Green astro-comb for HARPS-N

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ABSTRACT

We report the design, installation and testing of a broadband green astro-comb on the HARPS-N spectrograph at the TNG telescope. The astro-comb consists of over 7000 narrow lines ($<10^{-6}$ nm width) spaced by 16 GHz (0.02 nm at 550 nm) with wavelengths stabilized to the Global Positioning System (GPS) and with flat power from 500 to 620 nm. The narrow lines are used to calibrate the spectrograph and measure its line profile. The short term sensitivity of HARPS-N is measured to be less than 2 cm/s and the long-term drift of the spectrograph is approximately 10 cm/s/day. The astro-comb has been partially automated with future work planned to turn the astro-comb into a fully automated, push button instrument.

Keywords: spectroscopy, radial velocity, exoplanets, HARPS-N, calibration, Earth-like

1. INTRODUCTION

The search for Earth-like exoplanets is a key goal of observational exoplanet astronomy. Exoplanets, once very difficult to find, are now found routinely with over a thousand confirmed planets and several thousand more candidates. The radial velocity method for exoplanet detection looks for the reflex motion of the host star due to a companion planet orbiting the barycenter of the system. A time series of high-resolution spectra are taken with the goal of measuring an oscillatory Doppler shift. If such an oscillatory signal is detected, the source may be inferred as an exoplanet.

The High Accuracy Radial velocity Planet Search for the Northern hemisphere (HARPS-N) is a high resolution (R > 100,000) spectrograph located in the Canary Islands on the Telescopio Nazionale Galileo (TNG). HARPS-N is capable of detecting planets with a precision of about half a meter per second. Detecting Earth-like exoplanets around sun-like stars, however, requires a radial velocity sensitivity of below 9 cm/s. Laser frequency combs enable an improvement in calibration sensitivity of more than an order of magnitude bringing the sensitivity below that required for detection of Earth-like exoplanets.[1-10] Thus we have installed a broadband green astro-comb at the TNG that is capable of sub 10 cm/s calibration with the aim of improving calibration on HARPS-N to the necessary precision for Earth-like exoplanet detection.

The astro-comb consists of an infrared laser frequency comb (source comb), a wavelength shifter, and two filter cavities to match the repetition rate of the comb to the resolution of HARPS-N (See Fig. 1). The source comb is an octave spanning 1 GHz repetition rate Ti:Sapphire frequency comb with pulse duration of about 6 fs. The source comb feeds a custom tapered photonic crystal fiber (PCF), which coherently shifts the near-IR frequency comb light into the visible. The result is a broadband comb in the visible wavelength region. The comb is then sent through two Fabry-Pérot filter cavities with a free spectral range of approximately 16 GHz and matched to be an integer multiple of the source comb repetition rate. Thus the resulting astro-comb is a visible wavelength frequency comb with repetition rate set to about 2.5 resolution elements on HARPS-N.

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In the next section we will discuss the details of astro-comb components and the lab measurements to calibrate it. The third section contains a discussion on the measurements made to calibrate the HARPS-N spectrograph. In the fourth section we will show our ongoing work to automate the astro-comb, with the goal of developing a push button calibration instrument. Finally we will discuss future work and measurements to be taken.

2. ASTRO-COMB SETUP

Shown below in Figure 1 is a block diagram of the astro-comb setup, which consists of three main elements. The first is a 1 GHz, femtosecond titanium:sapphire frequency comb, or source comb. The source comb is fed to a nonlinear element for spectral shifting: a custom tapered photonic crystal fiber (PCF). Finally, the comb is filtered through two Fabry-Pérot cavities in order to match the repetition rate of the comb to the resolution of the HARPS-N spectrograph.[11, 12] Each element is discussed in detail below..

