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Operation of a broadband visible-wavelength astro-comb with a high-resolution astrophysical spectrograph: supplementary material

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This document provides supplementary information to "Operation of a broadband visible-wavelength astro-comb with a high-resolution astrophysical spectrograph," http://dx.doi.org/10.1364/optica.2.000250. Additional details are given of the measurements we have made to confirm the <10 cm/s RV calibration accuracy and stability provided by the green astro-comb, as claimed in the main article.

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S.1 Characterization of Fabry-Perot spectral filter

A key requirement for wavelength calibration of an astrophysical spectrograph is broadband wavelength coverage, which in the green astro-comb is primarily limited by the dispersion of the mirrors in the Fabry-Perot cavities (FPCs) that filter out the undesired comb lines. In addition to minimal dispersion to allow the desired comb lines to be transmitted, the FPCs must also have sufficiently high finesse to reject the undesired comb lines to the point that they do not influence the wavelength calibration at the <10 cm/s level across the same bandwidth. Limited suppression of the unwanted source comb lines ("astro-comb sidebands") by the FPCs may lead to systematic shifts of the astro-comb peak centroids as recorded on the astrophysical spectrograph. The shift, expressed as a radial velocity, δRV, may be estimated by [1, 2]:

$$\frac{\delta RV}{c} = \frac{\delta f_A}{f_A} \approx \frac{f_R}{f_A} \sum_{s=-P/2}^{P/2} s \cdot I_s \Big/ \sum_{s=-P/2}^{P/2} I_s \qquad (1)$$

where f_A is the optical frequency of the main astro-comb line, δf_A is the shift of the astro-comb line as measured on the spectrograph which does not resolve individual 1-GHz comb lines, f_R is the repetition rate of the source comb, I_s is the power of sideband s (the comb line at an optical frequency $s\times f_R$ from the astro-comb line), P is the number of sidebands over which to sum determined by the comb line spacing and the spectrograph point spread function (PSF), and c is the speed of light. To achieve 10 cm/s RV accuracy, the power of all the comb lines needs to be suppressed by 40 dB (10^{-4}) below the power of the main astro-comb line (comb lines resonant with the FPC). An FPC with Free Spectral Range (FSR) = $16\times f_R$ ≈16 GHz and finesse ≈105 suppresses unwanted comb lines by >22 dB. Our sideband filter is composed

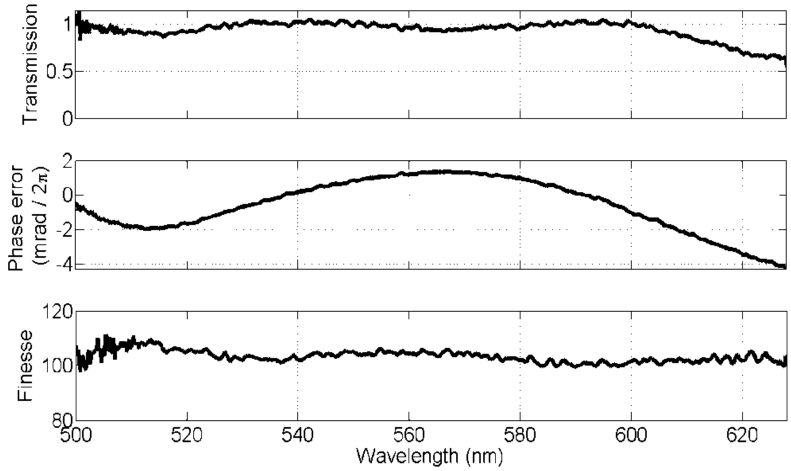

Figure S1: Measured throughput, phase error, and finesse of a single Fabry-Pérot cavity (FPC) constructed from a pair of complementary-chirped mirrors. The phase error of the FPC is smaller than 20 mrad and the throughput and the finesse are almost constant over a bandwidth of more than 120 nm. The transmission curve only accounts for loss due to phase error in the cavity.

of two identical FPCs and, therefore, is expected to suppress sidebands by >44 dB, which is sufficient to ensure better than 10 cm/s accuracy of all the astro-comb lines.

