Infrared Astronomical Spectroscopy for Radial Velocity Measurements with 10 cm/s Precision

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Abstract: We detail the first infrared precision astronomical spectroscopy results from the combination of an electro-optic laser frequency comb and the Habitable Zone Planet Finder spectrograph at the 10 m Hobby-Eberly telescope.

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The search for and subsequent study of exoplanets around stars beyond our Sun is driven by profound scientific questions: Are Earth and our solar system unique? What is the mass-radius relationship of exoplanets? Is there life elsewhere and what are the conditions under which it evolves? Precision astronomical spectroscopy plays a critical role in answering these questions. For example, measurements of a periodic radial velocity (RV) Doppler shift of a nearby star provides evidence of an unseen orbiting planet and information on its mass. This Doppler RV technique has been used extensively to identify hundreds of planets, but with notable challenges in detecting terrestrial mass planets in Habitable Zones [1]. Specifically: (1) The sensitivity of traditional RV spectroscopy with precision at the 1 m/s level has been insufficient to identify earth analogs; and (2) The highest precision RV measurements have largely focused on the visible region of the spectrum <700 nm [2], and not the infrared. This second point means that 70% of the stars in our galaxy—M dwarfs, which primarily emit in the near infrared—have been outside the efficient spectral grasp of the best RV spectroscopic instruments.

In this paper, we address these shortcomings and report on the infrared optical instrumentation and techniques that for first time provide the necessary precision for discovering and characterizing planetary systems around M dwarf stars. We introduce a 30 GHz optical frequency comb spanning 700-1600 nm built on integrated electro-optic (EO) modulators and high-efficiency nonlinear waveguides to provide a robust platform for long-term operation at the telescope. This comb-based calibrator provides tailored light to the ultra-stable Habitable Zone Planet Finder (HPF) spectrograph [3], designed and built from the ground up for precision infrared Doppler RVs. Both the frequency comb and spectrograph have been installed at the 10 m Hobby-Eberly Telescope, and we have demonstrated precision at 10 cm/s using simultaneous calibration, an unprecedented level in this wavelength regime.

Although frequency combs have been recognized as critical for precision RV astronomical spectrographs, the desired parameters for most 'astrocombs' are not well matched to the capabilities of traditional comb technology, making development beyond the proof-of-concept stage a challenging realization. The most demanding constraints are the combination of broad spectral coverage, 10+ GHz mode spacing, and operational robustness in a telescope

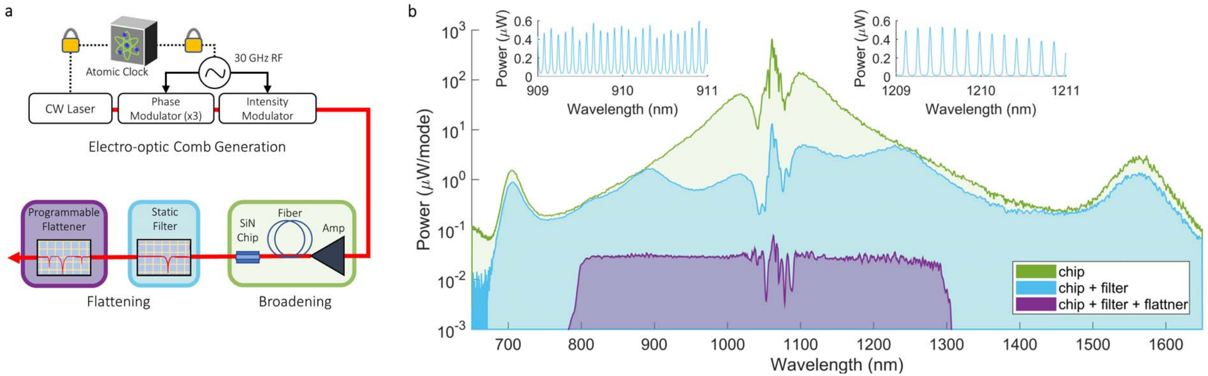

Fig 1. 30 GHz astrocomb for infrared precision Doppler radial velocity spectroscopy. (a) The optical setup: electro-optic comb generation followed by a nonlinear stage of broadening and two subsequent amplitude filtering stages to tailor the spectrum. (b) Optical spectra envelopes recorded with an OSA at different points in the setup: Green - at the output of the SiN waveguide, Blue - after a static amplitude filter, and Purple-after a programmable amplitude filter. The two insets show resolved 30 GHz comb modes centered at 910 and 1210 nm, respectively.

