



NASA SBIR 2020 Phase I Solicitation

S2.05 Technology for the Precision Radial Velocity Measurement Technique

Lead Center: JPL

Participating Center(s): GSFC

Technology Area: TA8 Science Instruments, Observatories & Sensor Systems

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. Since 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 instrument precision needed for detecting and characterizing Earth-like planets in the Habitable Zone of their Sun-like host stars. While “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 with Size, Weight and Power (SWaP) suitable for space qualified operation to calibrate the next generation of high-resolution spectrographs with precision corresponding to $< \sim 1$ cm/s over multiple years of observations.

This subtopic solicits proposals to develop cost effective component and subsystem technology for low SWaP, long-lived, robust implementation of radial velocity measurement instruments both on the ground and in space.

Research areas of interest include but are not limited to:

- Integrated photonic spectrographs
- PRV spectrograph calibration sources
- High efficiency photonic lanterns
- Advanced fiber scrambling techniques for modal noise reduction
- Software for advanced statistical techniques to mitigate effects of telluric absorption and stellar jitter on RV precision and accuracy

References

Precision Radial Velocity:

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- Fischer et al. (2016) State of the Field: Extreme Precision Radial Velocities <http://adsabs.harvard.edu/abs/2016PASP..128f6001>
 - Plavchan et al. (2015) Radial Velocity Prospects Current and Future: A White Paper Report prepared by the Study Analysis Group 8 for the Exoplanet Program Analysis Group (ExoPAG) <http://adsabs.harvard.edu/abs/2015arXiv150301770P>
 - Plavchan et al. (2019) EarthFinder Probe Mission Concept Study (Final Report): <https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/Ea...>

Photonic Lanterns:

- Gris-Sanchez et al. (2018) Multicore fibre photonic lanterns for precision radial velocity Science: <https://academic.oup.com/mnras/article/475/3/3065/4769655>
- Jvanovic, N. et al. (2012). Integrated photonic building blocks for next-generation astronomical instrumentation I: the multimode waveguide. *Optics Express*, 20:17029.

Astrocombs:

- Yi, X., et al. (2016) Demonstration of a near-IR line-referenced electro-optical laser frequency comb for precision radial velocity measurements in astronomy. *Nature Communications*, 7:10436.
- Halverson, S., et al, (2014) "The habitable-zone planet finder calibration system", Proc. SPIE 9147, Ground-based and Airborne Instrumentation for Astronomy V, 91477Z: <https://doi.org/10.1117/12.2054967>
- Suh, M.-G., et al. (2019) Searching for exoplanets using a microresonator astrocomb. *Nature Photonics*, 13(1):25–30.
- Obrzud, E., et al. (2019) A Microphotonic Astrocomb. *Nature Photonics*, 13 (1):31–35.

Nonlinear Waveguides:

- Chang, L., et al. (2018) Heterogeneously integrated GaAs waveguides on insulator for efficient frequency conversion, *Laser Photonics Reviews*, 12, 1800149: <https://doi.org/10.1002/lpor.201800149>
- Halir, R., et al. (2012) Ultrabroadband supercontinuum generation in a CMOS-compatible platform, *Optics letters*, 37, 1685: <https://di.org/10.1364/OL.37.001685>

Spectral Flattening:

- Probst, R.A., et al. (2015) Spectrally Flattened, Broadband Astronomical Frequency Combs https://di.org/10.1364/CLEO_SI.2015.SW4G.7

Expected TRL or TRL range at completion of the project: 3 to 5

Desired Deliverables of Phase II

Hardware/software

Desired Deliverables Description

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

- Integrated photonic spectrographs that meet PRV specifications (e.g. wavelength coverage, resolution, throughput, and polarization). These devices should be able to accept multiple fibers - at least two for the science light and simultaneous calibration light source. Ideally, they should be able to include on-chip cross-dispersion to eliminate bulk optics.
- PRV spectrograph calibration sources, particularly optical frequency combs (a.k.a. "astrocombs") from the

UV through the NIR (~350 nm – ~2400 nm) with ~10-30 GHz mode spacing, potentially self-referenced, or line stabilized for Allan Deviation $<1E-11$ over 100 seconds to years