To show that the above analysis holds across the full astro-comb spectrum, we measured the cavity dispersion, which can be parameterized as a phase error, i.e., the fraction of the FSR that the cavity resonance is shifted relative to the comb at a given wavelength for a given cavity tuning. The method of measurements of the finesse and the phase error of the FPCs are described in detail in [1]. Briefly, after optimizing the FPC tuning to transmit the maximal green comb bandwidth, the offset frequency between the cw laser used to lock the FPCs and the frequency comb (and thus the FPC tuning) is changed in discrete steps and the spectrum transmitted through the cavity is recorded by an optical spectrum analyzer. The FPC phase error and finesse is then derived from the recorded spectra with an appropriate model. As shown in Figure S1, the measured phase error is <20 mrad and the finesse is ~105 over the desired spectral range of 500 to 620 nm.

S.2 Measurements of sideband suppression

In addition to dispersion, FPCs can have other imperfections: misalignment, non-flat mirror surfaces, input beam diffraction, higher order transverse modes, and finite isolation between FPCs that can reduce both the astro-comb transmission and the suppression of the sidebands. While an ideal planar mirror FPC has the same longitudinal mode filtering for all input transverse modes, finite mirror curvature breaks this degeneracy, leading to a filter transmission function with reduced sideband suppression for high order transverse modes. The inevitable slight misalignment of the cavity mirrors and input beam, as well as mirror surface imperfections beyond simple curvature, similarly break the longitudinal mode degeneracy and also couple lower order transverse modes into higher order modes. Lastly, the finite isolation between filter cavities modifies the combined two cavity transmission function compared to each cavity independently, potentially degrading the sideband suppression. The deviation of the FPCs from the ideal is evident in the measured finesse of ~105, described in Supplementary section S1, which is less than the theoretical value of 125 based on the mirror reflectivity. Note, however, that finesse measurements near the transmission resonance do not determine the effect of FPC imperfections on sideband suppression, as the sidebands are far from the transmission resonance. To ensure that the sidebands are suppressed to <–40 dB of the astro-comb lines, the level necessary to guarantee <10 cm/s RV accuracy for wavelength calibration when starting with a 1-GHz source comb, we performed a set of independent measurements, detailed below, all of which are consistent with <–40 dB remnant sidebands.

S.2.1 Sideband suppression determined from measured FPC transmission

The suppression of undesired sidebands can be estimated from the transmission function of each FPC as measured by the cw laser that co-propagates with the comb and is used to lock the cavities' lengths. To perform this measurement, we fix the frequency of the cw laser (532 nm), sweep the cavity length of the FPC using a piezo actuator, and measure the transmitted power of the cw laser with a photodetector. We find that the transmission functions of the two FPCs are very similar and are insensitive to the beam positions on the mirrors with a beam waist in the range of 0.6 mm – 1.5 mm, suggesting that the deviation from the theoretical finesse is due to mirror surface imperfections at length scales smaller than the beam waist and not limited by diffraction. Shown in Figure S2 is the total transmission function, i.e., the product of the measured transmission function of each FPC. The black dots are the estimated transmission of the sidebands, where the round trip phase delay of the p-th sideband is approximately $2\pi*p/K$ (*mod* 2π), with K=16 for our astro-comb. This measurement suggests that, after the two FPCs, the sidebands are suppressed by >44 dB and the suppression difference between the higher- and lower-frequency sidebands is <1 dB. Such uniformity in suppression indicates that the breaking of longitudinal mode degeneracy is slight and coupling to other transverse modes is limited to lowest order modes. The measured transmission curve is consistent with expectations from standard theory and the FPC finesse.

Note that the transmission function is measured after the finesse of the FPCs has been optimized, but the finesse typically degrades from 105 to 80 over several days due to drift of a few μrad in the parallelism of the planar mirrors forming the FPCs. Nonetheless, for such relatively small fractional changes in finesse, the transmitted astro-comb line amplitudes are reduced by 2.4 dB, and hence the overall suppression of the first sidebands by the two FPCs is expected to degrade from 45 dB to 42 dB, which is still more than sufficient for astro-comb wavelength calibration at

HARPS-N with 10 cm/s RV accuracy over a several day period. For the present realization of the green astro-comb, we could routinely restore optimal finesse and hence sideband suppression with a few minutes of manual adjustment of the apparatus.

