Astro-comb calibrator and spectrograph characterization using a turn-key laser frequency comb

Aakash Ravi,[a,*] David F. Phillips,[b] Matthias Beck,[c] Leopoldo L. Martin,[d] Massimo Cecconi,[d] Adriano Ghedina,[d] Emilio Molinari,[d] Albrecht Bartels,[c] Dimitar Sasselov,[b] Andrew Szentgyorgyi,[b] and Ronald L. Walsworth[a,b]
[a]Harvard University, Department of Physics, Cambridge, Massachusetts, United States
[b]Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts, United States
[c]Laser Quantum GmbH, Konstanz, Germany
[d]INAF—Fundación Galileo Galilei, Breña Baja, Spain

Abstract. Using a turn-key Ti:sapphire femtosecond laser frequency comb, an off-the-shelf supercontinuum device and Fabry-Perot mode filters, we report the generation of a 16-GHz frequency comb spanning a 90-nm band about a center wavelength of 566 nm. The light from this astro-comb is used to calibrate the HARPS-N astrophysical spectrograph for precision radial velocity measurements. The comb-calibrated spectrograph achieves a stability of ∼1 cm/s within half an hour of averaging time. We also use the astro-comb as a reference for measurements of solar spectra obtained with a compact telescope and as a tool to study intrapixel sensitivity variations on the spectrograph detector. © *2017 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JATIS.3.4 .045003]

1 Introduction

Finding and characterizing Earth-like planets orbiting Sun-like stars is one of the most challenging goals of modern radial velocity (RV) exoplanet science.[1] Such searches place very demanding requirements on the wavelength calibration of astrophysical spectrographs, specifically, detecting ∼10 cm/s RV shifts over the course of months to years, corresponding to sub-MHz changes in Doppler-broadened stellar absorption lines that are many GHz broad. Atomic emission lines from hollow cathode lamps and absorption lines from iodine vapor cells have been the workhorse calibration tools. However, these sources neither have uniform spectral coverage nor long-term stability. A laser frequency comb (LFC) that is referenced to an atomic clock provides an excellent solution to this problem, as it provides a very large set of equispaced frequency markers with very accurately known absolute frequencies.[2–4]

Although LFCs for the calibration of astrophysical spectrographs ("astro-combs") have been successfully demonstrated,[2–11] they have not yet seen widespread adoption as primary calibrators in the astronomical community due to their complexity and cost. The operation of astro-combs has so far required significant laser expertise. It is, therefore, imperative to simplify the use of astro-combs[11,12] to make them viable for the next generation of high-precision RV measurements.

Astro-combs need to have a large mode spacing (≳10 GHz) to match the resolution of astrophysical spectrographs. Ti:sapphire-based astro-combs facilitate this because these lasers are available with intrinsically larger mode spacing compared with fiber lasers. However, contrary to their fiber laser counterparts, these lasers require occasional realignment. Recently, however, this disadvantage has been overcome with the advent of turn-key Ti:sapphire LFCs.

Here, we demonstrate the simplification of the operation of an astro-comb using a turn-key Ti:sapphire LFC, an off-the-shelf supercontinuum device, and existing Fabry–Perot (FP) mode filters. The laser is alignment free and, therefore, greatly simplifies the use of the astro-comb. We study the stability of our system, use it as a reference for measurements of solar spectra, and employ it to perform characterization of an astrophysical spectrograph. We also discuss some potential future improvements to the system.

2 Experimental Setup

The astro-comb is located at the Telescopio Nazionale Galileo (TNG), on the island of La Palma in the Canary Islands, where it is used to calibrate the HARPS-N spectrograph.[13] Figure 1 shows a schematic of the experimental setup.

