

Laser Frequency Comb Use in Near-Infrared Doppler Spectroscopy

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Discovering new exoplanets around nearby stars has been a scientific endeavor for years in the search for other places where there exist conditions for life outside of Earth. These planets need to have similar composition to Earth and be within the habitable zone of their star. The first technique used to detect these exoplanets consistently was doppler spectroscopy.² Doppler spectroscopy is complemented by photometric measurements of the transiting exoplanet to obtain the mass, radius, and density of the exoplanet which are important parameters for assessment of habitability.¹ Doppler spectroscopy uses the variation of stellar radial velocity from the gravitational interaction with a large planet as a detection method with the precision needed for this method happening in the 1990's.² The first exoplanet discovered using doppler spectroscopy was 51 Pegasi B on October 6, 1995.⁵ 51 Pegasi B is about 50 lightyears away from Earth and has about 47% less mass than Jupiter.⁵ However, precision problems plagued doppler spectroscopy even with the first detections of exoplanets for next near 20 years. Highest precision measurements were limited to the visible region of the spectrum and excluded the infrared, so the *M*-dwarf stars of the Milky Way galaxy have been out of the spectral abilities.¹ This excludes 70% of stars in the Milky Way since these *M*-dwarf stars emit in the near infrared and are particularly important due to having a habitable zone closer into the star like that of Earth.¹ The lack of better precision in the near-infrared has been due to multiple factors such as low-noise silicon detector arrays are inefficient in the infrared and calibration of such an instrument has been found to be not as effective as the calibrations for the visible.¹

Another downside to visible spectral radial velocity technique is that convection and magnetic activity of the *M*-dwarf star can lead to noise that obfuscates the small signals of these planets, but those noise sources are suppressed in the near-infrared.¹

Hence, fixing the issues surrounding infrared (and near-infrared) doppler spectroscopy

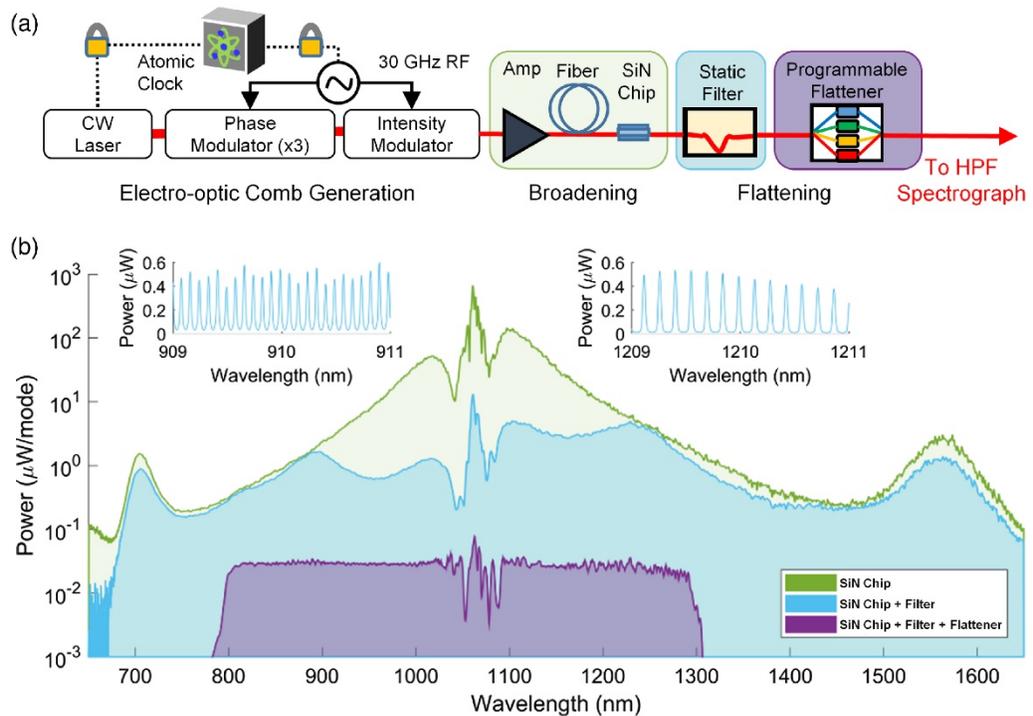


Figure 1. The 30 GHz electro-optic frequency comb is shown from Ref 1. (a) The frequency comb is generated via electro optical modulation of the continuous laser followed by nonlinear spectral broadening and amplitude filtering to tailor the spectrum.¹ (b) The spectral envelopes recorded at different points in the setup with the colors corresponding to the colored boxes in (a).¹ The two insets are high-resolution recordings of the 40 GHz comb modes centered at 910 (upper left) and 1210 nm (upper right).¹

would open up many new opportunities for stellar spectroscopy. In comparison, another exoplanet-detecting method akin doppler spectroscopy is the transit method, which detects the changes in solar intensity.^{3,4} The solar intensity decreases when an exoplanet orbits in between its star and Earth, but the presence of other astrophysical phenomena that may mimic transits can lead to false positives.⁴ Both the transit method and doppler spectroscopy preferentially detect exoplanets that orbit closer to their host stars and are larger in mass or size.³

