Scope Title
Control of Scattered Starlight with Coronagraphs

Scope Description
This scope 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, 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 to 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 that operate at visible and near-infrared wavelengths. The ultimate application of these instruments is to operate in space as part of a future observatory mission concept such as the Habitable Exoplanet Observatory (HabEx) and Large Ultraviolet Optical Infrared Surveyor (LUVOIR). 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 that include, but are not limited to, the following areas:

Starlight diffraction control and characterization technologies:

- Diffraction control masks for coronagraphs and scaled starshade experiments, which includes transmissive scalar, polarization-dependent, spatial apodizing, and hybrid metal/dielectric masks, including those with extremely low reflectivity regions that allow them to be used in reflection.
- Systems to measure spatial optical density, phase inhomogeneity, scattering, spectral dispersion, thermal variations, and to otherwise estimate the accuracy of high-dynamic range apodizing masks.
- Methods to distinguish the coherent and incoherent scatter in a broadband speckle field.

Wavefront control technologies:

- Small-stroke, high-precision, deformable mirrors scalable to 10,000 or more actuators (both to further the state of the art towards flight-like hardware and to explore novel concepts). Multiple deformable mirror 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, power consumption, connectivity, stability, and performance precision of current devices.

- High-precision, stable, deformable mirrors whose nominal surface can carry optical prescriptions for dual use as imaging optics such as off-axis parabolas and apodizing elements. Like other technologies, scalable actuator arrays between hundreds and thousands of actuators are encouraged.
- Driving electronics, including multiplexers and application-specific integrated circuits (ASICs) with ultra-low power dissipation for electrical connection to deformable mirrors.

Optical coating and measurement technologies:

- Instruments capable of measuring polarization crosstalk and birefringence to parts per million.
- Polarization-insensitive coatings for large optics.
- Methods to measure the spectral reflectivity and polarization uniformity across large optics.

Expected TRL or TRL Range at completion of the Project

3 to 5

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description

Under this scope, a concept study provided as a final report in Phase I is acceptable, and a prototype for Phase II is acceptable.

State of the Art and Critical Gaps

Coronagraphs have been demonstrated to achieve high contrast in moderate bandwidth in laboratory environments. The extent to which the telescope optics will limit coronagraph performance is a function of the quality of the optical coating and the ability to control polarization over the full wavefront. Wavefront control using deformable mirrors is critical. Controllability and stability to picometer levels is required. To date, deformable mirrors have been up to the task of providing contrast approaching $10^{10}$, but they require thousands of wires, and overall wavefront quality and stroke remain concerns.

Relevance / Science Traceability

These technologies are directly applicable to mission concept studies such as HabEx, LUVOIR, starshades, and any space telescopes that could potentially be used for exoplanet imaging and characterization.

References
See SPIE conference papers and articles published in the Journal of Astronomical Telescopes and Instrumentation on high contrast coronagraphy, segmented coronagraph design and analysis, and starshades.

- Exoplanet Exploration - Planets Beyond Our Solar System: https://exoplanets.jpl.nasa.gov
- Exoplanet Exploration Program: https://exoplanets.nasa.gov/exep/
  - Specifically, the technology pages and those addressing coronagraphs: https://exoplanets.nasa.gov/exep/technology/technology-overview/
  - The 5-year technology development plan: https://exoplanets.nasa.gov/technology/technology-overview/446/
- Goddard Space Flight Center: https://www.nasa.gov/goddard

Scope Title

Control of Scattered Light with Starshades

Scope Description

As with coronagraphs, this scope 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, 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 to 1.5 arcsec are typical of these objects. Achieving a very low background requires control of both scattered and diffracted light. The starshade’s shape is designed to control the diffraction of starlight and form a deep shadow around the distant telescope. In this way, high contrast is achieved with a diffraction-limited telescope that does not require an internal high-precision wavefront control system. Sources of scatter include sunlight glinting on the sharp edges of the starshade, and multiple reflections between petal surfaces and edge assemblies. Earthshine on the telescope-facing surfaces must also be considered.