The astro-comb light source is the taccor comb (Laser Quantum), based on a turn-key 1-GHz Ti:sapphire mode-locked laser with a carrier-envelope offset (CEO) detection unit. The LFC operates at a center wavelength of about 800 nm and outputs ∼30 fs pulses at a repetition rate f_r stabilized to a 1.000010870-GHz signal sourced from an RF synthesizer. The LFC CEO frequency f_0 is detected by sampling the optical output and sending it through a short length of nonlinear fiber to an $f - 2f$ detection unit, which directly locks the CEO frequency to 261.5 MHz. Both synthesizers are referenced to a GPS-disciplined 10-MHz Rb clock.

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*Address all correspondence to: Aakash Ravi, E-mail: aravi@physics.harvard.edu
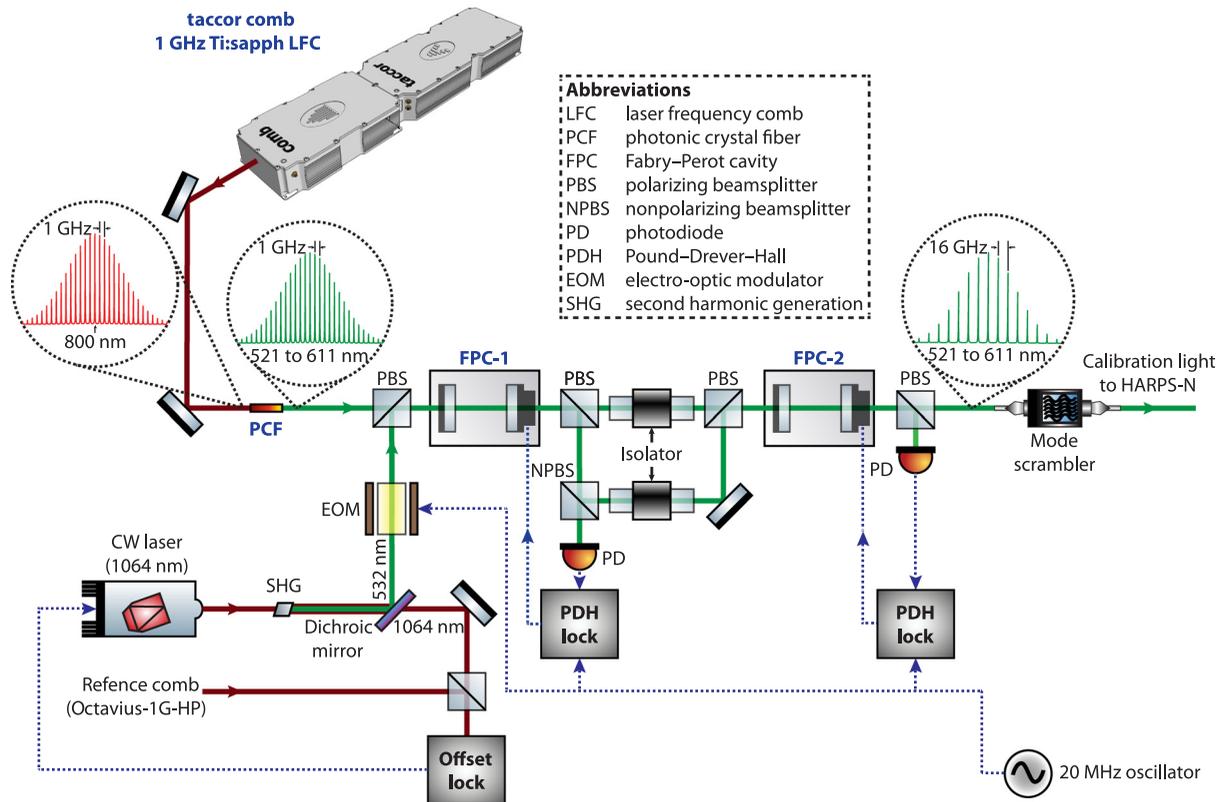
Fig. 1 Astro-comb block diagram showing a turn-key LFC that generates 1-GHz-spaced comb teeth about a center wavelength of 800 nm, a commercial PCF that coherently shifts the light into the visible wavelength range, and custom-built FP cavities that suppress 15 out of every 16 lines to match the resolution of the astrophysical spectrograph to be calibrated. (Abbreviations defined in figure; see text for more details.)

