National Aeronautics and Space Administration

A Self-Referenced Electro Optic Modulation Frequency Comb for Extreme Precision Radial Velocity Detection

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Program: Strategic Initiative

Project Objective:

The overall goal of our research was to provide a robust, compact, low power, and highly stable frequency standard at red and near-infrared wavelengths for exoplanet science. We accomplished this by building a laser frequency comb (LFC) spanning an octave across the near-infrared and red-visible suitable for use in astronomical spectrographs (R>100,000) for extremely high precision radial velocity observations to detect exoplanets and determine a lower limit of their masses. Such a comb could yield a theoretical PRV capability in the sub cm/s regime and would allow us to focus on reducing other noise sources in the instrument, in the atmosphere, and in the stellar signal itself.

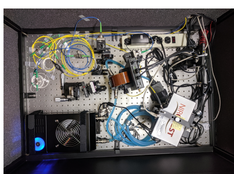
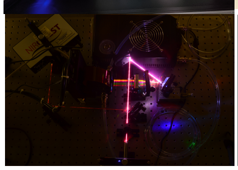
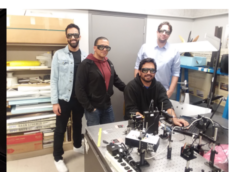
FY18/19 Results:

The technology described here addresses three critical aspects of implementing OFCs for astronomy: 1) spectral broadening to cover one octave in frequency; 2) maximizing spectral flatness over a broad passband; and 3) accomplishing *f-2f* self-referencing enabled by second harmonic generation. In years 1 and 2 of this project, we built an octave-spanning EOM comb and detected the *f-2f* beat note. Our plan in this 3rd and final year of the program was to:

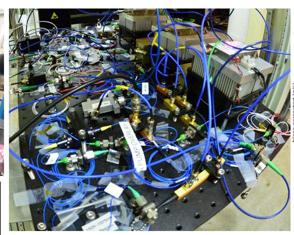
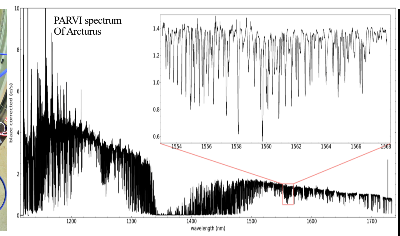
- Automate the comb for remote operation (Q1 FY19)
- Support laboratory testing of the PARVI spectrograph (Q2-Q3 FY19)
- Demonstrate the automated line-referenced comb at Palomar Observatory (Q3-Q4 FY19)
- Lock the comb pump laser to a fiber comb in place of directly self-referencing the EOM comb due to the use of free-space optics and concerns over long-term operation at a remote location. (Sept 2019)

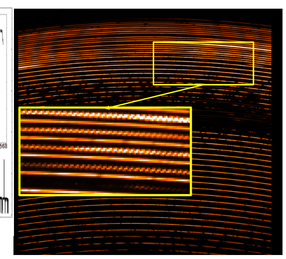
We successfully interfaced the EOM comb with the PARVI spectrograph, first in the Cahill laboratory on campus to aid in instrument development, and then ultimately at Palomar Observatory, where it has been used since PARVI instrument commissioning in June of 2019. It is presently being used in a line-referenced configuration where the comb pump laser is locked to a HCN line near 1560 nm. We recently participated in a "comb camp" organized by the National Institute of Standards and Technology where we were able to construct two compact fiber laser combs, both octave-spanning and generating *f-2f* beat notes for self-referencing at repetition rates of ~150 MHz. These combs will be useful for locking the EOM comb pump laser in future upgrades at Palomar, similar to the configuration of the Habitable Planet Finder frequency comb at the Hobby Eberly Telescope.

We also built a spatial light modulator (SLM)-based spectral flattener after the technique described by Probst *et al* [4] in order to obtain a spectrally flat comb across PARVI's passband of 1200 nm - 1800 nm. The flattener effort was supported in part by a Capstone Senior Design Project team at the California State University, Los Angeles (CSULA). The CSULA team participation was arranged by the JPL University Crowdsourcing Initiative (JUCI). An advancement not made in other spectral flatteners but accomplished here was the implementation of a dynamic look-up table to keep the comb intensity profile constant throughout an observation run.

Spectral flattener team at CSULA (above, right), top view of optical breadboard at Palomar (above, left), and long exposure (left) showing beam path using a supercontinuum light source.

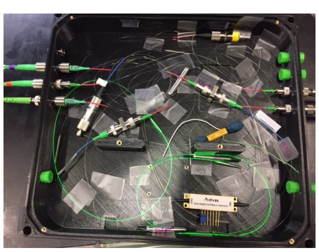


Comb breadboard (left), First Light on the PARVI spectrograph with the star Arcturus (center), and as seen on the PARVI H2RG detector with comb lines (right).

Benefits to NASA and JPL:

This program has demonstrated the feasibility of self-referenced electro optic modulation LFCs as frequency standards in the red and near-infrared for application to exoplanet detection and characterization. LFCs operating in both the visible and near-IR will be critical to achieving <1 cm^{-1} long term stability compared to the 9 cm^{-1} signal of an Earth analog orbiting a solar type star, and to mitigating the observational uncertainty imposed by stellar jitter in such stars. The ability to determine the orbits and masses of Earth-analogs is important for advising direct imaging missions such as future NASA Flagship missions, HabEx and LUVOIR. These LFCs will work with new ground-based facilities, but it may prove necessary to conduct a space mission such as the EarthFinder Probe [3] due to telluric line contamination of the stellar spectra and restricted observing cadence, in which case self-referenced LFCs represent an enabling technology. The success demonstrated in the past 3 years has put JPL and Caltech scientists and technologists in an excellent position to play a key role in the Extreme Precision Radial Velocity Initiative now being developed by NASA and the NSF. Furthermore, the investment made by JPL in this technology has directly resulted in laboratory expertise that has led to positive outcomes in competed proposals to both NASA and the NSF.

Compact fiber laser comb (octave spanning, ~160 MHz) under construction at NIST. The comb can be used to reference the pump laser for the EOM comb



Publications and References:

•[1]"Demonstration of a near-IR line-referenced electro-optical laser frequency comb for precision radial velocity measurements in astronomy," Yi, X., Vahala, K., Li, J., et al.\ 2016, Nature Communications, 7, 10436

•[2] "Searching for exoplanets using a microresonator astrocomb" Suh, M.-G., Yi, X., Lai, Y.-H., et al.\ 2019, Nature Photonics, 13, 25

•[3] "EarthFinder: A Precise Radial Velocity Probe Mission Concept for the Detection of Earth-Mass Planets Orbiting Sun-like Stars," Plavchan, P., Cale, B., Newman, P., et al.\ 2018, arXiv e-prints, arXiv:1803.03960

•[4] "Spectrally Flattened, Broadband Astronomical Frequency Combs," Probst, R.A., et al. in *CLEO: 2015*, OSA Technical Digest (online) (Optical Society of America, paper SW4G.7.

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