The research focuses on:

- Low-scatter, low-reflectivity, sharp, flexible razor-sharp edges for control of solar scatter at the perimeter of the starshade.
- Large-area (hundreds of square meters) anti-reflection and thermal-control coatings for flexible optical shield surfaces that are robust to cleaning and handling for starshade optical surfaces.
- Particulate contamination mitigation measures, including (but not limited to) dust-resistant coatings, vacuum-ultraviolet-eroding coatings, and on-orbit cleaning technologies.

Expected TRL or TRL Range at completion of the Project

2 to 5

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware
Desired Deliverables Description

Under this scope a concept study provided as a final report in Phase I is acceptable, and a prototype for Phase II is acceptable.

State of the Art and Critical Gaps

The optical design of the starshade has been tested at laboratory scales and shown to achieve $10^{-10}$ contrast in broadband light in flight-like geometries. Model validation of perturbation sensitivities have also been demonstrated for contrast levels of $10^{-8}$. A full-scale 10-m disk including the optical shield has been constructed, deployed, and shown to meet flight deployment requirements. Half-scale petals have been constructed and tested, validating the required thermal stability. Formation flying sensitivity has been demonstrated in the laboratory and through modeling to levels required for flight. Critical gaps relevant to this call include the fabrication of sharp optical edges and optical edge assemblies as well as methods to mitigate both particulate and molecular contamination of the edges and the telescope-facing surfaces.

Relevance / Science Traceability

These technologies are directly applicable to mission concept studies such as Habitable Exoplanet Observatory (HabEx), Large Ultraviolet Optical Infrared Surveyor (LUVOIR), starshade missions, and any space telescopes that could potentially be used for exoplanet imaging and characterization.

References

Technology development reports, concept videos, and prototype deployment videos:
https://exoplanets.nasa.gov/exep/technology/starshade/

Scope Title

Technology for Extreme Precision Radial Velocity

Scope Description

Astronomical spectrographs have proven to be powerful tools for exoplanet searches. When a star experiences periodic motion due to the gravitational pull of an orbiting planet, its spectrum is Doppler modulated in time. This is the basis for the precision radial velocity (PRV) method, one of the first and most efficient techniques for detecting and characterizing exoplanets. Because spectrographs have their own drifts, which must be separated from the periodic Doppler shift, a stable reference is always needed for calibration. Optical frequency combs (OFCs) and line-referenced etalons are capable of providing the spectral rulers needed for PRV detection of exoplanets. Although “stellar jitter” (a star’s photospheric velocity contribution to the RV signal) is unavoidable, the contribution to the error budget from Earth’s atmosphere would be eliminated in future space missions. Thus, there is a need to develop robust spectral references, especially at visible wavelengths to detect and characterize Earth-like planets in the habitable zone of their Sun-like host stars, with size, weight, and power (SWaP) suitable for space-qualified operation to calibrate the next generation of high-resolution spectrographs with precision corresponding to $<1$ cm/sec over multiple years of observations.

This scope solicits proposals to develop cost-effective component and subsystem technology for low-SWaP, long-lived, robust implementation of RV measurement instruments both on the ground and in space. Research areas of interest include but are not limited to:

- Integrated photonic spectrographs.
- Spectrograph gratings.
- PRV spectrograph calibration sources.
- High-efficiency photonic lanterns.
- Advanced optical fiber delivery systems and subsystems with high levels of image scrambling and modal noise reduction.
Software for advanced statistical techniques to mitigate effects of telluric absorption and stellar jitter on RV precision and accuracy.