S.2.2 Sideband suppression determined via heterodyne detection

While transmission function measurements of the FPCs using the 532 nm cw laser imply sufficient suppression of undesired astro-comb sidebands to achieve 10 cm/s RV accuracy, the cw and comb lasers utilize several different optical components, such as isolators. (See Fig. 1 of the main text.) Thus, direct measurement of the sideband suppression is required to assure full wavelength calibration accuracy. We directly measured sideband suppression for several astro-comb spectral lines using a double heterodyne detection system consisting of a first stage of optical heterodyne detection followed by a second stage of RF heterodyne detection

calibration accuracy. We directly measured sideband suppression for several astro-comb spectral lines using a double heterodyne detection system consisting of a first stage of optical heterodyne detection followed by a second stage of RF heterodyne detection

(Fig. S3). Two stage heterodyne detection is necessary to compensate for the relatively large linewidth of the beat note between the 532-nm cw laser, used as the local oscillator, and the comb. This large linewidth, ~1 MHz, is due to the loose phase lock of the cw laser to the comb (tighter locks add noise to the cw laser and the FPC lock). To realize a sufficient signal-to-noise ratio to observe astro-comb sidebands suppressed by >40 dB, we require a narrow (<1 Hz) detection bandwidth, and hence a narrow signal linewidth, so we use a second heterodyne stage to cancel the phase noise between the cw laser and the comb as explained below.

As shown in Figure S3, the first stage of heterodyne detection consists of fast photodetection of the difference frequency between the astro-comb and the 532-nm cw laser used for FPC stabilization in the astro-comb. The frequency of the resultant RF signal corresponding to the nearest astro-comb line is $f_{cc} \approx 10$ MHz and is determined by the reference RF frequency used in the phase lock of the cw laser to the comb. The RF frequencies of the nearest sidebands are then given by $f_R+f_{cc} \approx 1010$ MHz and $f_R - f_{cc} \approx 990$ MHz, where f_R is the repetition rate ≈1 GHz.

The second heterodyne stage (Fig. S3) mixes the RF beat signals from the astro-comb with a RF local oscillator generated from the beat between the green comb before the filter cavities and the 532-nm cw laser, which is then shifted by 30 MHz to avoid mixing to DC in the second heterodyne stage. Since both inputs to the second mixing stage contain the same phase fluctuations between the comb and cw laser, they are cancelled in the mixing process and the overall signal linewidth is determined by the linewidth (<<1 Hz) of the 30 MHz frequency source. Therefore, the resultant intermediate frequency has a bandwidth <1 Hz, making it possible to detect the RF signal corresponding to the sidebands (optical power <100 fW).

After the second stage of the heterodyne system, the RF signals at frequencies of 30 MHz, f_R+30 MHz ≈1030 MHz, and f_R-30 MHz ≈970 MHz are proportional to the electric field amplitudes of the astro-comb lines and the nearest two sidebands. To determine the sideband suppression, we measure the power of these three RF peaks before and after the FPCs (Fig. S4a). Our results are consistent with expectations from scanning the FPCs described above: ~45 dB sideband suppression with two FPCs, and a suppression difference of <1 dB between the higher and lower frequency sidebands. We performed this measurement every 30 minutes for 10 hours and found that the suppression of the sidebands degraded by <2 dB, as shown in Figure S4b, due to drift in the parallelism alignment of the FPC mirrors.

Heterodyne measurements of sideband suppression were performed only at 532 nm, limited by the tuning range of our cw laser. Combined with the measurement of the phase error and finesse of the FPCs described above, which show a consistent finesse and no modulation in the cavity phase, indicating no back-reflections into the cavity and hence good isolation, we have strong indirect evidence that sideband suppression in the optical bandwidth of 500 nm to 620 nm is better than 40 dB, which ensures 10 cm/s RV accuracy of each astro-comb line. However, we also made direct sideband suppression measurements across the bandwidth using a Fourier Transform Spectrometer (FTS), as described below and in the main text.

