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Astro-comb calibrator using a turn-key laser frequency comb

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Abstract: Using a turn-key Ti:sapphire femtosecond laser frequency comb and an off-the-shelf supercontinuum device, we report the generation of a 16 GHz frequency comb spanning an 80 nm band about a center wavelength of 570 nm. The light from this turn-key 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 turn-key astro-comb to perform calibration of solar spectra obtained with a compact telescope, and to study intrapixel sensitivity variations on the CCD of the spectrograph.

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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 $\sim$ 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 equidistant frequency markers with very precisely known absolute frequencies [2–4].

Although LFCs for the calibration of astrophysical spectrographs ("astro-combs") have been successfully demonstrated [5,6], 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 often also requires significant laser expertise. It is therefore imperative to simplify the use of astro-combs [6,7] to make them viable for the next generation of high-precision RV measurements.

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

2. Experimental setup

The turn-key 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 [8]. Fig. 1 shows a simplified 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 $\sim$ 30 fs pulses at a repetition rate f_r stabilized to a 1.000010870 GHz signal sourced from a RF synthesizer. The LFC carrier-envelope offset 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 carrier-envelope offset frequency to 261.5 MHz. Both synthesizers are referenced to a GPS-disciplined 10 MHz Rb clock.

Approximately 300 mW of the LFC light is coupled into a supercontinuum device (NKT Photonics FemtoWHITE 800) to perform spectral broadening, with output wavelengths relevant to calibrating the HARPS-N spectrograph ranging from 530 nm to 610 nm, and also with significant power into the near IR. The supercontinuum device preserves the $\sim$ 1 GHz repetition rate of the LFC. This light is then filtered by two 16 GHz free-spectral-range (FSR) Fabry-Perot 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 [9], are optimized for operation between 500-650 nm. The cavity lengths are stabilized to a frequency-doubled 1064 nm

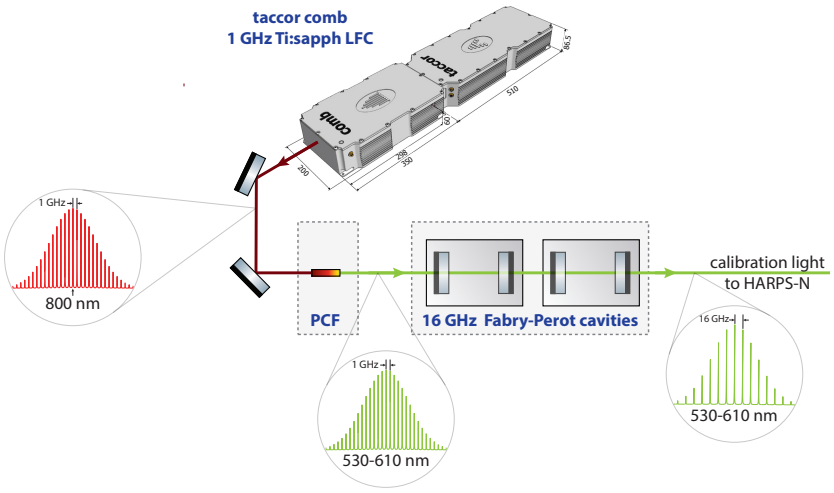


Fig. 1. Simplified astro-comb block diagram showing a turn-key laser frequency comb (LFC, dimensions in mm) that generates 1 GHz-spaced comb teeth about a center wavelength of 800 nm, a commercial photonic crystal fiber (PCF) that coherently shifts the light into the visible wavelength range, and custom-built Fabry-Perot (FP) filter cavities that suppress 15 out of every 16 lines so as to match the resolution of the astrophysical spectrograph to be calibrated.

CW single-frequency laser (JDSU NPRO 126N-1064-500) using a standard Pound-Drever-Hall technique. As the cavities have residual dispersion, the offset 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). Note that a second LFC is not essential to the present scheme: it was used purely for convenience as the hardware already existed for offset locking. The second LFC was referenced to the same GPS-disciplined signal sources as the Laser Quantum LFC used for astro-comb light generation.

