The questions "How did we get here?" and "Are we alone?" have driven mankind to explore and expand our understanding of the universe and our role in it since before recorded history. Today, we move our attention to the cosmos. Understanding of how galaxies, stars, and planetary systems formed in the early universe will provide a basis for future exploration. Are planetary systems and Earth-like planets typical? Is life beyond the Earth rare or non-existent? If life in the universe is robust, has it spread throughout the galaxy? Current missions using innovative technology research are Space Interferometer Mission (SIM) and Terrestrial Planet Finder (TPF). New missions in the planning phase, which requires innovative technology, are Space Astronomy Far Infrared Telescope (SAFIR), Life Finder and Planet Imager. The Origins technology program develops the means to achieve the most ambitious and technically challenging measurements ever made. New large space telescopes and instruments are required to detect the extremely faint signatures from the deep universe. Innovations are needed in these areas: Precision constellations for interferometry, advanced astronomical instrumentation, deployable precision structures, high-contrast astrophysical imaging, large aperture lightweight telescope mirrors, and wavefront sensing and control. These technologies will enable NASA to explore the early universe, find planets around other stars, and search for life beyond Earth.

Subtopics

S3.01 Precision Constellations for Interferometry

Lead Center: JPL

This subtopic seeks hardware and software technologies necessary to establish, maintain and operate hyper-precision spacecraft constellations to a level that enables separated spacecraft optical interferometry. Also sought are technologies for analysis, modeling, and visualization of such constellations.

In a constellation for large effective telescope apertures, multiple, collaborative spacecraft in a precision formation collectively form a variable-baseline interferometer. 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\&\#150;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.

Innovations that address the above precision requirements are solicited for distributed constellation systems in the following areas:

- Integrated optical/formation/control simulation tools;
- Distributed, multitiming, 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 testbeds.

S3.02 High Contrast Astrophysical Imaging

Lead Center: JPL

Participating Center(s): ARC

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. Examples include planetary systems beyond our own and the detailed inner structure of galaxies with very bright nuclei. Contrast ratios of one million to one billion over an angular spatial scale of 0.05\&\#150;1.5 arcsec are typical of these objects. Achieving a very low background against which to detect a planet, 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 any starlight cancellation scheme.

This innovative research focuses on advances in coronagraphic instruments, interferometric 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 Origins Program theme will be similar in character to instruments used for present day space astrophysical observations. The performance and observing efficiency of these 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, coronography, 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 $\sim 1 \text{ \AA} \mu \text{m}$.
- 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 $\text{\AA} \mu \text{m}$ wavelength.
- Methods of polarization control and polarization apodization.
- 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.
• 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.

S3.03 Precision Deployable Lightweight Cryogenic Structures for Large Space Telescopes

Lead Center: JPL

Planned future NASA Origins Missions and Vision Missions such as the Single Aperture Far-IR (SAFIR) telescope, Life Finder, and Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) require 10–30 m class telescopes that are diffraction limited at wavelengths between the visible and the near IR, and operate at temperatures from 4–300 K. The desired areal density is 3–10 kg/m². Wavefront control may be either passive (via a high stiffness system) or active control. Potential architecture implementations must package into an existing launch volume, deploy and be self-aligning to the micron level. The environment is expected to be L2.

This topic solicits proposals to develop enabling component and subsystem technology for these telescopes in the areas of precision deployable structures, i.e., large deployable optics manufacture and test; innovative concepts for packaging integrated actuation systems; metrology systems for direct measurement of the structure; deployment packaging and mechanisms; active control implemented on the structure (downstream corrective and adaptive optics are not included in this topic area); actuator systems for alignment (2 cm stroke actuators, lightweight, submicron dynamic range, nanometer stability); mechanical and inflatable deployable technologies; new thermally-stable materials for deployables; new approaches for achieving packagable structural depth; etc.

The goal for this effort is to mature technologies that can be used to fabricate 20 m class lightweight 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 volume and disturbances, along with the estimate of system performance should be included in the discussion. A successful proposal shows a path toward a Phase II delivery of demonstration hardware on the scale of 3 m for characterization.

S3.04 Large-Aperture Lightweight Cryogenic Telescope Components & Systems

Lead Center: MSFC
Planned future NASA infrared, far infrared and submillimeter missions such as the Single Aperture Far-IR (SAFIR) telescope, Space Infrared Interferometric Telescope (SPIRIT) and Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) require both 10\,m and 2\,m class telescopes that are diffraction limited at 5\,mm and operate at temperatures from 4\,K. The desired areal density is 3\,kg/m². Wavefront control may be either passive (via a high stiffness system) or active control. Potential architecture implementations include 2\,m class segments, 4\,m class mirrors, or membrane systems. It is anticipated that active cooling will be required. Potential telescope system architectures require transporting 1\,W of heat at 15\,K with 5\,W/K, while others require 100\,mW at 4\,K with 1\,W/K. This topic solicits proposals to develop enabling component and sub-system technology for cryogenic telescopes, including but not limited to: large-aperture lightweight cryogenic optic manufacture and test; thermal management, distributed cryogenic cooling, multiple heat lift; structure, deployment, and mechanisms; deployable cryogenic coolant lines; active wavefront control; etc. The goal for this effort is to mature technologies that can be used to fabricate 2\,m and 10\,m class lightweight cryogenic flight-qualified telescope primary mirror systems at a cost of less than $300,000 per square meter. Proposals to fabricate demonstration components and subsystems with direct scalability to flight will be given preference.