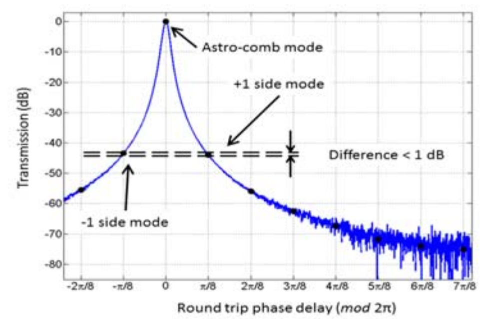

Figure S**2**: Transmission of the two-FPC sideband filter measured with a cw laser (blue line). Black dots are the estimated transmission of the *p*-th sidebands. The measurement indicates that all sidebands should be suppressed by >40 dB and the difference between the higher and lower sidebands is <1 dB. (*See text for details of measurement method.*)

S.2.3 Direct sideband suppression measurements with Fourier Transform Spectrometer

To ensure accuracy of astro-comb lines to <10 cm/s at different wavelengths across the full astro-comb bandwidth, we performed a direct measurement of the sideband suppression using a broadband Fourier Transform Spectrometer (FTS). This FTS, built from stock optical components and described in [3], has an unapodized instrument line shape of 90 MHz FWHM that, with appropriate apodization, is able to resolve comb lines separated by 1 GHz at –40 dB (10^{-4}) relative to the astro-comb line power level.

In practice, the sensitivity of the FTS for astro-comb sideband measurements is limited by the relative intensity noise (RIN) of the astro-comb, which is predominantly caused by fluctuations of the cavity length of the FPCs (note that an echelle spectrograph such as HARPS-N is immune to such amplitude noise). To compensate for

RIN, we measure the total intensity of the astro-comb and use this information to correct the overall signal intensity during data processing. However, this only reduces common mode noise of all comb lines and is limited by the dispersion of the FPCs. To reduce the effects of dispersion on the RIN compensation, we use interference filters, limiting the optical bandwidth in one measurement to 10 nm; we then repeat the measurement for different portions of the full green astro-comb spectrum. With this technique we demonstrate >40 dB relative sideband suppression, ensuring 10 cm/s RV accuracy of astro-comb lines when measured on an astrophysical spectrograph, as described in the main text of the paper.

To achieve sensitivity to sidebands suppressed by >40 dB, data are averaged across 25 consecutive astro-comb lines. Fourier analysis of raw, unaveraged suppression data at a given offset frequency shows no spectral features above 10 cm/s, confirming that no periodic features (e.g., from back reflections or other undesired etalon behavior) are hidden by the averaging process. This conclusion is under the model assumption that such etalon behavior is low finesse, which is a reasonable assumption given the smoothness of the astro-comb spectrum, and that any unwanted etaloning does not have significant dispersion across the band sampled so that its power is in a few bins of the power spectrum.

S.3 Operation at HARPS-N

In January, 2013 we deployed the green astro-comb at the Telescopio Nazionale Galileo (TNG) on La Palma in the Canary Islands as a wavelength calibrator for the HARPS-N spectrograph (Fig. S5a). HARPS-N is a fiber-fed echelle spectrograph, using 69 diffraction orders to cover the 383-690 nm spectral band [4]. Light from two different sources, typically an astronomical object (with light acquired by the TNG) and a wavelength calibrator, is coupled into HARPS-N through two multimode input fibers and then measured simultaneously. As a demonstration of the green astro-comb serving as the HARPS-N wavelength calibrator for a bright astronomical object, we observed reflected Sun-light from the asteroid Vesta 4 coupled into one input fiber and the green astro-comb coupled into the second input fiber. Figure S5b displays an example section of the raw 2-D image, showing portions of six spectrograph orders in which the horizontal line is the spectrum of the sun reflected from Vesta and the circular dots are the astro-comb reference. We performed multiple observations of Vesta over the course of an hour on three nights, achieving high signal-to-noise ratios of greater than 200 from Vesta, and astro-comb references with calibration sensivity of 10 cm/s. Analysis of these results to determine the absolute accuracy of the HARPS-N spectrograph are ongoing.

