



NASA SBIR 2021 Phase I Solicitation

S2.05 Technology for the Precision Radial Velocity Measurement Technique

Lead Center: JPL

Participating Center(s): GSFC

Scope Title:

Components, Assemblies, and Subsystems for Extreme Precision Radial Velocity Measurements and Detection of Extrasolar Planets

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/s over multiple years of observations.

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This subtopic 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, infusion potential into ground or space operations, 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 ($R \sim 150,000$) with simultaneous UV, visible, and NIR coverage and exquisite long-term stability are required for PRV studies. Classical bulk optic spectrographs traditionally used for PRV science impose architectural constraints due to 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.

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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. Hence, 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 all aspects of the 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.

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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 GHz. Significantly, EOM combs avoid the line filtering step required by commercial mode-locked fiber laser combs. Comb frequency stabilization can be accomplished 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.

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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.

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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 dynamical (PRV) measurements can provide such information. Thus, highly precise and highly stable PRV measurements are absolutely critical to the complete characterization of habitable worlds.

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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/s at wavelengths longer than ~700 nm and greater than 30 cm/s 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.

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