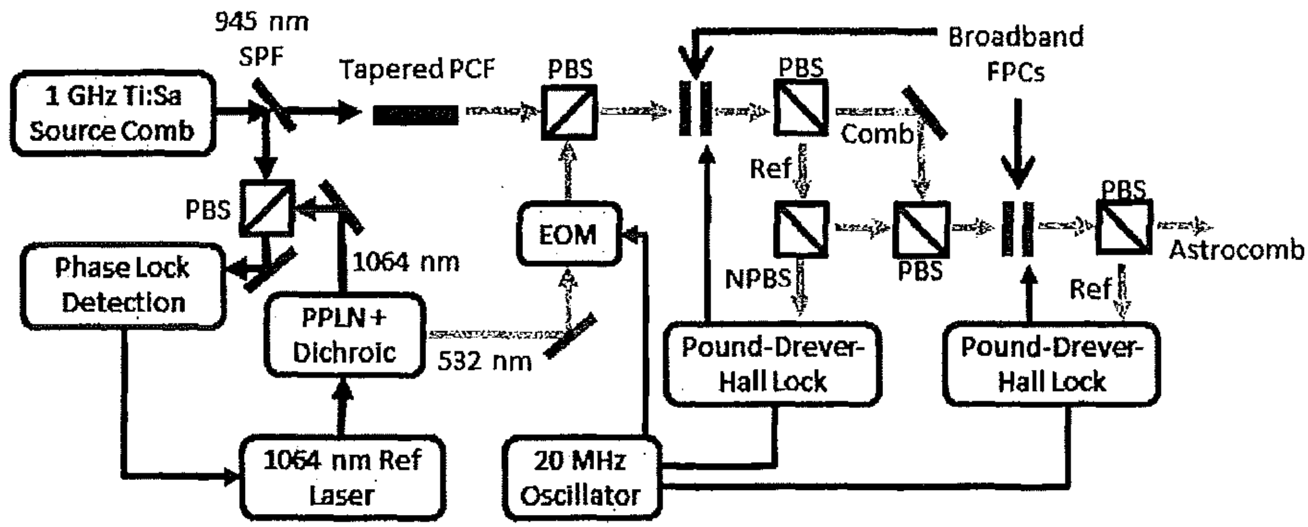

Figure 1. The astro-comb setup. A 1 GHz, femtosecond Ti:Sapphire (Ti:Sa) frequency comb (source comb) is split by a 945 nm short pass filter (SPF) into IR and visible components. The IR component is used to phase lock a 1064 Nd:YAG reference laser to the source comb. The visible component is coupled into a custom tapered PCF for spectral shifting to green wavelengths. The reference laser is frequency doubled with a periodically poled lithium niobate (PPLN) crystal, given 20 MHz sidebands via an electro-optical modulator (EOM), and combined with the comb light via a polarizing beam splitter (PBS). The comb and reference laser light is then coupled into two Fabry-Pérot cavities (FPC) that accept every 16th comb line and reject other lines. After each cavity the reference laser and the comb light are separated and the reference laser light is used to lock the cavities using the Pound-Drever-Hall method. (NPBS: non-polarizing beam splitter.)

2.1 Source comb

The source comb is an Idesta LLC Octavius octave-spanning frequency comb with 6 fs pulses, an average power of 800 mW, and a repetition rate of f_R = 1 GHz. The spectrum contains over 10^5 lines and peaks near 850 nm, with significant power from 600 nm to 1.2 microns. A frequency comb consists of spectral lines spaced evenly in the frequency domain with an offset frequency[13]: ($f_m = f_0 + m \times f_R$), where f_m is the frequency of the m^{th} comb line, f_0 and f_R are the offset frequency and repetition rate measured in the radiofrequency domain, and m is an integer labeling each comb line. Stabilizing both f_0 and f_R leads to stabilization of all the calibration lines. The repetition rate, f_R, is detected using a PIN diode and stabilized by adjusting the laser cavity length. The carrier envelope offset frequency, f_0, is measured with an avalanche photodiode using the f - $2f$ self-referencing method: comb lines near 1.2 microns are frequency doubled and beat against comb lines near 0.6 microns. The beat signal is then used to lock f_0 by adjusting the intensity of the pump laser, a frequency doubled 7.8 W Coherent Inc. Verdi 8, and thus the intra-cavity dispersion. Accuracy of the source comb lines below 1 cm/s is achieved by locking both f_0 and f_R to low noise RF synthesizers, which are in turn stabilized to Global Positioning System (GPS) time.

2.2 Tapered photonic crystal fiber

Spectra of solar type stars have a high density of lines and peak intensity in the green spectral region. Thus, RV measurements of such stars should be made in this spectral region. Therefore, we shift the red and near IR comb lines into the green using a nonlinear element: solid core tapered photonic crystal fiber (PCF) as shown in Fig. 2b. While the fiber core is fabricated from fused silica, it is highly nonlinear due to the short temporal pulse length from the laser (6 fs) and the small mode field diameter of the fiber core (core diameter ≈ 1.7 microns after tapering). Coupling a spectrally broad pulse into such a small core fiber is quite challenging as one must overcome spatial chirp of the pulse, high numerical aperture (NA) of the fiber, and chromatic aberration of the input coupling optics. To overcome these challenges, we taper NKT PM850 solid core PCF (core diameter ≈ 3.0 microns) adiabatically to 1.7 microns. The larger input end is 6 mm long, followed by a 2 mm transition region, and finally a 3 mm long shifting and output end (Fig. 2a). To further improve the input coupling, the comb is pre-chirped before the PCF to account for dispersion in the input coupling optics. This is accomplished with 3 double-chirped mirrors and a Semrock 945 nm shortpass filter upstream of the input coupling lens. The short temporal pulse is thus preserved and an input coupling of 30% is achieved, resulting in 200 mW of comb power downstream of the PCF.