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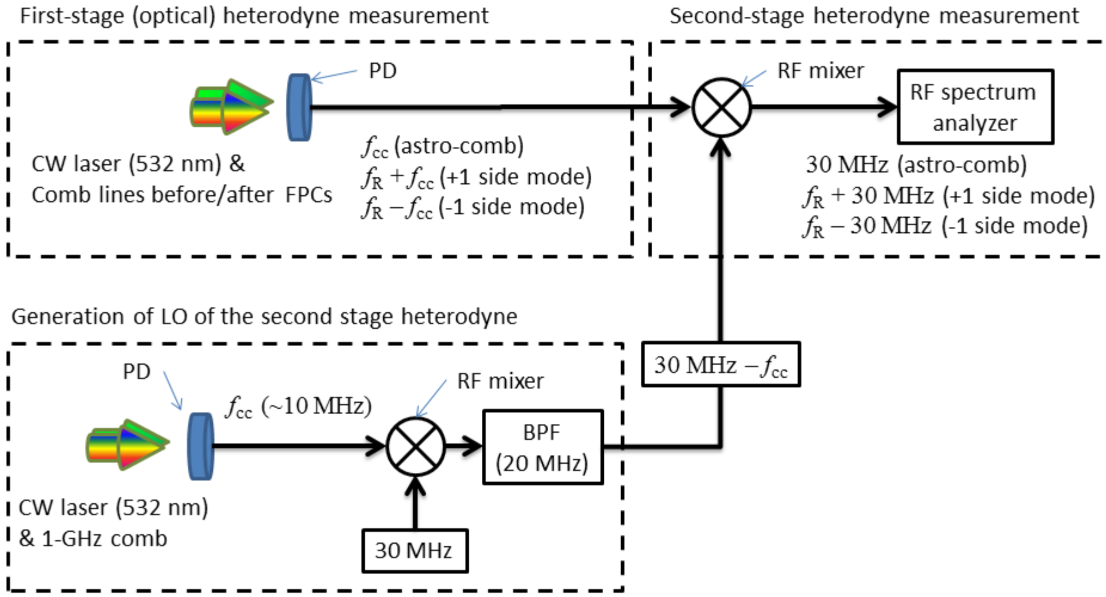

Figure S3: Block diagram for heterodyne measurements of sideband suppression. The difference frequency between comb lines before/after FPCs and a 532-nm laser are detected by a fast photodetector. The frequency of the resultant RF signal corresponding to the astro-comb line nearest the frequency of the 532 nm laser and its higher and lower sidebands are at $f_{cc} \approx 10$ MHz, $f_R+f_{cc} \approx 1010$ MHz and $f_R-f_{cc} \approx 990$ MHz. The second stage heterodyne measurement mixes the RF beat signals with a local oscillator derived from the beat between the green 1 GHz comb and the 532-nm cw laser, shifted by 30 MHz after conversion to RF in the photodetector to avoid mixing to DC with the second-stage of the heterodyne system. (PD: photodetector; BPF: band pass filter; 3-port circle: RF mixer; LO: local oscillator.)

