognized future NASA space science mission, science measurement objective or science sensor for a Discovery, Explorer, Beyond Einstein, Origins, GOESS, New Millennium, Landmark-Discovery, or Vision mission.

Proposals in the following areas are specifically solicited:

- Design and construction of UV, optical, infrared or far-infrared beam combiners suitable for wavelength-resolved fringe measurements from a large number of independent apertures with flat response over a broad wavelength range;

- Development of a metrology system suitable for monitoring path lengths in the meter to kilometer range with incremental resolutions of picometers and milliseconds, and sub-micron absolute distance resolution;

- Development and test of low cost laser metrology gauges and optical pathlength control devices for alignment and control in multi-stage, multi-vehicle formations;
• Single frequency, long lifetime (>10 years), visible, IR stable semiconductor lasers in the power range 1 to 10 watt for metrology of optical systems, wavefront sensing and control and interferometry;

• High throughput, radiation hard, large area, X-ray imaging devices such as Fresnel Zone plates and masks;

• Wavelength division demultiplexers, integrated optics waveguide, fiber optic and light pipe devices for spectral analysis of scene information from UV to IR;

• Innovative mirror substrate material/fabrication/test technologies and mounting/support technologies for large aperture lightweight low-cost x-ray, ambient and cryogenic applications in space telescopes;

• Optical coatings: broad-band polarization preserving and polarizing for UV to Far-IR/Sub-MM; high-reflectivity EUV; large area, high acceptance angle narrow-band optical filters; broad-band wide-acceptance angle UV anti-reflection on PMMA substrates; environmentally stable protected silver.

• Components or devices for spectroscopy and imaging applications using hyperspectral, polarometric, Stokes photo-polarimeters, etc. technology for visible to infrared.