Instrumentation for precise infrared doppler spectroscopy measurements was developed in 2019 using an optical frequency comb as seen in Figure 1a.¹ Optical frequency combs consist of an equally spaced array of laser frequencies, and those for high precision radial velocity measurements have challenges regarding the spectral coverage over hundreds of nanometers needed in an astronomical observatory environment.¹ This component is critical for high-precision radial velocity measurements, and is generated by electro-optical modulating a continuous wave laser.¹ After this modulation, the spectrum is tailored by nonlinear spectral broadening and filtering the amplitude.¹ The spectral envelopes at the different stages of tailoring can be seen in Figure 1b with the most tailoring seen in the purple spectral envelope.¹ The teeth of this comb is seen in insets of Figure 1b, and these uniform teeth are compared to starlight to detect any minute changes.¹

Starlight collected by the Hobby-Eberly telescope from southwest Texas and the light from a frequency comb with teeth spaced 30 GHz apart were coupled to the highly stabilized Habitable Zone Planet Finder (HPF) spectrograph as seen in figure 2.¹ The HPF spectrograph was used to track minute wavelength changes in the stellar spectrum with the precise calibration grid provided by the laser frequency comb as mentioned earlier.¹ The frequency comb spanned 700-1600 nanometers provided a robust calibrator for long-term operation at the telescope.¹ This optical frequency comb was integrated into the HPF calibration system and has been operating both continuously and autonomously since May 2018.¹

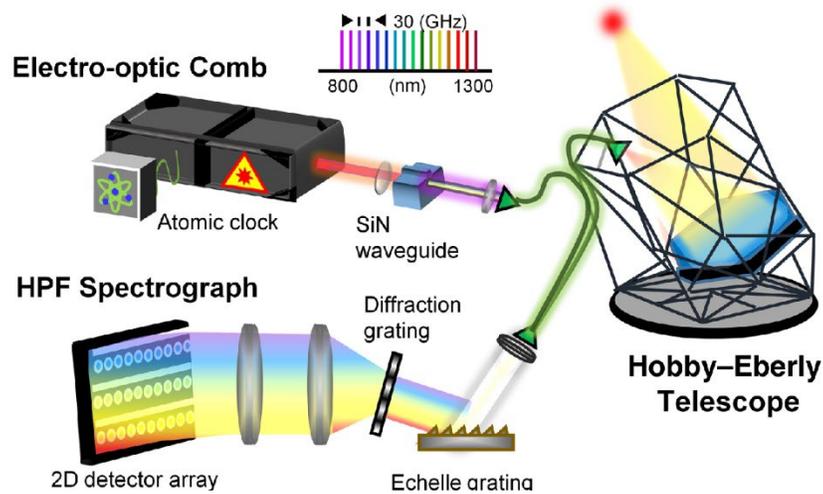


Figure 2. The instrumentation for precision infrared radial velocity spectroscopy is shown from Ref 1. Starlight was collected by the Hobby-Eberly telescope and directed to an optical fiber. To generate a frequency comb with teeth spaced 30 GHz, lasers, electro-optics, and nanophotonics were used, and the comb was stabilized using an atomic clock. Both the starlight and frequency comb light were coupled to the highly stabilized Habitable Zone Planet Finder (HPF) spectrograph.

Characterizing this system's present radial velocity precision was done using on-sky stellar observations of stable *M*-dwarf stars with known orbiting planets.¹ Barnard's star is a bright nearby star with its radial velocity measurements showing a low-amplitude signal attributed to an exoplanet.¹ It is among the most stable *M*-dwarf stars known, and the perfect choice to test out this new measurement

scheme.¹ Over a three month period, 118 high signal-to-noise measurements of residual radial velocities of Barnard's star was measured.¹ The scatter of individual radial velocity measurements of 5 minutes was 2.83 m/s, and data within 1 hour observation window was binned, the scatter is reduced to 1.53 m/s.¹ This type of precision has been unprecedented in the near-infrared and has approached that of the best measurements with visible-band spectrometers for Barnard's star.¹ The comb-calibrated HPF can support precision as low as 6 cm/s, so further improvements towards this limit are possible with improvements in algorithm and modal scrambling.¹ The near-infrared instrumentation using a frequency comb has a precision level comparable to the visible light instrumentation which shows that this is relevant in the search and characterization of exoplanets.

References

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