We tapered the PCF using a Vytran GPX 3000 machine. The Vytran provides highly reproducible fibers, with tolerances less than 5 microns in length and 0.05 microns in core diameter. As a final step in the tapering process, the PCF is fire sealed: the two ends of the fiber are melted such that the air holes collapse to form a homogenous fiber facet. The necessity of the fire sealing stems from observed dust accumulation on the core of the fiber when the PCF is not fire sealed. This dust accumulation can happen on a timescale of days or even hours and severely disrupts the beam quality and spectral composition of the output comb. A fire sealed PCF also has the added benefit of reducing the NA of the fiber, which in turn reduces the effects of aberrations in the coupling optics. We have been using a fire sealed PCF for over a year both in the lab and at the TNG with no dust accumulation observed.

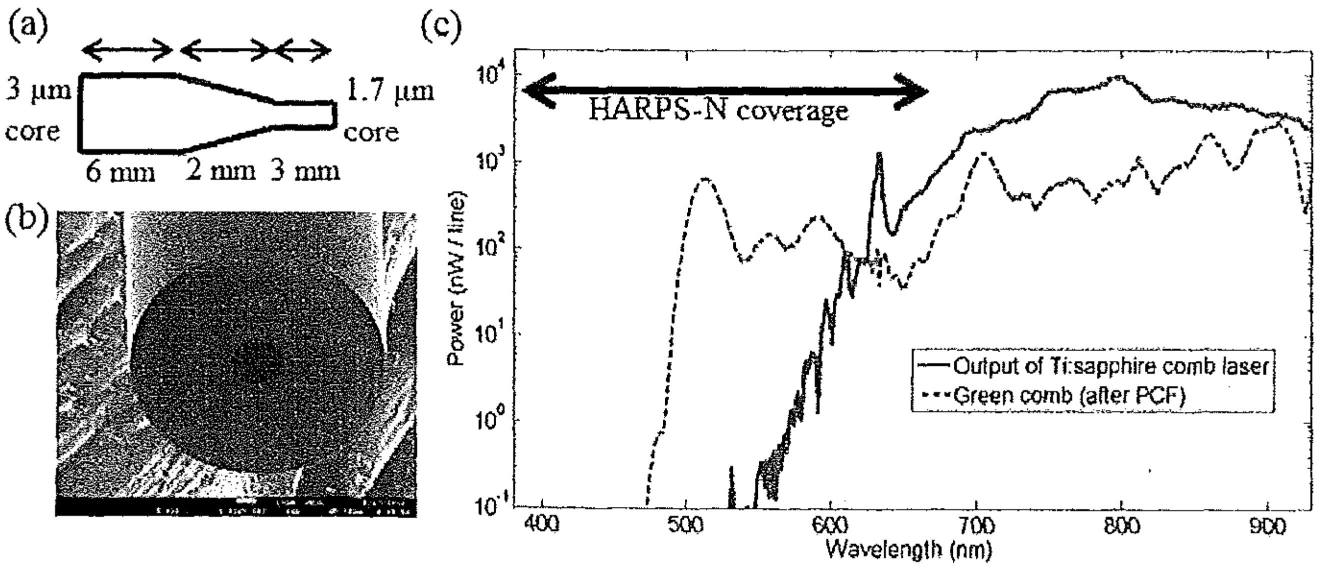

Figure 2. (a) Dimensions (not to scale) of the photonic crystal fiber (PCF). Input core size is 3 μm and the output core is tapered to 1.7 μm. The input region extends for 6 mm, the tapering region for 2 mm, and the small core region for 3 mm. (b) An SEM image of the PCF output before fire sealing (PCF outer diameter = 74 μm). After fire sealing, the air holes collapse and a homogenous output facet remains. (c) Input spectrum (solid red line) to the PCF from the Ti:Sapphire laser and PCF output (dashed green line) after the custom tapered PCF. The 1 GHz line spacing is unresolved by the optical spectrum analyzer.

Green comb lines are generated inside the PCF by a process referred to as fiber optic Cherenkov radiation (FOCR). We model the nonlinear propagation of comb pulses through the PCF using the nonlinear Shrödinger equation[14] and optimize the output spectrum for smoothness, flatness, and span of bandwidth by comparing observed spectra from tapered fibers with calculation and adjusting the tapering parameters. After several iterations of fabricating tapered fibers and comparing them to simulation an optimized PCF design was determined. A typical spectrum before and after the optimized PCF is shown in Figure 2c. The power in the green comb lines is about 100 nW per line and the spectrum is flat (less than 8 dB variation) from 500 to 620 nm. The spectrum may be changed by adjusting any of several parameters such as the spatial chirp, the input power, the PCF zero dispersion wavelength, and the dimensions of the PCF taper. With these parameters fixed, however, the spectrum is stable over many months and reproducible over individual PCFs.