Approximately 300 mW of the source light is coupled into a supercontinuum device (NKT Photonics FemtoWHITE 800) to spectrally broaden the 1-GHz repetition rate comb. This 12-cm-long aluminum-body device contains a photonic crystal fiber (PCF) with a 1.8-μm core diameter and a 750-nm zero dispersion wavelength. The device also features hole-collapsed, sealed fiber ends that are mounted in quartz ferrules. The output wavelengths relevant to calibrating the HARPS-N spectrograph are in the ~500- to 600-nm range, but there is also a significant amount of light produced at longer wavelengths, up into the near-infrared region. This light is then filtered by two 16-GHz free spectral range FP cavities in series, achieving >40 dB suppression of undesired comb teeth.[5] The broadband cavities, which are based on zero group delay dispersion mirror pairs,[14] are optimized for operation between 500 and 650 nm. The cavity lengths are stabilized to a frequency-doubled 1064-nm CW single-frequency laser (JDSU NPRO 126N-1064-500) using a Pound–Drever–Hall scheme[15] in transmission. As the cavities have residual dispersion, the frequency of the CW laser was empirically tuned to maximize the bandwidth transmitted by the cavities. This laser, in turn, is offset locked by heterodyning some of the 1064-nm light with a nearby tooth of an existing Ti:sapphire LFC (Menlo Systems Octavius-1G-HP), which is also referenced to the same GPS-disciplined signal sources as the taccor comb. We would like to stress that, in the permanent setup, the reference laser will be offset locked directly to the taccor comb by heterodyning some of the frequency-doubled reference laser light at 532 nm with a nearby tooth of the PCF-broadened light from the taccor comb. Due to the limited time available for this demonstration, however, we locked the reference laser to the existing Octavius comb as in Ref. 5.

The spectrally broadened and filtered astro-comb light is coupled into a multimode fiber and sent through a mode scrambler[5] to eliminate dynamic modal noise. The light is then sent via multimode fiber to HARPS-N,[13] which is a high-resolution ($R = 115{,}000$) cross-dispersed echelle spectrograph with spectral coverage from 380 to 690 nm. HARPS-N achieves approximately few m/s RV stability prior to calibration by careful design, operation in vacuum, and temperature stabilization on the millikelvin level. Sub-m/s RV precision depends crucially on wavelength calibration, as well as simultaneous monitoring of potential calibration drifts while science exposures are performed. To this end, two input channels to HARPS-N are present: star light is injected into the "science channel" and calibration light into the "reference channel." In the present work, we study the performance of the astro-comb by injecting its light into one or both channels of the HARPS-N spectrograph.

3 Astro-Comb Characterization

Figure 2 shows the broad spectrum of the astro-comb, as measured on the HARPS-N spectrograph. The −20-dB points of the spectrum lie at 521 and 611 nm. On a finer scale, individual comb spectral lines spaced by about 16 GHz are visible. The contrast of astro-comb peaks (peak height divided by background level) on HARPS-N is ~100. We believe this is due to long tails in the HARPS-N instrument profile as the contrast
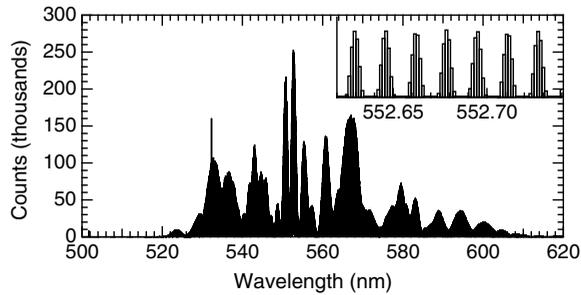
Fig. 2 Astro-comb spectrum measured with HARPS-N spectrograph. The strong peak at 532 nm is the CW reference laser used to stabilize the filter cavity lengths. Inset: at higher spectral resolutions, individual comb teeth (spectral lines) are observed.