The spectrally broadened and filtered astro-comb light is coupled into a multimode fiber and sent through a dynamic mode scrambler [5] to eliminate speckle. The light is then sent via multimode fiber to HARPS-N [8], which is a high resolution (R = 115000) cross-dispersed echelle spectrograph with spectral coverage from 380 nm to 690 nm. HARPS-N achieves ~ few m/s RV stability prior to calibration by careful design, operation in vacuum, and temperature stabilization on the millikelvin level. Crucial to achieving sub-m/s RV observations is 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: during standard operation star light is injected into one channel and calibration light into the other. In the present work, we study the performance of the turn-key astro-comb by injecting its light into one or both channels of the HARPS-N spectrograph.

3. Astro-comb characterization

Fig. 2 shows the broad spectrum of the turn-key astro-comb, spanning ~ 530-610 nm, as measured on the HARPS-N spectrograph. On a finer scale, individual comb spectral lines spaced by about 16 GHz are visible. 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

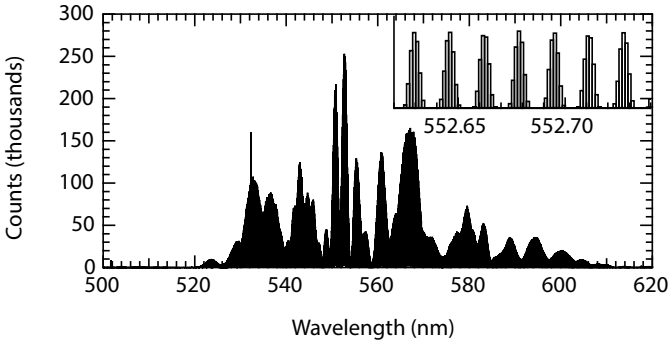


Fig. 2. Turn-key astro-comb spectrum measured with HARPS-N spectrograph. The strong peak at 532 nm is the CW reference laser used to stabilize the filter cavity lengths. (Inset) At higher spectral resolution, individual comb teeth (spectral lines) are observed.

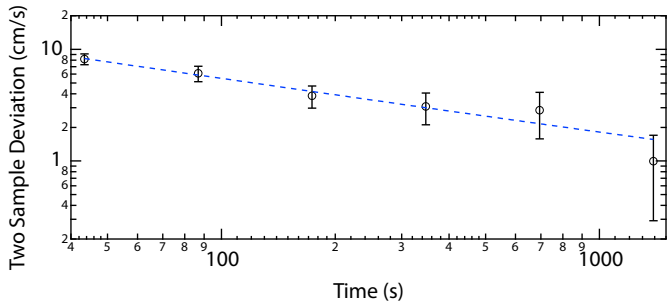


Fig. 3. Two-sample deviation of the measured frequency stability (in radial velocity units) of the turn-key astro-comb vs. averaging time. Black circles are measured stability and dashed line is a fit consistent with the photon (shot) noise floor.

photonic crystal fiber for this LFC, with such efforts 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 [10].

We operated the turn-key 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. This wavelength calibration is more than sufficient for RV detection of an Earth-analog exoplanet ($\sim$ 9 cm/s RV modulation).

4. Comb-calibrated solar spectra

As an example astronomical application, we performed solar spectral observations with HARPS-N calibrated by the turn-key astro-comb. Using an automated compact solar telescope located at the TNG facility [11], 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 calibration channel. We took 20 second exposures for several hours, with a break due to clouds. Fig. 4a shows the difference between the observed RVs and the expected RVs from the JPL *Horizons* ephemeris.