2.3 Fabry-Pérot filter cavities

To calibrate HARPS-N, we must increase the spacing between comb lines from 1 GHz of the laser and the output of the PCF to a spacing that can be resolved on the spectrograph. Therefore, we filter the green comb using two plane-parallel Fabry-Pérot cavities (FPC) in series, each with a free spectral range (FSR) tuned to $16 \times f_R = 16$ GHz. This FSR is chosen to optimize spectral calibration, and corresponds to about 2.5 times the resolution of the spectrograph.[1]

We measure the resonance frequencies of the FPCs using a single wavelength "reference" laser and then stabilize the FPCs relative to the source comb. The reference laser is a low noise (sub 10 kHz jitter) Nd:YAG laser at 1064 nm which is frequency doubled using a periodically poled lithium niobate (PPLN) crystal. A dichroic is used to split the laser into its IR (1064 nm) and visible (532 nm) components and the IR component is then phase locked to a nearby comb line with a 269 MHz frequency offset. This offset frequency is chosen so as to optimize the bandwidth of the FPCs. The visible component is then given 20 MHz sidebands with an electro optical modulator (EOM) and injected along with light from the green comb into single mode fiber (SMF) so as to match the spatial profiles of the two sources, after which, light from both the reference laser and green comb is sent through the FPCs. An optical Faraday isolator between the two FPCs provides greater than 25 dB suppression of back scattered light into the first FPC. After each cavity, reference laser light is separated from comb light and used to measure the FPC frequencies, which are stabilized via the Pound-Drever-Hall method using a field programmable gate array (FPGA) controlling a PZT supporting one of the FPC mirrors. Comb light output from the second FPC is sufficiently filtered to be resolved on the spectrograph and provides accurate wavelength calibration to better than 10 cm/s.

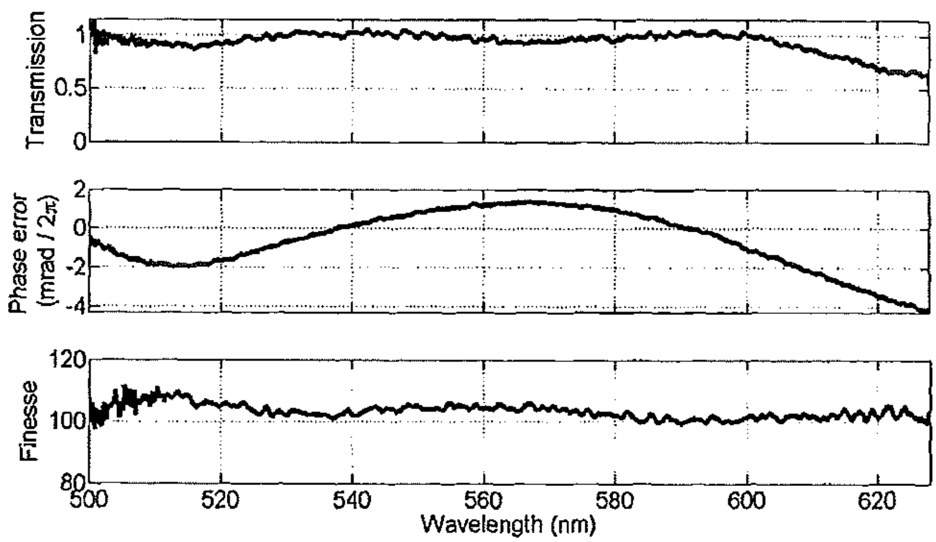

Figure 3. The (a) transmission, (b) phase error, and (c) finesse of the Fabry-Pérot filter cavities measured over the astro-comb bandwidth. The transmission is above 60% for all wavelengths from 500 to 620 nm. No evidence of unwanted etaloning is seen in the phase error and it is below 4 mrad over the entire bandwidth. The finesse of slightly above 100 is less than the theoretical finesse, presumably from mirror and alignment imperfections.

To obtain a large calibration band, the effective path length inside the FPCs must be constant across a large optical bandwidth. Therefore, the FPCs are constructed from complimentary chirped mirror (CCM) pairs[15]. CCMs are pairs of mirrors of opposite group delay dispersion (GDD) such that wavelengths that penetrate deeper in one mirror penetrate much shallower in the other. This provides a broad bandwidth for which light experiences the same phase delay. The resulting cavities have a phase error less than 13 mrad and constant finesse of 105 over the desired 120 nm bandwidth (Fig. 3). The cavity mirrors are also wedged by half a degree so as to suppress unwanted etaloning from mirror substrates.[5] In order to suppress low frequency noise, the FPCs are suspended above an 8" by 8" aluminum breadboard with a trampoline-style suspension. The aluminum breadboard is also temperature stabilized to better than 100 mK and held at 5 K above ambient temperature. The FPCs are enclosed in 1 cm thick particle board and metal foam to filter noise from DC to 2 kHz.