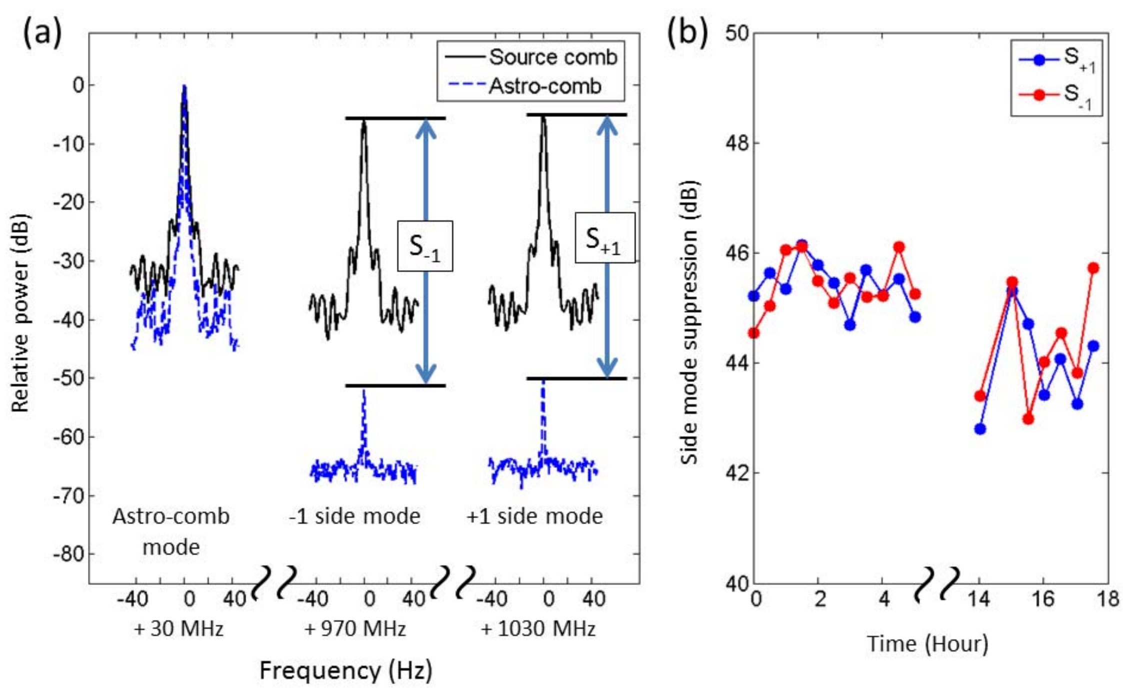

Figure S4: Heterodyne measurements of the suppression of the first higher (+1) and lower (-1) sidebands of one astro-comb line near 532 nm. (a) Amplitudes of the higher and lower sidebands before and after the FPCs. The suppression is >40 dB and the suppression difference is <1 dB, sufficient to ensure 10 cm/s accuracy of the astro-comb spectrum on HARPS-N. (b) Measurements were performed everything 30 minutes over ~18 hours. The sideband suppression degraded by <2 dB over this period.

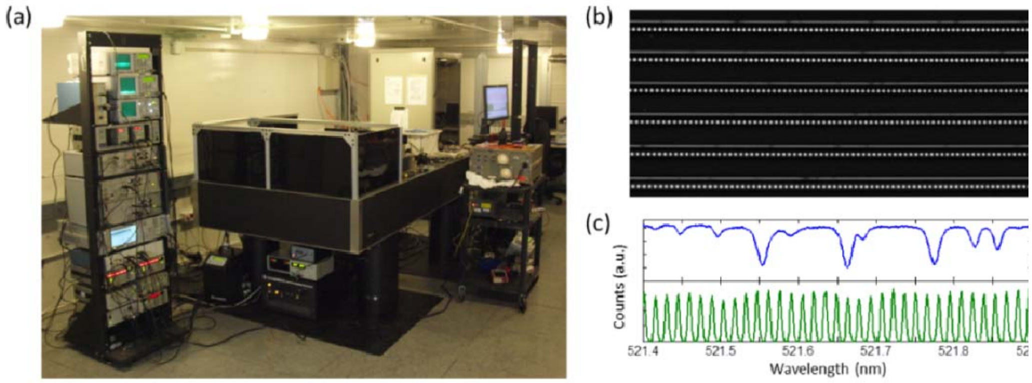

Figure. S5. (a) Photograph of the green astro-comb located at the TNG telescope facility. The astro-comb system worked reliably as a wavelength calibrator for HARPS-N with minimal tending over several months. (b) Example small region of a 2D spectral image, recorded by the CCD camera on the focal plane of HARPS-N, showing light from the asteroid Vesta 4 observed with the TNG telescope and illuminating one HARPS-N input fiber (continuous lines) along with green astro-comb calibration light illuminating the other HARPS-N input fiber (dotted lines). Green astro-comb lines cover 24 out of 69 echelle orders of the HARPS-N spectrograph (order No. 36-59). (c) Example section of 1D spectra reduced from echelle order 41 of both input fibers showing the Vesta 4 spectrum and the 16 GHz green astro-comb spectrum from 521.4 nm to 521.9 nm.