Detecting Earth-Sized Planets with Laser Frequency Combs

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Abstract

Detection of Earth-mass exoplanets from the Doppler shift of stellar spectral lines is limited by the range and resolution of available reference spectra. Laser frequency combs are shown to produce a spectra of evenly-spaced lines spanning the optical into the infrered. Options for calibrating the comb and determining line positions are explained. Combining an Er:fiber laser frequency comb with an echelle spectograph is calculated to provide radial velocity measurements with 6 cm/s precision. Laser frequency combs are presented as the cutting edge of technology that will make it possible to discover Earth-mass exoplanets.

1. Introduction

Extrasolar planets are most commonly observed indirectly. The gravitational attraction between a star and its planet will cause both bodies to orbit about the system's center of mass, which is often still inside the radius of the star. Nonetheless, the wavelength of spectral emission lines from the star decreases as star moves toward the observer and increases as it moves away. The star's radial velocity is measured from the Doppler shift of its spectral lines. When a series of spectra are taken over time, the existence of an extrasolar planet can be inferred from periodic variations in the parent star's radial velocity.

Detecting rocky, Earth-mass planets in stellar habitable zones is a challenge. A Jupiter-mass planet at a particular radius exerts a stronger gravitational force and causes a larger radial velocity change than an Earth-mass planet. The Earth causes the Sun's radial velocity to shift by just ± 0.1 m/s per year. Even at its larger radius, each orbit of Jupiter causes a change of ± 13 m/s. Doppler wobble from the spectra of a parent star is more noticeable for more massive planets. The precision required to observe periodic Doppler shifts in stellar spectra is the main limitation for finding Earth-mass planets around solar mass stars.

The range of radii within which a planet could sustain liquid water and Earth-like life changes based on the size of the star. M stars, which are less than half the mass of the Sun, have habitable zones that lie closer in. Searching for Earth-mass planets becomes more practical with M stars as candidates. An Earth-mass planet orbiting an M star causes a larger velocity shift (2 m/s) than the Earth does orbiting the Sun. The smaller radius means Earth-mass planets orbiting M stars have shorter orbital periods (~3 days). Variability data can be collected much faster than waiting a full year for an Earth-mass planet to orbit a solar mass star. This improved detectability and their abundance in the solar neighborhood make M stars good targets for exoplant searches. The drawback is that M stars are brighter in the infrared than in the optical, due to their cooler temperatures. Infrared wavelengths lack reference spectra to compare with the stellar spectra.

Laser frequency combs provide the precision necessary to detect cm/s radial velocity shits and solve the problem of not having reference spectra in the infrared. Section 2 explains how the laser frequency comb apparatus produces a spectra with well-determined line positions. Section 3 discusses the practicalities of using a laser frequency comb with an astrophysical spectrograph. The anticipated velocity precision is calculated. Section 4 summarizes the feasibility of detecting exoplanets using laser frequency combs.

2. Laser Frequency Combs

Laser frequency combs get their name from the regularly-spaced spike pattern that appears when pulses of light emitted by a laser are Fourier transformed from the time domain to the frequency domain. The laser emits pulses of light that have a periodic group velocity. Each pulse is separated by the round trip time for light reflecting in the laser cavity. The round time time is twice the length of the cavity divided by the group velocity:

$$T=2\mathrm{L}/v_g$$

The pulse envelope travels at the group velocity. However, the carrier wave has a phase velocity that shifts by an amount $\Delta\varphi$ with every round trip through the cavity (Figure 1).

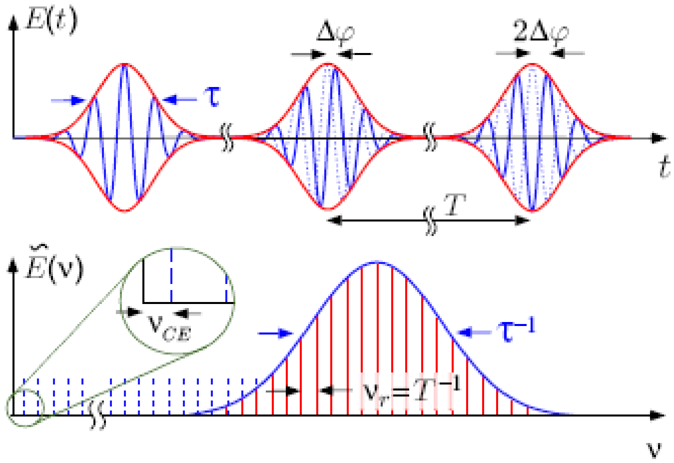

Figure 1: Fourier transform of laser light

(Figure: Murphy et al., 2007)