2.4 Coupling to HARPS-N

The input to HARPS-N for both the science and calibration channels is a multimode optical fiber with a core diameter ≈100 microns corresponding to a 1 arcsec aperture in the telescope focal plane. Interference inside the multimode fiber between the many optical paths available to the coherent comb light causes a speckle pattern at the re-imaged output of the multimode fiber, leading to a reduction in the signal-to-noise ratio (SNR) for astro-comb calibration. Because a typical HARPS-N exposure is of the order tens to hundreds of seconds, we minimize the speckle by shaking the fiber several times per second using an auxiliary multimode optical fiber attached to the arm of a hard drive and driven at 20 Hz with an amplitude of about 1 cm. This washes out the speckle pattern and produces a flat image of the fiber facet. The resulting astro-comb light is coupled into the HARPS-N front end for calibration. The calibration spectrum covers 500 to 620 nm with comb lines spaced 16 GHz apart (2.5 times the spectrograph resolution). A typical spectrum measured on the spectrograph CCD is shown in Figure 4.

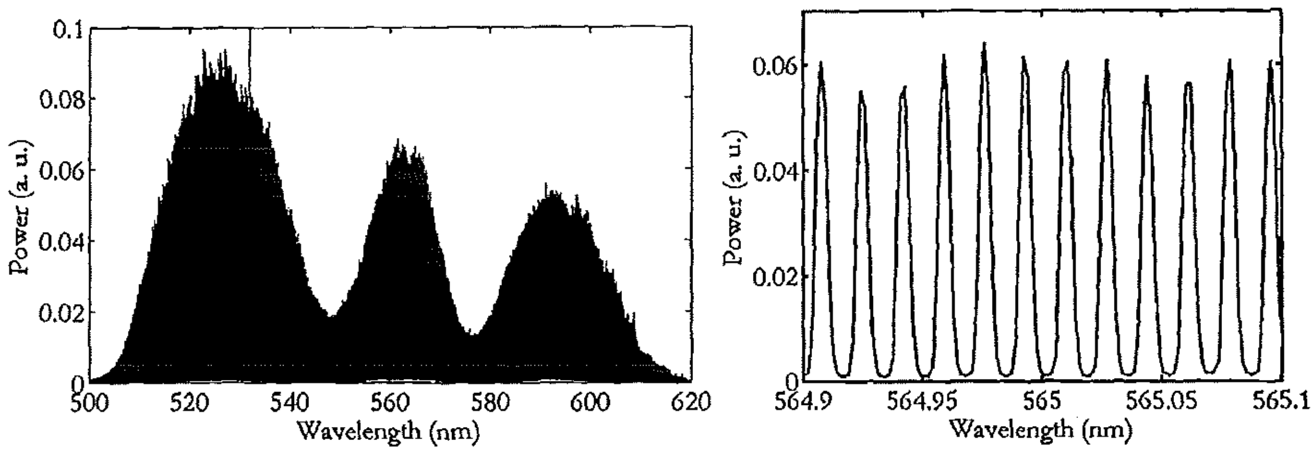

Figure 4. Astro-comb spectrum measured on HARPS-N. On the left is the full spectrum from 500 to 620 nm and is flat to within 8 dB. The spectrum contains over 7000 lines spaced by 16 GHz (0.02 nm at 550 nm). The right is a few calibrations lines from the same data set. As the astro-comb linewidth is below 1 MHz (less than 0.001 of the resolution of HARPS-N), the lineshape seen is the HARPS-N line profile.

3. PERFORMANCE ON HARPS-N

The astro-comb has been operating at the TNG with the HARPS-N spectrograph since January of 2013. A series of measurements have been taken on HARPS-N to study the short and long term stability of calibration, determine the instrument profile, and characterize the performance of the spectrograph. This section will highlight the details of these measurements.

3.1 Instrument profile of HARPS-N

Since the astro-comb produces over 7000 evenly spaced lines from 500 to 620 nm that have a linewidth less than 1 MHz, the comb serves as an excellent resource for measuring the line profile of the HARPS-N spectrograph. With a repetition rate of 16 GHz, the comb lines are spaced too closely to effectively study the wings of the line profile as the neighboring comb lines will overpower the wings. Thus, for a series of line profile studies, we adjusted the spacing of the Fabry-Pérot cavities to 28 GHz, allowing more detailed study of the wings of the line profile. We then measured the astro-comb spectrum with HARPS-N and fit a convolution of the fiber profile (a skewed half circle), optical aberrations (16 orders of Hermite-Gaussian modes), and the CCD pixel response (top hat function) to these spectra and extracted the line profile. The results indicate an instrument line profile consistent with the design of HARPS-N: a line profile varying slowly in width and shape across each order of the spectrograph. On the blue end of an order the PSF is narrower and skewed to the blue relative to pixel center and on the red end the PSF is broader and skewed to the red relative to the pixel center (Fig. 5). Note that upon completing these line profile measurements, we returned the FPC spacing to its nominal value for 16 GHz astro-comb line spacing.

