A green astro-comb for Earth-like exoplanet searches

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Abstract: Our astro-comb, providing >7000 lines spaced by 16 GHz from 500-620 nm, has been deployed at TNG telescope as a wavelength calibrator for HARPS-N spectrograph. It provides sub-10 cm/s calibration accuracy required for *exo-Earth* searches.

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1. Why green astro-combs?

Searches for Earth-like extra-solar planets (exoplanets) around Sun-like stars using periodic Doppler shift of stellar spectrum require better than 10 cm/s precision in the measurement of stellar radial velocity (RV) over years. Given the RV precision limits based on traditional wavelength calibrators such as thorium-argon emission lamps and molecular iodine absorption cells, the success of this method was confined to the discovery of short-period, massive exoplanets that induce >0.5 m/s RV wobbles on their parent stars [1]. It has been suggested recently that an order-of-magnitude improved RV precision may be achievable via improved spectrograph performance and better spectrograph calibration using an astro-comb [2-5], a wide line-spacing laser frequency comb optimized for astrophysical spectrograph wavelength calibration with accuracy and long-term stability better than 10 cm/s.

To transfer the accuracy of the astro-comb to the stellar RV measurements using an astrophysical spectrograph, an astro-comb must have 1) many spectral lines (typically >2000) resolvable by the spectrograph, 2) homogenous line intensity, and 3) broad wavelength coverage over the stellar spectral bands (typically 400-600 nm [6]). The green astro-comb we developed provides >7000 lines, equally spaced by 16 GHz, over a spectral bands of 500-620 nm (Fig. 1a). The power of most of the lines varies by <8 dB. With the astro-comb referenced to the Global Positioning System (GPS), the frequency of each astro-comb line as measured on an astrophysical spectrograph is accurate to <200 kHz (≈10 cm/s). The full astro-comb spectrum provides sufficient SNR to realize a calibration precision of <10 cm/s with a single exposure of the spectrograph (Fig. 1b). In January 2013, this green astro-comb has been deployed as a wavelength calibrator for the HARPS-N spectrograph at the Telescopio Nazionale Galileo (TNG) on La Palma in the Canary Islands, to perform RV observations of bright stars for *exo-Earth* detection.

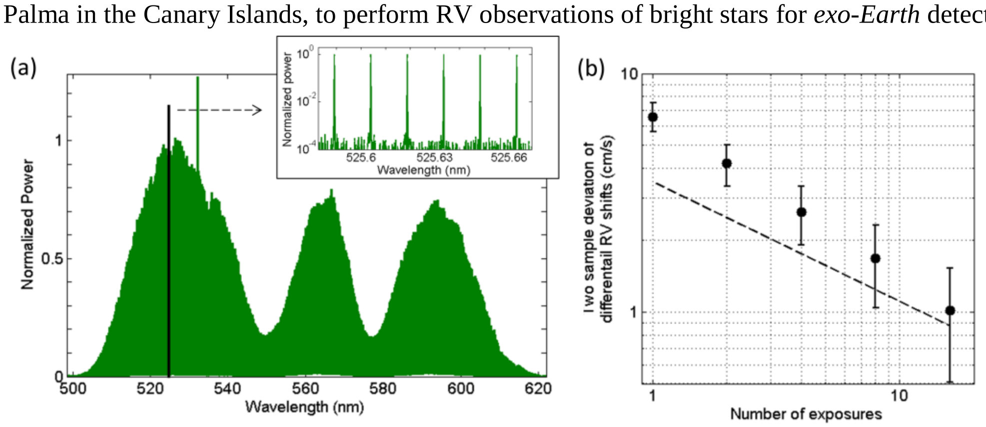

Fig. 1 (a) Spectrum of the green astro-comb with >7000 ultra-accurate lines equally spaced by 16 GHz from 500-620 nm. The broadband spectrum is measured by a commercial optical spectrum analyzer and the insert spectrum is measured with a high resolution Fourier transform spectrometer. (b) Two sample deviation of the measured spectrum shift between the two HARPS-N fibers when both are illuminated by green astro-comb light, with one sigma error bars. Dashed line is the expected photon shot noise limit.