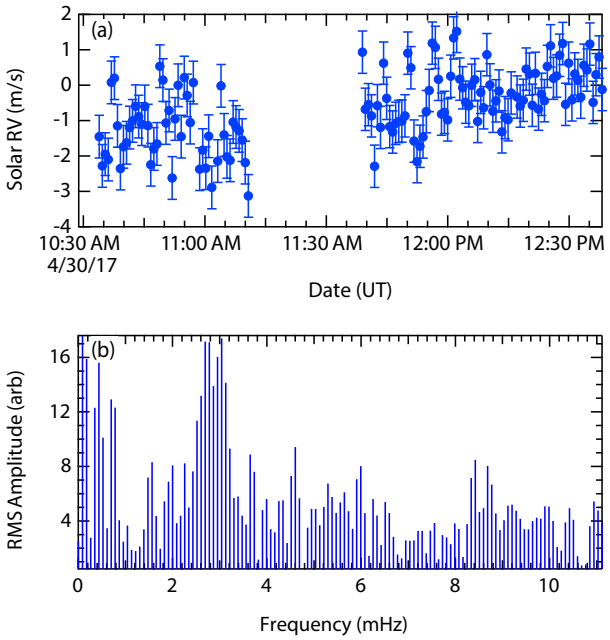


Fig. 4. (a) Comb-calibrated solar RV observations. (b) Power spectrum of the data.

The power spectrum of these differences (Fig. 4b) prominently shows the 5-minute (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 [12].

5. Studies of intrapixel sensitivity variations of the spectrograph CCD

A source of systematic error in RV measurements with an astrophysical spectrograph is non-uniformity in the detector. One example is intrapixel sensitivity variations [1, 13–15] in the CCD. To study this effect, we took a sequence of exposures while shifting the turn-key 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).

To track the shifting teeth, we inject astro-comb light into the science channel of the spectrograph, while we inject into the calibration channel light from a passively stabilized Fabry-Perot (FP) cavity illuminated by broadband white light (a laser-driven plasma source). Using a standard cross-correlation analysis, we calculate the mean shift in all the lines relative to the FP spectrum, assuming that the FP's drift is negligible during an entire measurement. Fig. 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 $n = 523,000$ which is a good estimate for n in $f_n = f_0 + nf_r$.

To search for intrapixel sensitivity variations, we fit all 365 astro-comb spectral peaks in order 50 of the HARPS-N spectrograph (a bright central order near 570 nm) to Gaussian profiles. As seen in the inset of Fig. 2, typical linewidths are a few pixels, ranging from $\sim 1.5 - 2.5$ pixels. 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. frac $\left(P_i^j\right) = P_i^j - \left\lfloor P_i^j \right\rfloor$ 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

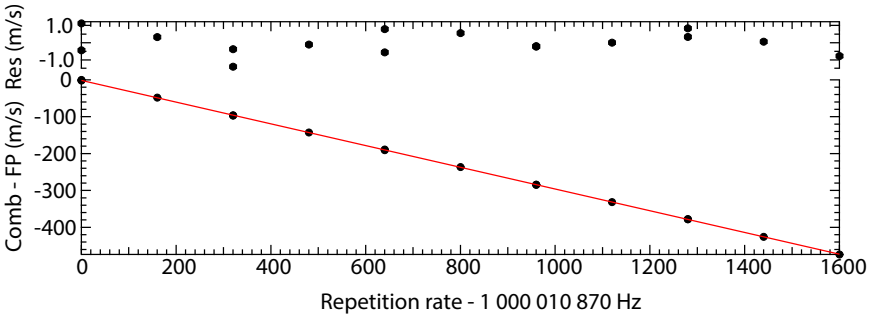


Fig. 5. Measured mean difference in turn-key astro-comb spectral lines relative to a white light FP spectrum (black circles) as a function of comb repetition rate, with a linear fit (red line), and residuals shown at the top of the figure.