of the Octavius LFC-based astro-comb, observed with HARPS-N, is similar while its contrast on a high-resolution Fourier transform spectrometer is >10,000.[5] The strong modulation in the envelope of the spectrum is a result of the nonlinear processes in the supercontinuum device used for spectral broadening. Improved spectral uniformity and even extending spectral coverage can be addressed by designing an optimized PCF for this LFC, and such efforts are currently underway. Alternatively, if the minimum number of counts in the present spectrum is satisfactory for calibration purposes, one could improve spectral uniformity by simply employing a lossy spectral flattening scheme with a spatial light modulator.[16]

Ultimately, the bandwidth of our astro-comb is limited by the residual dispersion of filtering FP cavities.[17] Extending cavity mirror spectral coverage is currently under investigation. An alternative approach that has been successfully demonstrated[7–9,12] is to filter a narrowband comb with a series of narrowband high-finesse cavities and then perform the spectral broadening with a nonlinear fiber. This approach extends the bandwidth of the comb at the expense of system complexity, including added demands on FP cavity performance.

We operated the astro-comb for several days, investigating its performance and stability. To collect information about frequency stability, we injected astro-comb light into both channels of the HARPS-N spectrograph and monitored the deviation of their difference as a function of averaging time as shown in Fig. 3. We consistently achieved RV sensitivity of nearly 1 cm/s at one half hour with no signs of spectrograph drift. Moreover, the two-sample deviation is consistent with the shot noise limit
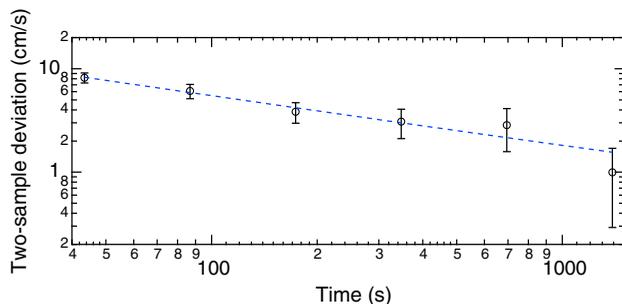

Fig. 3 Two-sample deviation of the measured frequency stability (in RV units) of the astro-comb versus averaging time. The black circles are the measured stability, and the dashed line is a fit consistent with the shot noise floor. The overall duration of the measurements was ∼1 h.
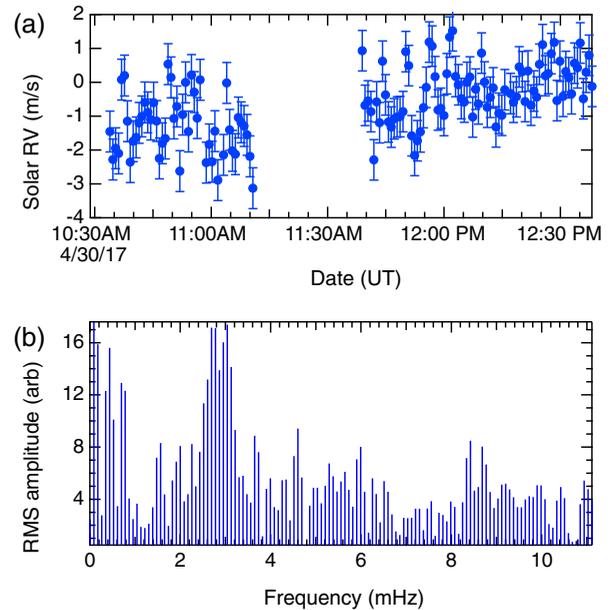

Fig. 4 (a) Comb-referenced solar RV observations and (b) power spectrum of the data.

up to this point. This wavelength calibration is more than sufficient for RV detection of an Earth-analog exoplanet (∼9 cm/s RV modulation).