A periodic envelope function

A(t) = A(t-T)

describes the carrier wave amplitude. The electric field outside the cavity is

$$E(t)=A(t)\mathrm{e}^{-i2\pi\nu_c t}=\sum_n A_n e^{-i2\pi(n\nu_{rep}+\nu_c)t}$$

A periodic pulse therefore generates peaks in frequency space that are exactly the width of the repetition frequency, $\nu_{rep}=1/T$. Due to the phase shift in the time domain, the nth frequency domain peak is at $n\nu_{rep}+\nu_c$, where $\nu_c=\frac{\Delta\varphi\,\nu_{rep}}{2\pi}$.

The laser is mode-locked to a cesium atomic clock so that Δφ stays the same. Laser frequency combs produce lines with known spacing offset from the repetition frequency by ν_c .

2.1 Calibration

The repetition frequency and the carrier frequency must both be determined to know the frequency of each tooth in the comb. A photodetector can measure the repetition frequency from the beam, and the carrier frequency is obtained from self-referencing the comb (Figure 2). A nonlinear fiber optic cable extends the frequency range of the comb so that it spans an optical octave. A low frequency mode n is doubled and compared with the 2n high frequency mode. The frequency-doubled mode is superimposed on the high frequency mode for the photodetector to read. The carrier frequency is the difference between frequency-doubled n and 2n.

$$2(n\nu_{rep}+\nu_c)-(2n\nu_{rep}+\nu_c)=\nu_c$$

Self-referencing different pairs of modes can be used to verify consistency across the frequency range.

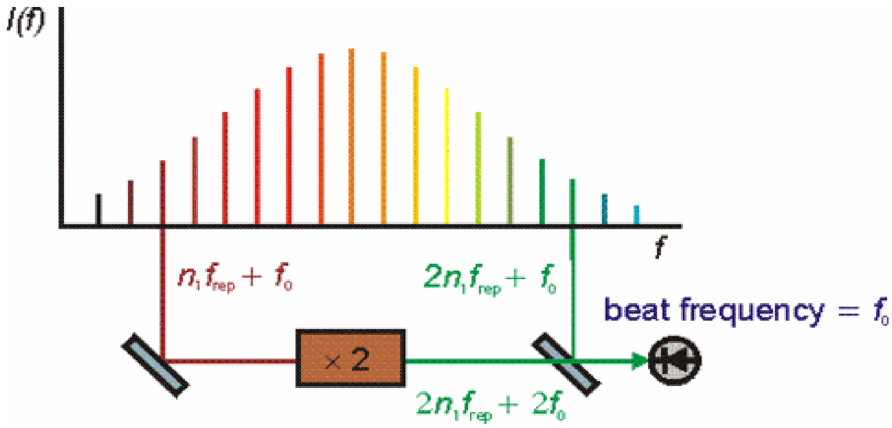

Figure 2: Comparision of frequency-doubled mode n with 2n mode

(Figure: National Physics Laboratory website)

Alternatively, the frequency comb can be calibrated by referencing one line to a continuous wave single-frequency laser. Once the frequency of one line is known, all the rest are determined by adding integer multiples of the repetition frequency. For this calibration technique, it is not necessary to know the carrier frequency. The continuous wave single-frequency laser introduces additional uncertainty, so self-referencing the laser frequency comb is more precise.

3. Spectroscopy

When a laser frequency comb is used to calibrate stellar spectra, the laser output is transmitted to the spectrograph with an optical fiber (Figure 3). The laser frequency comb spectrum is recorded next to the stellar spectrum on the CCD (Figure 4). Having more teeth in the frequency comb improves the precision of the wavelength calibration. However, the spectrograph must be able to resolve the line spacing of the laser frequency comb. A calibration spectra that is beyond the resolution of the spectrograph would not be useful. An optimal line spacing can be determined so that the teeth are frequent enough to provide a precise calibration, but sparse enough to preserve the contrast between neighboring lines.