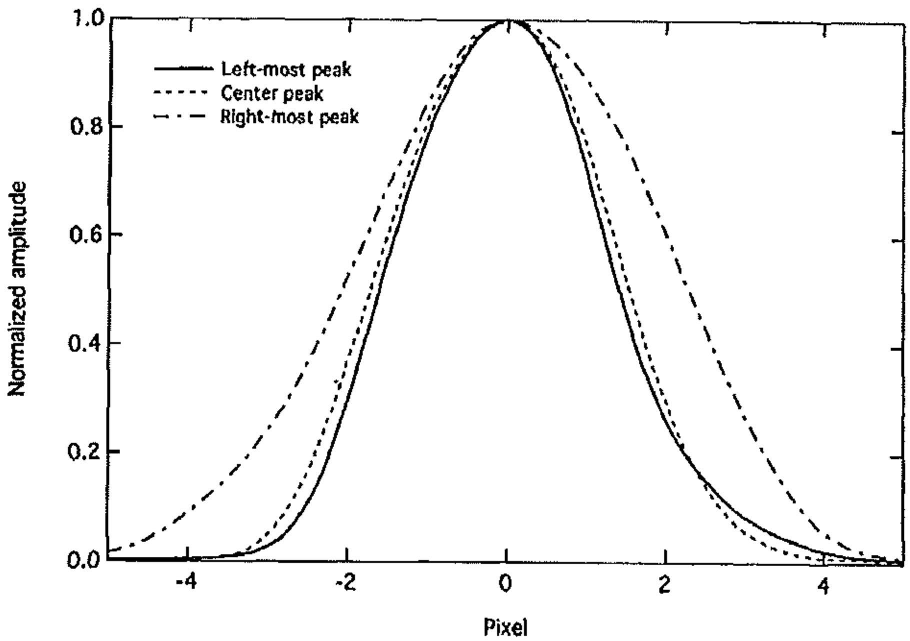

Figure 5. Measurement of the HARPS-N line profile using the astro-comb. The line profile is consistent with the design of the spectrograph, with the width and asymmetry varying slowly across each order. The black curve shows the line profile at the blue end of one order and is slightly skewed toward the blue. The green curve shows the profile at the red end and is much wider and skewed toward the red. The red curve shows the line profile in the middle of the order.

3.2 HARPS-N performance

In addition to line profile fluctuations across orders, we have also characterized pixel size variations due to CCD mask errors. When the spectrograph CCD electrodes are patterned, a 256 x 512 pixel mask is stepped across the CCD to form the larger 4096 x 4096 pixel CCD. Errors in positioning the mask at each step can lead to pixel size variations at the boundaries of the masks. These pixel size variations manifest themselves as variations in the response of uniform illumination of the CCD and discontinuities in the mapping of pixels to wavelength from calibration with the astro-comb. An LED was used to illuminate the spectrograph CCD to measure these pixel size variations (Fig. 6a). The mask error is then computed by binning in the cross dispersion direction (Fig. 6b). Fractional jumps in amplitude of 2×10^{-3} of the LED illumination can clearly be seen every 256 pixels (Fig. 6c). These results from the LED amplitude measurements can then be compared to residuals of wavelength solutions from the astro-comb (Fig. 6d), which show corresponding jumps at mask boundaries. The mask errors can be corrected but the data suggests additional pixel size variations of about 0.01 m/s/pixel.

3.3 Stability of calibration

The astro-comb has been used extensively to study the calibration of the HARPS-N spectrograph. During observing, stellar light from the telescope is coupled into the science channel and a calibration source, typically a thorium-argon emission lamp, is coupled into the calibration channel. Variations in the mapping of pixels to wavelength can then be obtained for each exposure by measuring shifts in the calibration channel of the known wavelengths of the calibration source. The offset between the two channels is obtained by measuring the calibration source in both channels before each observing night. We have performed the same measurements with the astro-comb to study the stability of HARPS-N under astro-comb calibration. We typically achieve a peak SNR of over 350 and a calibration uncertainty of about 2.5 m/s for each peak in a 10 second exposure. Residuals from fits to individual astro-comb calibration spectra are within 10% of photon shot-noise. However, our measurement-to-measurement repeatability when calibrating the difference between the science and calibration fibers is *only* 6 cm/s (Fig. 7a), 50% above expectations from photon shot noise, limited by short-term oscillations in the spectrograph calibration, which can be observed directly in rapid calibration measurements. Repeated measurements of the difference in wavelength calibration between both channels average out these fluctuations and show a standard deviation below 2 cm/s and consistent with residuals from fits to individual exposures after averaging several exposures. We have repeated these measurements in multiple visits to the TNG over the course of about a year and we observe a drift in the calibration of roughly 10 cm/s/day (Fig. 7b).