4 Comb-Referenced Solar Spectra

As an example of an astronomical application, we performed solar spectral observations with HARPS-N referenced to the astro-comb. Using an automated compact solar telescope located at the TNG facility,[18] we collect light from the full disk of the Sun and feed an integrating sphere to discard spatial information. This light is then injected into the science channel of the HARPS-N spectrograph, with the astro-comb light simultaneously injected into the reference channel. We took 20-s exposures for several hours, with a break due to clouds. In these short-term measurements, the astro-comb primarily provides a simultaneous reference as the RV is only measured relative to the initial reference exposures for a few hours. We also derive a wavelength solution from the astro-comb spectrum injected in the science channel. Figure 4(a) shows the difference between the observed RVs (calculated using a cross-correlation technique with an empirical template and averaged across the orders of HARPS-N with significant astro-comb light) and the expected RVs from the JPL "Horizons" ephemeris. The power spectrum of these differences [Fig. 4(b)] prominently shows the 5-min (3 mHz) p-mode solar acoustic oscillations. However, there is also significant low-frequency noise present that is likely associated with granulation effects in the Sun.[19]

5 Studies of Intrapixel Sensitivity Variations of the Spectrograph Detector

A source of systematic error in RV measurements with an astrophysical spectrograph is nonuniformity in the detector. One example is intrapixel sensitivity variations[20–22] in the charge-coupled device (CCD). To study this effect, we took a sequence of exposures while shifting the astro-comb lines across half a pixel. Specifically, we shift the comb repetition rate f_r since even a small change in f_r gets magnified by the mode number n

through the relation defining the frequency of the n'th line, $f_n = f_0 + nf_r$. For example, a step of 3.2 kHz in the repetition rate amounts to moving a comb tooth across an entire pixel ($\sim$1.6 GHz). Note that we continue to take $f_r = 1.000010870$ GHz to remain consistent with our discussion of the source comb; however, only every 16th line appears on the spectrograph.

To track the shifting astro-comb teeth as the repetition rate is changed, we inject comb light into the science channel of the spectrograph and light from a passively stabilized FP cavity illuminated by broadband white light (a laser-driven plasma source) into the reference channel as a fixed reference. Using a standard cross-correlation analysis, we calculate the mean shift in all the lines relative to the FP spectrum, assuming that the drift of the FP cavity is negligible during the entire measurement. Figure 5 shows the results of this analysis, a linear shift due to a change in repetition rate of the astro-comb of 0.298(2) m/s/Hz, implying $n \approx 523,000$, which is a good estimate for the mean value of n in $f_n = f_0 + nf_r$. The upper panel of Fig. 5 shows the residuals from the fit with error bars representing the statistical uncertainty of $\approx$10 cm/s. We attribute additional scatter in the residuals to systematic errors induced by changes in astro-comb power versus wavelength as the repetition rate and reference laser are retuned. These variations do not affect the results reported below and in Fig. 6 as the analysis is henceforth done for each astro-comb peak independently.

To search for intrapixel sensitivity variations, we fit all 365 astro-comb spectral peaks in a single echelle order at $\sim$570 nm (near the center of the astro-comb band) on the HARPS-N spectrograph to Gaussian profiles. As seen in the inset of Fig. 2, typical peaks have 3 to 4 pixel full width at half maximum. We model the mean intrapixel sensitivity variation of all the pixels in this order as follows: let P_i^j be the pixel value of the fitted peak position of the i'th peak in the j'th exposure, where i runs from 0 to 364, while j runs from 0 to 15. $\mathrm{frac}(P_i^j) = P_i^j - \lfloor P_i^j \rfloor$ gives the fractional part of the peak position. Note that a value of 0 or 1 corresponds to pixel center while a value of 0.5 corresponds to a pixel boundary. We then compute a residual R_i^j of the shift of the observed peak i in exposure j relative to the initial exposure compared with the expectation from shifting the repetition rate f_r as
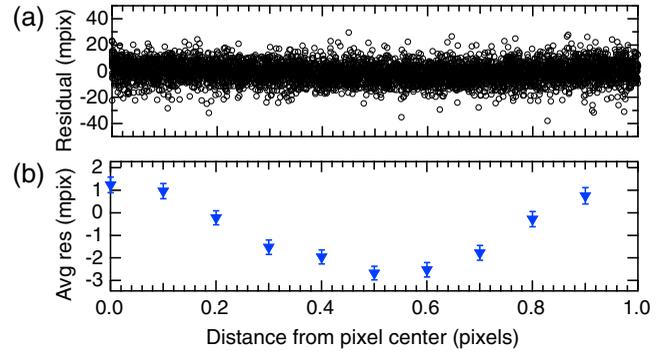
Fig. 6 (a) Difference between expected and actual astro-comb peak position, as a function of peak position inside a pixel. The uncertainty for each point is consistent with the $\sim$10 millipixel scatter observed. (b) Data shown in panel (a) averaged into bins with 0.1 pixel width.

