Visible wavelength astro-comb

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Abstract: We demonstrate a tunable laser frequency comb operating near 420 nm with mode spacing of 20-50 GHz, usable bandwidth of 15 nm and output power per line of ~20 nW. Using the TRES spectrograph at the Fred Lawrence Whipple Observatory, we characterize this system to an accuracy below 1m/s, suitable for calibrating high-resolution astrophysical spectrographs used, e.g., in exoplanet studies.

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References and links

1. M. T. Murphy, T. Udem, R. Holzwarth, A. Sizmann, L. Pasquini, C. Araujo-Hauck, H. Dekker, S. D'Odorico, M. Fischer, T. W. Hansch, and A. Manescau, "High-precision wavelength calibration of astronomical spectrographs with laser frequency combs," Mon. Not. R. Astron. Soc. **380**(2), 839–847 (2007).
2. S. T. Cundiff, and J. Ye, "Colloquium: Femtosecond optical frequency combs," Rev. Mod. Phys. **75**(1), 325–342 (2003).
3. T. Steinmetz, T. Wilken, C. Araujo-Hauck, R. Holzwarth, T. Hänsch, and T. Udem, "Fabry–Pérot filter cavities for wide-spaced frequency combs with large spectral bandwidth," Appl. Phys. B **96**(2-3), 251–256 (2009).
4. M. S. Kirchner, D. A. Braje, T. M. Fortier, A. M. Weiner, L. Hollberg, and S. A. Diddams, "Generation of 20 GHz, sub-40 fs pulses at 960 nm via repetition-rate multiplication," Opt. Lett. **34**(7), 872–874 (2009).
5. G. T. Nogueira, B. W. Xu, Y. Coello, M. Dantus, and F. C. Cruz, "Broadband 2.12 GHz Ti:sapphire laser compressed to 5.9 femtoseconds using MIIPS," Opt. Express **16**(14), 10033–10038 (2008).
6. L.-J. Chen, A. J. Benedick, J. R. Birge, M. Y. Sander, and F. Kärtner, "Octave-spanning, dual-output 2.166 GHz Ti:sapphire laser," Opt. Express **16**(25), 20699–20705 (2008).
7. A. Bartels, D. Heinecke, and S. A. Diddams, "10-GHz self-referenced optical frequency comb," Science **326**(5953), 681 (2009).
8. A. Sandage, "The change of redshift and apparrent luminosity of galaxies due to the deceleration of selected expanding universes," Astrophys. J. **136**, 319–333 (1962).
9. A. Loeb, "Direct Measurement of Cosmological Parameters from the Cosmic Deceleration of Extragalactic Objects," Astrophys. J. **499**(2), L111–L114 (1998).
10. S. Osterman, S. Diddams, M. Beasley, C. Froning, L. Hollberg, P. MacQueen, V. Mbele, and A. Weiner, "A proposed laser frequency comb-based wavelength reference for high-resolution spectroscopy," in *Techniques and Instrumentation for Detection of Exoplanets III*, (SPIE, 2007), 66931G–66939.
11. C.-H. Li, A. J. Benedick, P. Fendel, A. G. Glenday, F. X. Kärtner, D. F. Phillips, D. Sasselov, A. Szentgyorgyi, and R. L. Walsworth, "A laser frequency comb that enables radial velocity measurements with a precision of 1 cm s(-1)," Nature **452**(7187), 610–612 (2008).
12. T. Steinmetz, T. Wilken, C. Araujo-Hauck, R. Holzwarth, T. W. Hänsch, L. Pasquini, A. Manescau, S. D'Odorico, M. T. Murphy, T. Kentischer, W. Schmidt, and T. Udem, "Laser frequency combs for astronomical observations," Science **321**(5894), 1335–1337 (2008).
13. D. A. Braje, M. S. Kirchner, S. Osterman, T. Fortier, and S. A. Diddams, "Astronomical spectrograph calibration with broad-spectrum frequency combs," Eur. Phys. J. D **48**(1), 57–66 (2008).
14. T. Wilken, C. Lovis, A. Manescau, T. Steinmetz, L. Pasquini, G. Lo Curto, T. W. Hänsch, R. Holzwarth, and T. Udem, "High-precision calibration of spectrographs," Mon. Not. R. Astron. Soc. Lett. **405**(1), L16–L20 (2010).
15. F. Bouchy, F. Pepe, and D. Queloz, "Fundamental photon noise limit to radial velocity measurements," A&A **374**(2), 733–739 (2001).
16. C.-H. Li, A. G. Glenday, A. J. Benedick, G. Chang, L.-J. Chen, C. Cramer, P. Fendel, G. Furesz, F. X. Kärtner, S. Korzennik, D. F. Phillips, D. Sasselov, A. Szentgyorgyi, and R. L. Walsworth, "In-situ determination of astro-comb calibrator lines to better than 10 cm s(-1)," Opt. Express **18**(12), 13239–13249 (2010).
17. J. W. Brault, "High precision fourier transform spectrometry: The critical role of phase corrections," Mikrochim. Acta **93**(1-6), 215–227 (1987).