environment. Here, we employ integrated electro-optic modulators to directly generate a comb with the required 30 GHz mode spacing, and a high-efficiency SiN waveguide instead of traditional non-linear fiber [4]. Our scheme is depicted in Fig.1(a). The comb generation starts by sending a 1064 nm CW laser through 4 integrated waveguide modulators to produce 100 comb lines spaced by 30 GHz. Both the CW laser and 30 GHz RF signal are stabilized to the SI second via a GPS-disciplined clock. The modulated pulse train is amplified and compressed to 330 fs, and ~2 W of average power is launched into a normal dispersion photonic crystal fiber (PCF). Normal dispersion fiber minimizes modulation instability and produces a smooth spectral phase such that a grating compressor further reduces the pulse width to 70 fs. A fraction of this pulse train with 525 mW power (16 pJ pulse energy) is focused into a SiN waveguide to achieve a supercontinuum spectrum spanning from 700-1600 nm. A static and programmable filter are then used in tandem to tailor the spectral profile. The output of each amplitude filtering stage is shown in Fig. 1(b) along with high resolution insets showing the resolved 30 GHz comb modes at 910 and 1210 nm. Independent optical heterodyne measurements confirm the stability of the comb to match that of the GPS-disciplined clock with stability of $2\text{x}10^{-11}$ at 1 s averaging—equivalent to an RV precision of 6 mm/s.

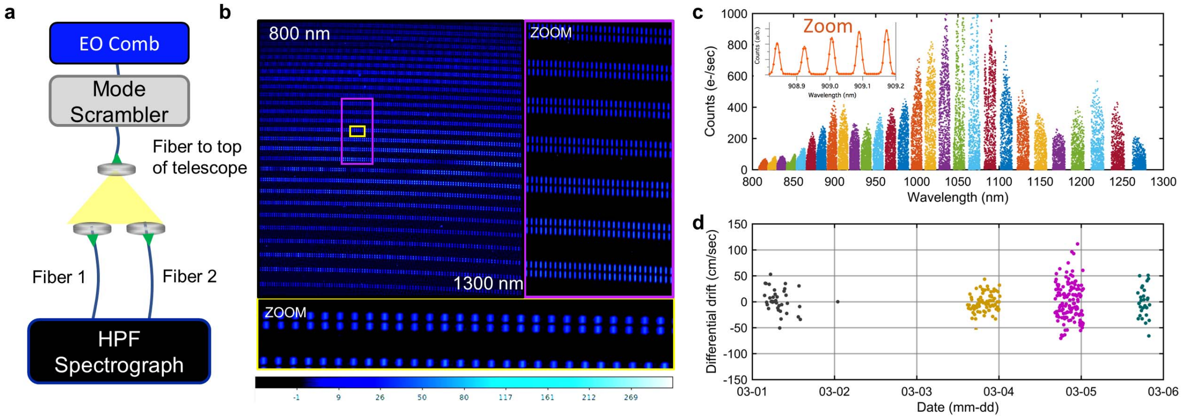

Fig 2. (a) Spectrograph calibration setup for measuring the differential drift between the science and calibration fibers that feed from the top of the telescope to the spectrograph. (b) Dispersed spectra on the HPF detector when comb light illuminates both fiber inputs to the spectrograph. (c) The reconstructed comb spectra after processing the detector readout. The different colors represent the different echelle orders, and the zoom in view shows a few of the comb lines around 900 nm. (d) The differential drift between the two fibers over a period of 6 days.

The entire frequency comb has been packaged on a 60 x 152 cm^2 breadboard and installed at the 10 m Hobby-Eberly telescope, together with the HPF spectrograph. The HPF is a vacuum-housed echelle crossed-disperser spectrograph that employs a HgCdTe infrared detector array. The spectrograph is optimized for stability with its optics platform cryogenically cooled and temperature stabilized at the mK level [5]. The HPF entrance slit is fed by 3 optical fibers that can be illuminated with star, sky, and calibration light. To determine the baseline RV stability we send the laser comb light through both the star and sky fibers (Fig2(a)) to characterize the relative stability of these two channels. Figure 2(b) shows the detector readout under these conditions, with the comb modes clearly resolved across all orders. Figure 2(c) shows the comb spectrum after processing the readout from the detector. The comb-comb calibrations were taken over multiple nights by recording the differential drift between the two comb-illuminated fiber paths every 10 minutes, with the results provided in Fig.2(d). The RMS scatter of a single measurement is at the 20 cm/s level and binning of multiple measurements yields a stability of <10 cm/s. We also observe no statistical significant long term or linear drift in the two fibers over 6 days. Changing to the more standard illumination configuration, with star light collected in one of the fibers, allows us to also measure differential stellar RV's. These results will be presented at the meeting.

Our results move beyond a technology or capability demonstration and open up of a new wavelength regime for the first time. The coupled HPF and EO comb on one of the largest optical telescopes in the world is the working model for future precision NIR RV spectroscopy and charts a path to discovery and characterization of Earth-mass planets in the Habitable Zones of the nearest stars.

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