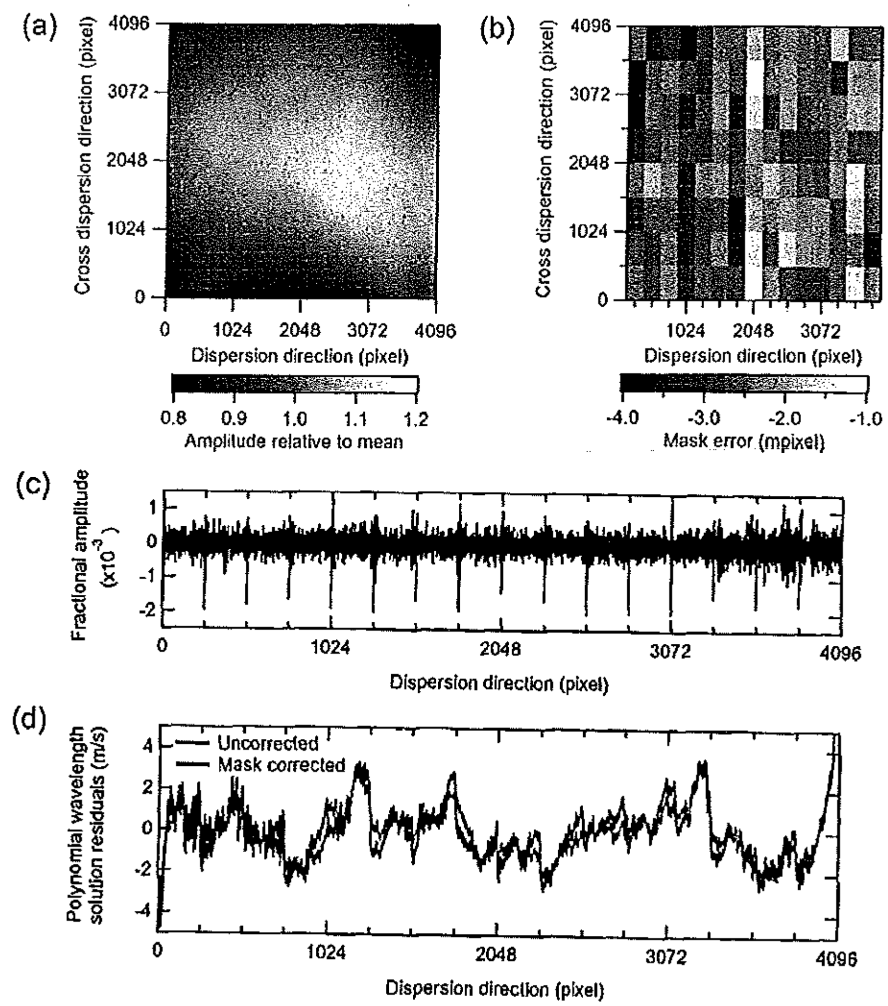

Figure 6. Characterization of pixel size inhomogeneity. (a) Normalized LED flat illuminating the entire CCD with +/- 20% illumination variation. (b) Estimated size of the CCD pixel mask stepping errors (*see text*) in the dispersion direction binned by mask size in the cross dispersion direction based on illumination variation in the LED flats. (c) Illumination variation in the LED flats averaged over one mask region in the cross dispersion direction and high-pass filtered to remove the slow variations seen in (a). Mask stepping errors are visible every 256 pixels. The effects of the high pass filter are taken into account when calculating the mask errors shown in (b). (d) Residual errors from a polynomial mapping between astro-comb wavelengths and pixel positions averaged over all astro-comb orders without and with taking into account the mask errors measured with the LED flats. This procedure shows excellent agreement between the illumination and wavelength measurements of the mask errors, but the wavelength solution indicates additional pixel size variations away from the mask boundaries, which show up as more gradual changes in the residuals. These changes of ~1 m/s over ~100 pixels in the wavelength solution residuals would lead to illumination variations approximately two orders of magnitude smaller than the mask errors shown in (c) and are thus not observable in the LED flats.

4. AUTOMATION

Currently, a laser expert must be present at the TNG to operate the astro-comb. Therefore, we have run the astro-comb for roughly 11 out of the past 70 weeks. To improve the uptime of the astro-comb, we are currently implementing automation of the system. Recent upgrades at the TNG include auto-alignment of the flat mirror Fabry-Pérot filter cavities (Fig. 8) and of the PCF wavelength shifting fiber. Between exposures, we scan the input coupling of the PCF and measure the output spectrum on a low-resolution optical spectrum analyzer and automatically optimize the astro-comb spectral bandwidth by adjusting steering of the source comb light into the PCF. This leads to push-button reproducibility of spectral coverage with the astro-comb. Similarly, the alignment of the Fabry-Pérot filter cavities are automatically aligned to optimize the finesse of the cavities. Work on automatic start-up and fine alignment of the titanium:sapphire laser continues in the laboratory.