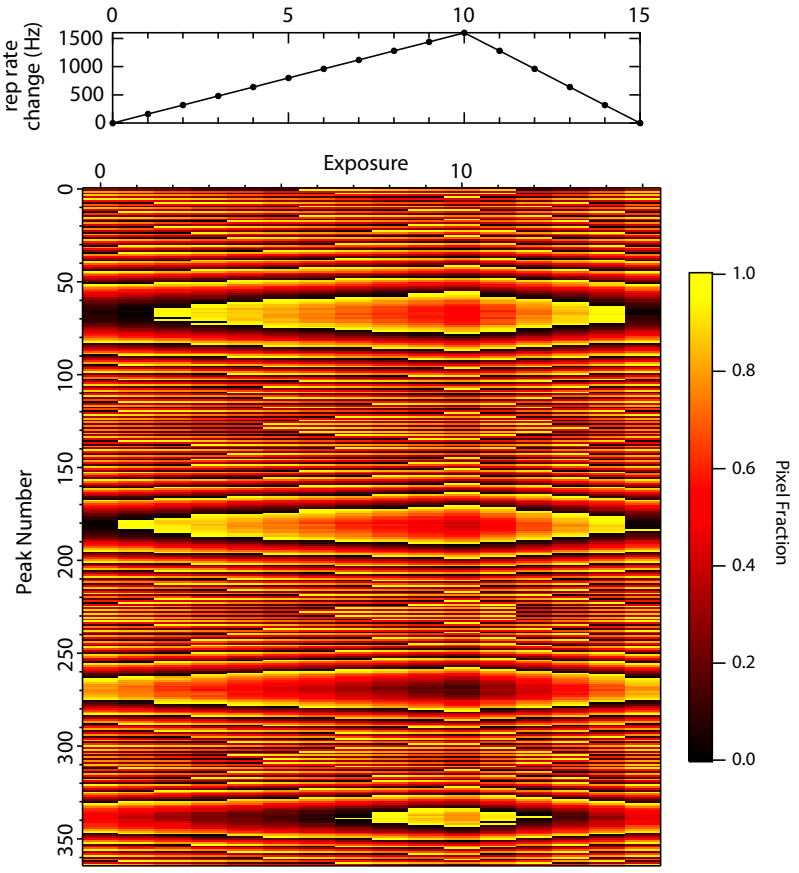


Fig. 6. Fractional CCD pixel values for 365 astro-comb spectral peaks in order 50 of the HARPS-N spectrograph. 16 consecutive exposures are shown. Color scale goes from black (0=pixel center) to yellow (1=neighboring pixel center). (Upper panel) In the first two-thirds of the exposures, the comb repetition rate ramps upward at 160 Hz per step; and in the last third it ramps downward at 320 Hz per step. In so doing, comb spectral teeth are swept up and back down a distance of half a pixel.

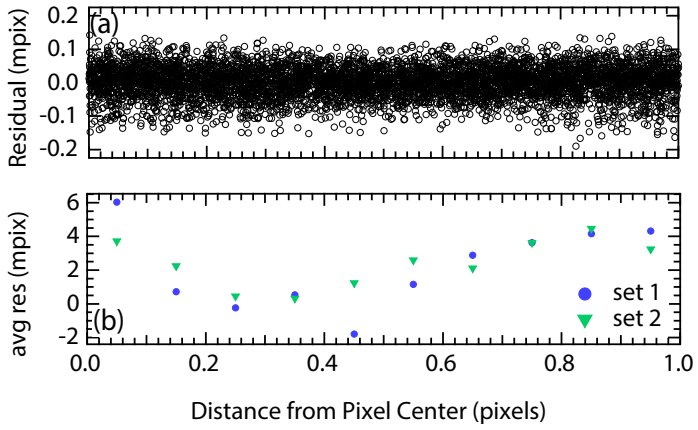


Fig. 7. (a) Difference between expected and actual astro-comb peak position, as a function of peak position inside a pixel, for the data shown in Fig. 6. (b) Data shown in panel (a) averaged into bins with 0.1 pixel width. Set 1 and set 2 are two separate iterations of the same experiment.

corresponds to a pixel boundary. Fig. 6 shows frac $\left(P_i^j\right)$ for each pair i, j. We then compute a residual

$$R_i^j = \left(P_i^j - P_i^0\right) - \Delta_{\rm xcor}^j \tag{1}$$

where $\Delta_{\rm xcor}^j$ is the mean shift for the $j^{\rm th}$ exposure derived from the cross-correlation analysis described above. Fig. 7a shows R_i^j as a function of frac $\left(P_i^j\right)$, for all i, j. Averaging the data shown in Fig. 7a into bins of 0.1 pixels leaves a systematic residual at roughly the 5 millipixel level, as shown in Fig. 7b, 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 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:sapph laser, a commercially available supercontinuum device, and existing Fabry-Perot mode filters. This turn-key astro-comb readily achieves RV stability of $\sim$ 1 cm/s within one half hour averaging time. It is also successfully used in the calibration 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 turn-key astro-comb.

7. Acknowledgements

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