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18. L.-J. Chen, G. Chang, C.-H. Li, A. Glenday, A. J. Benedick, D. F. Phillips, R. L. Walsworth, and F. X. Kärtner, "High-Finesse Dispersion-Free Cavities for Broadband Filtration of Laser Comb Lines," in *Ultrafast Phenomena,* (OSA, Snowmass, CO, 2010), TuF1.
19. A. Benedick, D. Tyurikov, M. Gubin, R. Shewmon, I. Chuang, and F. X. Kärtner, "Compact, Ti:sapphire-based, methane-stabilized optical molecular frequency comb and clock," Opt. Lett. **34**(14), 2168–2170 (2009).
20. J. R. Birge, and F. X. Kärtner, "Design of Optimal Dispersive Mirrors for Femtosecond Enhancement Cavities and Compressors by Minimizing Phase Distortion Power," in *Conference on Lasers and Electro-Optics/International Quantum Electronics Conference*, OSA Technical Digest (CD) (Optical Society of America, 2009), CThDD1.
21. G. Furesz, "Design and application of high resolution and multiobject spectrographs: Dynamical studies of open clusters," Phd Thesis, (University of Szeged, Hungary, 2008).

1. Introduction

A successful method for identifying planets in other star systems (exoplanets) is the radial velocity (RV) technique, which exploits small, periodic Doppler shifts in the spectrum of a target star to infer the existence of orbiting planets and determine characteristics such as orbital period and a lower limit to the planet's mass. Utilizing the RV method to find small, rocky exoplanets similar to the Earth in the habitable zone requires wavelength calibration precision and stability ~10 cm/s for the astrophysical spectrograph [1] used to measure the stellar spectrum. Because frequency combs provide a broad spectrum of highly stable and precisely known optical frequencies [2], which can be traced to a common reference such as GPS, they are an ideal wavelength calibration tool for astrophysical spectrographs. Spectral filtering of the frequency comb using a Fabry-Perot cavity [3,4] is generally required for the spectrograph to resolve individual comb lines from the frequency comb, though work is progressing to develop frequency combs with repetition rates high enough to eliminate the need for filter cavities [5–7]. Measurements of time-variation of the fundamental constants or of the expansion of the universe [8,9] may also be enabled by these types of calibration systems, with expansion of the universe requiring ~1 cm/s sensitivity over decadal timescales. In this work, we focus on calibrators for the near-term goal of exoplanet detection.

Frequency comb systems optimized for astrophysical spectrograph calibration ("astro-combs") [10–13] have been demonstrated at several wavelength regions to date [11–14] though recently there is a trend toward demonstrating systems operating in the short wavelength end of the emission spectrum of Sun-like stars (400-700 nm) [10,14]. In addition to providing the largest photon flux, this wavelength region is rich with spectral features of high quality most suitable for use with the RV method [15]. Shorter wavelengths also avoid fringing effects in the spectrograph's charge coupled device (CCD) caused by weak etaloning in the silicon substrate. This effect can be a serious complication for data analysis at wavelengths longer than 700 nm since correction of these fringes to a precision better than 1% is challenging.