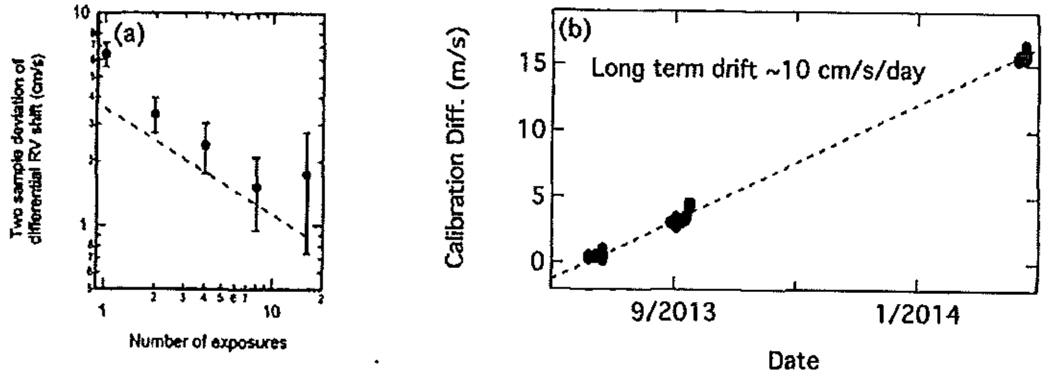

Figure 7. (a) Short-term calibration sensitivity of the astro-comb on HARPS-N reported using the two-sample deviation of the spectral shift between the science and calibration fibers when both are illuminated by astro-comb light, with one-sigma error bars. (Dashed line is the expected photon shot noise limit.). (b) Long term drift between science and calibration fiber as measured with the astro-comb. Differences between exposures are derived from cross-correlations with the sum of all exposures.

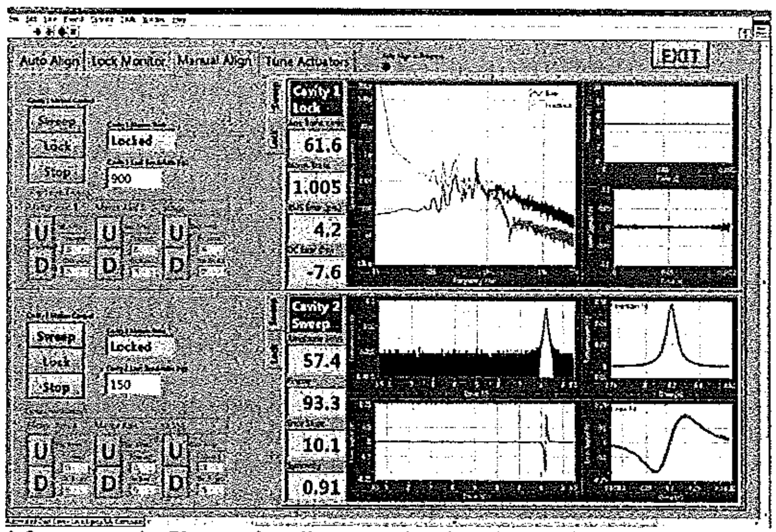

Figure 8. Control panel for automatic filter cavity alignment showing (lower plots) a single Fabry-Pérot cavity resonance measured with the reference laser and (upper plots) the noise spectrum of the reference laser transmitted through the locked cavity.

5. CONCLUSIONS AND FUTURE WORK

We have built and installed an astro-comb at the TNG telescope in the Canary Islands for calibration of the HARPS-N spectrograph. The astro-comb consists of three main elements: a 1 GHz, femtosecond, titanium:sapphire laser frequency comb, a nonlinear photonic crystal fiber (PCF) for generating comb light in the wavelength region of interest, and a pair of Fabry-Pérot filter cavities to convert the repetition rate to 16 GHz. The laser frequency comb is referenced to a GPS clock to provide stability of the calibration to better than 10 cm/s over decades. The photonic crystal fiber uses a process known as fiber optic Cherenkov radiation to broaden the IR comb into the visible producing a flat spectrum from 500 to 620 nm. The Fabry-Pérot filter cavities serve as a means of converting the 1 GHz repetition rate of the comb to 16 GHz by transmitting every 16th comb line and rejecting the 15 lines in between. Finally the resulting astro-comb is coupled into HARPS-N via a multimode fiber with a coherence destroying shaker. The result is broadband astro-comb with over 7000 lines for calibration that is capable of sub 10 cm/s stability.

The astro-comb was installed at the TNG in January 2013 and has been operated for roughly 11 out of 70 weeks since. The 1 MHz linewidth of the comb lines provides a delta function response on the HARPS-N CCD and thus has been used to measure the line profile of the instrument. The line profile measured agrees well with the design of the spectrograph, and we observe asymmetries in the line profile that vary slowly across each order on the CCD. We also use the comb – along with LED flats – to measure and correct for pixel size variations due to mask errors from the CCD fabrication process. We have also evaluated the short and long term stability of the spectrograph when calibrated by the astro-comb by coupling the comb into both the science and calibration channels of the spectrograph and measuring the offset in the CCD response. We find that on short time scales the differential radial velocity shift is below 2 cm/s and that over long time scales the calibration drifts by about 10 cm/s/day. We are currently implementing automation for the astro-comb at the TNG, with a goal of achieving push button operation in the near future. Fine alignment of the photonic crystal fiber and coupling into the Fabry-Pérot cavities have been successfully automated. Automated startup of the frequency comb is currently under investigation. We continue to continue to monitor the calibration and performance of the HARPS-N spectrograph.

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