Expected TRL or TRL Range at completion of the Project

3 to 5

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.2 Observatories

Desired Deliverables of Phase I and Phase II

- Hardware
- Software

Desired Deliverables Description

- Phase I will emphasize research aspects for technical feasibility, have infusion potential into ground or space operations, provide clear and achievable benefits (e.g., reduction in SWaP and/or cost, improved RV precision), and show a path towards a Phase II proposal. Phase I deliverables include feasibility and concept of operations of the research topic, simulations, and measurements; validation of the proposed approach to develop a given product (TRL 3 to 4); and a plan for further development of the specific capabilities or products to be performed in Phase II. Early development and delivery of prototype hardware/software is encouraged.

- Phase II will emphasize hardware/software development with delivery of specific hardware or software products for NASA, targeting demonstration operations at a ground-based telescope in coordination with the lead NASA center. Phase II deliverables include a working prototype or engineering model of the proposed product/platform or software along with documentation of development, capabilities, and measurements (showing specific improvement metrics); and tools as necessary. Proposed prototypes shall demonstrate a path towards a flight-capable platform. Opportunities and plans should also be identified and summarized for potential commercialization or NASA infusion.

State of the Art and Critical Gaps

High-resolving-power spectrographs (R ~ 150,000) with simultaneous ultraviolet (UV), visible, and near-infrared (NIR) coverage and exquisite long-term stability are required for PRV studies. Classical bulk optic spectrographs traditionally used for PRV science impose architectural constraints because of their large mass and limited optical flexibility. Integrated photonic spectrographs are wafer-thin devices that could reduce instrument volume by up to 3 orders of magnitude. Spectrometers that are fiber fed, with high illumination stability, excellent wavelength calibration, and precise temperature and pressure control represent the immediate future of precision RV measurements.

Traditional RV spectrographs would benefit from improvements in grating technology. Diffraction-limited PRV spectrographs require echelle gratings with low wavefront error and high efficiency—both of which are very challenging to achieve. Echelle spectrographs are designed to operate at high angle of incidence and very high diffraction order; thus, the grating must have very accurate groove placement (for low wavefront error) and very flat groove facets (for high efficiency). For decades, echelle gratings have been fabricated by diamond ruling, but it is difficult to achieve the level of performance required for PRV instruments. Newer grating fabrication techniques using lithographic methods to form the grooves may be a promising approach. As spectrograph stability imposes limits on how precisely RV can be measured, spectral references play a critical role in characterizing and ensuring...
this precision. Only laser frequency combs (LFCs) and line-referenced Fabry-Pérot etalons are capable of providing the broad spectral coverage and long-term stability needed for extreme PRV detection of exoplanets. Although both frequency combs and etalons can deliver high-precision spectrograph calibration, the former requires relatively complex hardware in the visible portion of the spectrum.

Commercial fiber laser astrocombs covering 450 to 1400 nm at 25 GHz line spacing and <3 dB intensity variations over the entire bandwidth are available for ground-based astronomical spectrographs. However, the cost for these systems is often so prohibitive that recent RV spectrograph projects either do not use a LFC or include it only as a future upgrade. Alternatively, astrocombs produced by electro-optic modulation (EOM) of a laser source have been demonstrated in the NIR. EOM combs produce modes spaced at a radiofrequency (RF) modulation frequency, typically 10 to 30, and they avoid the line-filtering step required by commercial mode-locked fiber laser combs. The comb frequency can be stabilized by referencing the laser pump source to a molecular absorption feature or another frequency comb. Where octave spanning EOM combs are available, f-2f self-referencing provides the greatest stability. EOM combs must be spectrally broadened to provide the bandwidth necessary for PRV applications. This is accomplished through pulse amplification followed by injection into highly nonlinear fiber or nonlinear optical waveguides.

Power consumption of the frequency comb calibration system will be a significant driver of mission cost for space based PRV systems and motivates the development of a comb system that operates with less than 20 W of spacecraft power. Thus, for flight applications, it is highly desirable to develop frequency comb technology with low power consumption; ~10 to 30 GHz mode spacing; compact size; broad (octave spanning) spectral grasp across both the visible and NIR; low phase noise; stability traceable to the International System of Units definition of the second; and importantly, long life.