The precision of the radial velocity measurement depends on the laser frequency comb line spacing. The error on the position of the comb line is approximated by:

$$\delta_v \approx A \frac{FWHM}{S/N \sqrt{n}}$$

S/N is the peak Signal to Noise of the line, n is the number of pixels sampling the Full Width Half Maximum, and A is a pre-factor that characterizes noise. These are all properties of the spectrograph.

A spectrograph with an echelle diffraction grating separates light into multiple orders that are imaged on a CCD. Each echelle order spans 2048 pixels of the CCD, which has 3-pixel FWHM sampling for a line. A comb line can occur every 2.5 resolution elements without saturating the detector. This results in the number of comb lines, N

$$N = \frac{2048\ pixels}{(3 \frac{pixels}{res\ elem})(\frac{2.5\ res\ elem}{1\ line})} = 272\ lines$$

The average precision for the comb spectrum is then:

$$\sigma_v \approx \frac{\delta_v}{\sqrt{N}} = A \frac{FWHM}{S/N \sqrt{n} \sqrt{N}}$$

A high-resolution spectrograph with a resolving power of R = 150000 has a FWHM of 2 km/s. Fitting the noise profile gives a pre-factor of A = 0.41.

$$\sigma_v \approx \frac{(0.41)(2 \times 10^5\ cm/s)}{(500)\sqrt{3 * 272}} \approx 5.7\ cm/s$$

Note that frequencies can be measured as velocities.

3.1 Controlling Line Spacing

A Fabry-Perot cavity widens line spacing in the laser frequency comb up to 40 GHz. The free spectral range of the Fabry-Perot cavity must be approximately an integer multiple of the repetition frequency to maintain the comb properties. The Fabry-Perot cavity preserves the frequency of the comb, while suppressing the amplitude of extraneous lines. A dichroic-atomic-vapor laser lock stabilizes the Fabry-Perot cavity.

4. Conclusions

The 6 cm/s precision of radial velocity measurements made using a laser frequency comb is enough to detect a ±10 cm/s change caused by an Earth-mass planet orbiting a stellar mass star. The range that a laser frequency comb can cover provides the infrared end of the spectrum with precise, abundant reference lines. Observations of M stars in the infrared are no longer constrained by lack of reference spectra. The precisions and range of laser frequency combs solve two major technical challenges for detecting exoplanets.

Laser frequency combs are currently being tested at small observatories with high-resolution spectrographs. The German Vacuum Tower Telescope has taken spectra of the Sun's photosphere in the infrared with the laser frequency comb from an Er:fiber laser. NIST also has plans to provide the FIRST spectrograph at the Apache Point Observatory with calibration in the infrared from an Er:fiber laser frequency comb. A Ti:sapphire laser frequency comb operates at the Whipple Observatory on Mount Hopkins in Arizona as a prototype for one that will be installed on the HARPS-NEF spectrograph in Chile. Astronomer's ability to detect exoplanets will improve as laser frequency combs become more prevalent at observatories.

As laser frequency combs transition from the developmental stage to astrophysical applications, instrumental effects are the limiting factor for precise measurements. Optimizing the interaction of laser frequency combs with the spectrographs is the next step for achieving precise spectra to detect exoplanets. The internal consistency of laser frequency combs will eventually facilitate comparisons of spectra from different observatories or epochs.