$$R_i^j = \left(P_i^j - P_i^0\right) - \Lambda\left(\Delta f_r, P_i^j\right) - \Delta_{\mathrm{FP}}^{j,0}\left(P_i^j\right), \quad (1)$$

where $\Lambda(\Delta f_r, P_i^j)$ is the expected shift in pixels of the comb peak at P_i^j due to the change in repetition rate Δf_r. The additional correction $\Delta_{\mathrm{FP}}^{j,0}(P_i^j)$ is the local shift (i.e., interpolated to P_i^j) of the FP simultaneous reference between the initial exposure and the j'th exposure. This parameter is extracted from a wavelength solution derived from the FP spectrum. Figure 6(a) shows R_i^j as a function of $\mathrm{frac}(P_i^j)$ for all i, j. Averaging the data shown in Fig. 6(a) into bins of 0.1 pixels leaves a systematic residual at roughly the 5 millipixel level, as shown in Fig. 6(b), which corresponds to $\sim$5 m/s in RV units. Averaging over all the observed lines in all the orders with different fractional CCD pixel values should reduce this systematic error below the 1-m/s level. Key challenges for future work are to determine such intrapixel sensitivity variations across the full HARPS-N spectrum and to mitigate its effects on astronomical RV observations.

6 Conclusions

In summary, we demonstrated an astro-comb employing a turn-key mode-locked Ti:sapphire laser, a commercially available supercontinuum device, and existing FP mode filters. This astro-comb readily achieves RV stability of $\sim$1 cm/s within one half hour averaging time. It is also successfully used as a reference for measurements of solar spectra and in the study of intrapixel sensitivity variations in the CCD detector of the HARPS-N spectrograph. We are currently working to extend the spectral coverage, improve the intensity uniformity, and fully automate the system (e.g., fiber alignment and filter cavity locks).
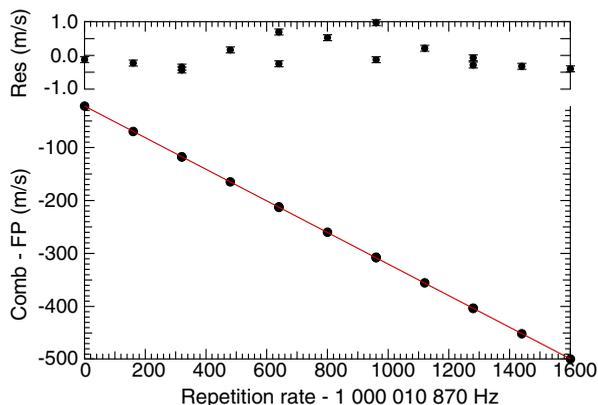
Fig. 5 Measured mean difference in astro-comb spectral lines relative to a white-light FP spectrum (black circles) as a function of comb repetition rate, with a linear fit (red line) and residuals (top trace). The error bars of the residuals plot are the statistical uncertainty of $\approx$10 cm/s (see text).

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Biographies for the authors are not available.