The intrinsic illumination stability of the spectrometer also sets a fundamental measurement floor. As the image of the star varies at the entrance to the spectrometer because of atmospheric effects and telescope guiding errors, so too does the recorded stellar spectrum, leading to a spurious RV offset. Current seeing-limited PRV instruments use multimode optical fibers, which provide some degree of azimuthal image scrambling, to efficiently deliver stellar light from the telescope focal plane to the spectrometer input. Novel-core-geometry fibers, in concert with dedicated optical double-scramblers, are often used to further homogenize and stabilize the telescope illumination pattern in both the image and pupil planes. However, these systems still demonstrate measurable sensitivity to incident illumination variations from the telescope and atmosphere. Furthermore, as spectral resolution requirements increase, the commensurate increase in instrument size becomes impractical. Thus, the community has turned to implementing image and pupil slicers to reformat the near or far fields of light entering the spectrometer by preferentially redistributing starlight exiting the fiber to maintain high spectral resolution, efficiency, and compact spectrometer size.

Relevance / Science Traceability

The NASA Strategic Plan (2018) and Space Mission Directorate Science Plan (2014) both call for discovery and characterization of habitable Earth analogs and the search for biosignatures on those worlds. These goals were endorsed and amplified upon in the recent National Academy of Science (NAS) Exoplanet Report, which emphasized that a knowledge of the orbits and masses is essential to the complete and correct characterization of potentially habitable worlds. PRV measurements are needed to follow up on the transiting worlds discovered by Kepler, K2, and Transiting Exoplanet Survey Satellite (TESS). The interpretation of the transit spectra that the James Webb Space Telescope (JWST) will obtain will depend on knowledge of a planet’s surface gravity, which comes from its radius (from the transit data) and its mass (from PRV measurements or, in some cases, transit timing variations). Without knowledge of a planet's mass, the interpretation of its spectrum is subject to many ambiguities.

These ambiguities will only be exacerbated for the direct-imaging missions such as the proposed Habitable Exoplanet Observatory (HabEx) and Large Ultraviolet Optical Infrared Surveyor (LUVOIR) flagships, which will obtain spectra of Earth analogs around a few tens to hundreds of stars. Even if a radius can be inferred from the planet’s brightness and an estimate of its albedo, the lack of a dynamical mass precludes any knowledge of the planet’s density, bulk composition, and surface gravity, which are needed to determine, for example, absolute gas column densities. Moreover, a fully characterized orbit is challenging to determine from just a few direct images and may even be confused in the presence of multiple planets. Is a planet in a highly eccentric orbit habitable or not? Only dynamic (PRV) measurements can provide such information. Thus, highly precise and highly stable PRV measurements are absolutely critical to the complete characterization of habitable worlds.
The NAS report also noted that measurements from space might be a final option if the problem of telluric contamination cannot be solved. The Earth’s atmosphere will limit precise radial velocity measurements to ~10 cm/sec at wavelengths longer than ~700 nm and greater than 30 cm/sec at wavelengths >900 nm, making it challenging to mitigate the effects of stellar activity without a measurement of the color dependence due to stellar activity in the PRV time series. A space-based PRV mission, such as has been suggested in the NASA EarthFinder mission concept study, may be necessary. If so, the low-SWaP technologies developed under this SBIR program could help enable space-based implementations of the PRV method.

**References**

**Precision radial velocity:**

- EPRV Working Group report. See this website for preliminary information and the final report from this group due in mid-August: [https://exoplanets.nasa.gov/exep/NNExplore/EPRV/](https://exoplanets.nasa.gov/exep/NNExplore/EPRV/)

**Photonic lanterns:**


**Astrocombs:**


**Nonlinear waveguides:**


**Spectral flattening:**