- Spectral flattening to provide uniform power across the spectral band covered by the instrument
- Spectral broadening to obtain wide spectral coverage, preferably octave-spanning to enable self-referencing
- Integrated photonic solutions including nonlinear waveguides, microresonators or other comb generators, pump lasers, and f-2f beat-note generation
- Low phase-noise solutions
- Tunability of comb lines to scan spectrograph detectors for pixel characterization
- Optical etalons with similar requirements for stability as the frequency combs
- High efficiency photonic lanterns
- Advanced fiber scrambling techniques for modal noise reduction
- Software for advanced statistical techniques to mitigate effects of telluric absorption and stellar jitter on RV precision and accuracy.

Proposals should show an understanding of the science needs, as well as present a feasible plan to fully develop the relevant subsystem technologies and to transition into future NASA program(s).

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 3-4), 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), documents 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

The classical bulk optic spectrographs that are traditionally used for PRV science impose architectural constraints due to their large mass and limited optical flexibility. The spectrograph is the single element that if replaced with a photonic alternative could dramatically alter the course of astronomical instrumentation. Integrated Photonic Spectrographs (IPS) are wafer thin devices that could reduce instrument volume by up to three orders of magnitude. Furthermore, 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. 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.

As spectrograph stability imposes limits on how precisely the Radial Velocity (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 (years) stability needed for extreme PRV detection of exoplanets. While both frequency combs and etalons can deliver high precision spectrograph calibration, the former requires relatively complex and sophisticated hardware in the visible portion of the spectrum. Visible band frequency combs for astronomy (a.k.a. astrocombs) were initially based on mode-locked laser comb technology. However, the intrinsic free spectral range of these instruments, 100s of MHz to 1 GHz, is too fine to be resolved by astronomical spectrographs of $R \sim 150,000$ or less. Thus, mode filtering of comb lines to create a more spectrally sparse calibration grid is necessary. The filtering step introduces complexity and additional sources of instability to the calibration process, as well as instrument assemblies too large in mass and volume for flight.

Commercial fiber laser astrocombs covering 450 - 1400 nm at 25 GHz line spacing and <3 dB intensity variations over the entire bandwidth are available for ground-based astronomical spectrographs and have been developed for HARPS-S and ESPRESSO RV instruments. However, the cost for these systems is often so prohibitive that recent

RV spectrograph projects such as CARMENES and Keck Planet Finder either do not use a frequency comb or include it only as a future upgrade, owing to the cost impact on the project.

Alternatively, frequency combs produced by Electro-Optic Modulation (EOM) of a laser source have been demonstrated at observatories for PRV studies in the near-IR. EOM combs produce modes spaced at a RF modulation frequency, typically 10-30 GHz, and are inherently suitable as ground-based astrocombs. Significantly, EOM combs avoid the line filtering step of commercial mode-locked fiber laser combs. Comb frequency stabilization can be accomplished in a variety of ways, including 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 octave bandwidth necessary for f-2f stabilization for stability traceable to the Standard International (SI) second. This is accomplished through pulse amplification followed by injection into Highly Non-Linear Fiber (HNLF) or nonlinear optical waveguides, but the broadening process is accompanied by multiplication of the optical phase noise from the EOM comb modulation signal and must be optically filtered. Also, at these challenging microwave pulse repetition rates, the pulse duty-cycle requires pulse amplification to 4-5 Watts of average optical power in order to generate the high enough peak intensity needed for nonlinear broadening. This necessitates use of high power, non-telecom amplifiers that are more prone to lifetime issues, making EOM combs not optimal for flight either. It is important to note that very little comb light is actually required on the spectrograph detectors for calibration. In fact, most of the generated comb light must be deliberately attenuated to avoid detector saturation.

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 Watts of spacecraft power. Thus, for flight applications, it is highly desirable to develop frequency comb technology with low power consumption, ~10 GHz mode spacing, compact size, broad (octave spanning) spectral grasp across both the visible and NIR, phase noise insensitivity, stability traceable to the definition of the SI second, and very importantly, long life.

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 which 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 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.

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 >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.