Here, we demonstrate operation of an astro-comb operating near 420 nm with FWHM bandwidth of about 15 nm, center wavelength tunable over 20 nm, and spectral line spacing of 22 and 51GHz. Systematics of this calibration system including dispersion, higher order transverse modes of the cavity filter and alignment of the frequency comb and cavity filter transmission resonances have been characterized. Using a scanned-cavity technique [16], the accuracy of the astro-comb system has been compared to the underlying laser frequency comb. This type of broadband characterization of an astro-comb system is necessary to ensure that the optical filtering process has not left unevenly suppressed source comb lines on either side of each astro-comb line. Identifying where uneven suppression has occurred can allow use of a much wider bandwidth than would normally be possible if only exactly even suppression could be tolerated.

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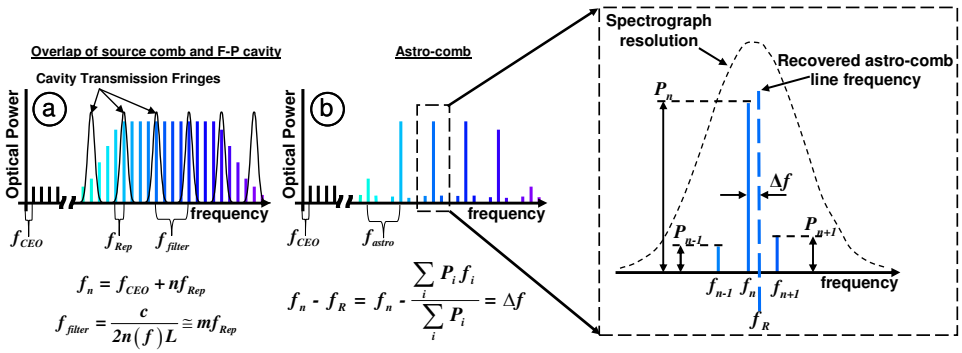


Fig. 1. Description of an astro-comb in the frequency domain. (a) Frequency-doubled source comb lines and analytic description of the optical spectrum in terms of the repetition rate, f_{rep}, and the carrier envelope offset frequency, f_{CEO}, of the underlying Ti:Sapphire laser. The frequency doubled spectrum is multiplied by the transmission function of the Fabry-Perot cavity, filtering the source comb spectrum which becomes the astro-comb spectrum shown in graph (b). The free spectral range of the transmission resonances of the filter cavity, f_{filter}, is ideally an integer multiple of the repetition rate of the source laser. However due to dispersion from air and mirror reflections, f_{filter} will generally be a function of frequency. In this example the integer $m = 4$ (typically m = 20-50 with our 1 GHz repetition rate laser) such that in (b) every 4th line (referred to as an astro-comb line) is fully transmitted. Because the spectrograph resolution (~>15 GHz) is generally larger than the repetition rate of the source comb, finite suppression of the source comb modes closest every astro-comb line results in a power weighted average frequency, f_R, to be reported by the spectrograph. The difference Δf must be recovered to realize the full accuracy of the astro-comb.

2. Astro-comb system

2.1 Calibration sensitivity

Astrophysical spectrographs used for high precision spectroscopy are generally configured as cross-dispersion spectrographs which disperse the input spectrum in two orthogonal directions to increase resolution and optical bandwidth. Focusing this cross-dispersed beam on a CCD creates a two dimensional image which transforms the frequency (or wavelength) of the input light to a physical position on the CCD. The ideal calibrator for such a spectrograph would be a single light source whose spectrum is composed of an ensemble of individual incoherent emitters, each with equal power and separated in frequency by slightly more than the spectrograph resolution [1]. Each emitter should also have a spectral width much less than the spectrograph resolution. Knowing the frequency of each component of this calibration spectrum allows recovery of the spectrograph's mapping of frequency (or wavelength) to CCD position as well as the point spread function of the spectrograph for all frequencies.