2. Green Astro-comb setup

A block diagram of the green astro-comb is shown in Fig. 2. A commercial Ti:sapphire comb laser pumped by 7.6 W doubled YAG laser generates 700 mW of pulses with 1 GHz pulse repetition rate (f_r). The octave-spanning output spectrum, from 600 nm to 1.2 um (red comb), is broad enough for the stabilization of the carrier envelope offset frequency (f_0) of the comb via the f-2f self-referencing method directly. Both f_r and f_0 are stabilized to an atomic clock referenced to GPS. After proper dispersion compensation using chirped mirrors and thin fused silica plates, ~200 mW of the red comb is coupled into an 11-mm long tapered solid-core photonic crystal fiber (PCF) to generate 1 GHz comb lines from 500nm to 620 nm (green source comb) with homogeneous line power via a nonlinear process known as fiber-optic Cherenkov radiation [7]. To convert the 1 GHz green source comb to a 16 GHz green astro-comb, the green source comb is filtered by two Fabry-Perot cavities (FPCs) in series. The FPCs, which are composed of plan parallel complementary chirped mirror pairs [8], have constant finesse ~105 and small phase errors from 500 to 620 nm. The free spectral range of the FPCs is 16 f_r (~16 GHz) such that they pass every 16th source comb line and suppress the intermediate comb lines ("side modes") by more than 45 dB, which is more than enough to diminish the residual side-mode induced systematic shifts of the line centroids of the astro-comb lines as measured by HARPS-N to <10 cm/s [9].

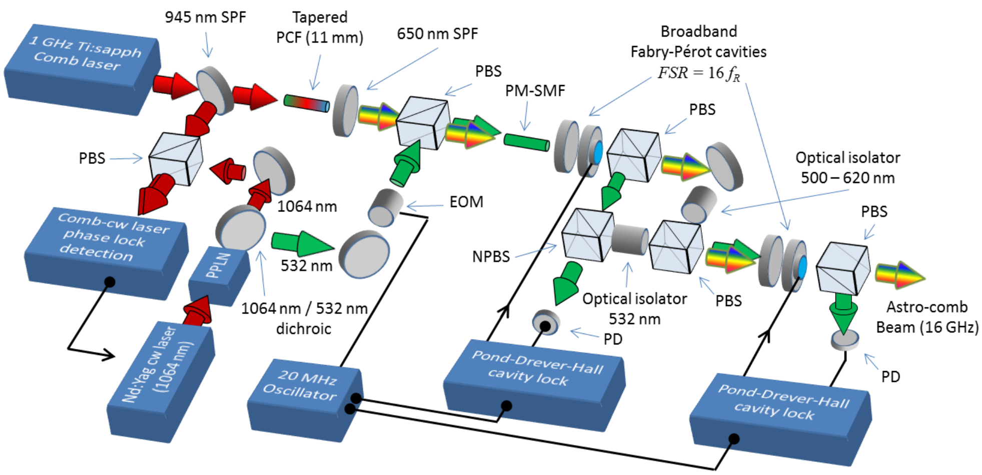

Fig. 2 Schematic of green astro-comb setup.

3. Calibration results on HARPS-N at TNG

In January 2013, the green astro-comb has been deployed at the TNG telescope as a wavelength calibrator for the HARPS-N spectrograph. HARPS-N is a fiber-fed echelle spectrograph, with 69 diffraction orders covering from 383 to 690 nm [10]. Light from two different sources, typically an astronomical object and a wavelength calibrator, is coupled into HARPS-N through two multimode fibers and measured simultaneously. Over a several month period, the system delivered reliable broadband green astro-comb operation in the environment of an astronomical telescope. We achieve a typical peak SNR of >350 for the green astro-comb as measured by HARPS-N and realize a single exposure RV calibration of HARPS-N with a one-sigma uncertainty ~6 cm/s (Fig. 1b).

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