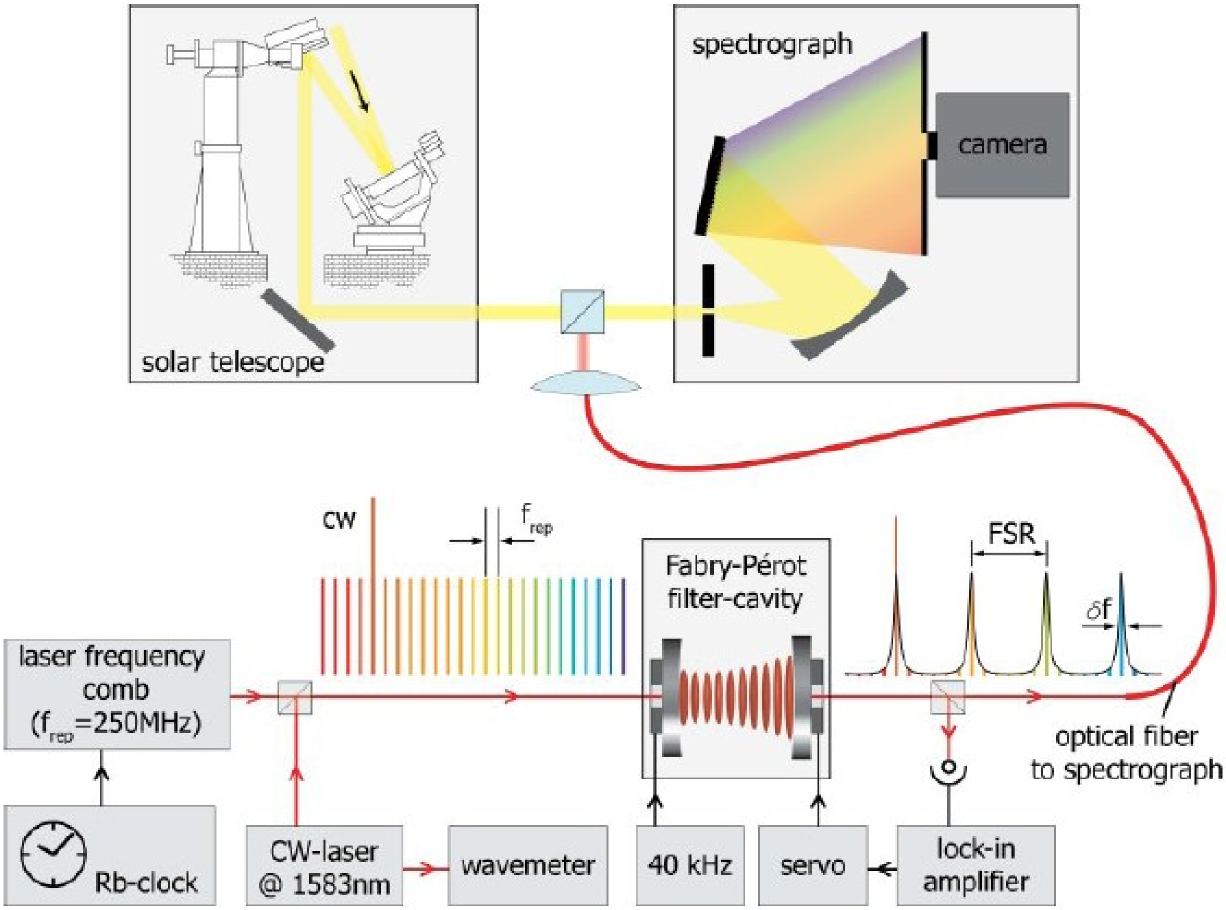

Figure 3: Vacuum Tower Telescope Er:fiber laser frequency comb apparatus diagram

(Figure: Steinmetz et al., 2008)

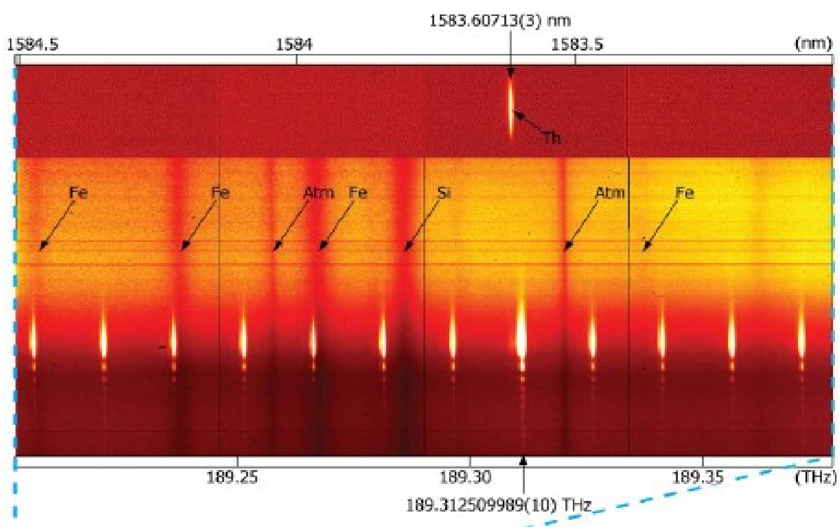

Figure 4: Laser frequency comb spectra (white) imposed on solar photosphere spectra from VTT

(Figure: Steinmetz et al., 2008)

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