Frequency combs based on mode locked lasers are currently the closest analogue to this ideal calibrator with the exceptions that their optical bandwidth is typically much narrower than the spectrometer's bandwidth and the frequency spacing between spectral features (comb lines) is much less than the resolution of the spectrometer. Overcoming the bandwidth limitation can be partially achieved by broadening the spectrum from the frequency comb in a nonlinear fiber or crystal and/or shifting the spectrum to a different wavelength range using a similar process. A Fabry-Perot cavity can be used to selectively remove all but every m^{th} comb line in the output spectrum of the frequency comb to generate a new comb whose comb lines are resolvable by the spectrograph, Fig. 1. The shot noise limited velocity uncertainty of a radial velocity measurement using the Doppler shift of a single spectral feature has previously been discussed as [1,17]

$$\sigma_V = \lambda A \frac{\delta \nu_{1/2}}{SNR\sqrt{n}} \quad (1.1)$$

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where A is a number close to one related to the specific line shape of the feature in question, $\delta\nu_{1/2}$ is the FWHM of the feature, SNR is the peak signal to noise ratio due to shot noise for the feature usually measured at peak center, n is the number of spectrograph CCD pixels sampling the spectral feature in the grating dispersion direction and λ is the center wavelength of the feature. Using all N emission features of a target star or all the lines from an astro-comb, the value given by (1.1) may be reduced by $1/N^{1/2}$. By matching the frequency spacing of the astro-comb lines to a value just larger than the resolution of the spectrograph ($\alpha \approx 3$) [1], and defining N as the ratio between the FWHM frequency bandwidth of the calibration spectrum $\delta\nu_{input}$ and the astro-comb repetition rate, we can re-write (1.1) including the spectrograph resolving power $R = \lambda/\delta\lambda$ as

$$\sigma_V = \frac{Ac}{SNR\sqrt{n}R^{3/2}}\sqrt{\frac{\alpha\lambda}{\delta\lambda_{input}}} \quad (1.2)$$

In addition to the benefits achieved by shifting the center wavelength of the RV measurement to shorter wavelengths as stated in the introduction, there is an additional precision benefit of $\sim 1/\sqrt{2}$ gained from frequency doubling the Ti:Sapphire laser. However large increases in the bandwidth of the calibration source are necessary to see significant gains in calibration precision for a given spectrograph with resolving power R. The sensitivity gain between calibrating 15 nm and calibrating the full octave spanning spectrum of the Ti:Sapphire laser (>300 nm) is a factor of ~4.5. The difficulty of achieving comb line filtering over 300 nm generates far greater challenges than those presented here [3,13,18].

2.2 Visible frequency comb generation

Our visible wavelength astro-comb (Fig. 2) follows the general approach outlined above by using a frequency doubled octave spanning Ti:Sapphire laser which is spatially and spectrally filtered before its spectrum is fiber coupled to the astrophysical spectrograph for calibration of the spectrograph's frequency (or wavelength) to CCD position mapping. Currently, nonlinear frequency conversion is the only method for generating a frequency comb in the 400-600 nm wavelength region, as no broadband laser materials in this region are known. We have chosen frequency doubling of a broadband Ti:Sapphire laser, Fig. 3, to provide a source comb at 400 nm, because we have previously [19] constructed stable and high power Ti:Sapphire lasers that are capable of operating unattended on day long timescales. Absolute referencing of such lasers is also more direct than with other systems, as Ti:Sapphire lasers can generate optical spectra directly from the laser cavity that cover more than one octave; this allows direct access to the carrier envelope offset frequency, f_{ceo}, control of which is required if all optical frequencies from the frequency comb are to be known.

Optical frequencies of comb lines from femtosecond lasers are uniquely described by $f = f_{ceo} + nf_{rep}$, where active control of both f_{ceo} and f_{rep} allows unique definition of the absolute frequency of each comb line. In the system depicted in Fig. 2, f_{rep} is detected using a PIN photodiode to recover the pulse repetition rate which is then phase locked to a low noise radio frequency oscillator using a low bandwidth feedback loop to control the length of the laser cavity. Control of the f_{ceo} frequency is achieved by modulation of the pump laser intensity using an AOM. A phase locked loop which generates the control signal for the AOM matches the f_{ceo} frequency detected using the f-2f method with a second low noise frequency synthesizer. Both synthesizers are phase locked to a commercial rubidium frequency reference to enable the entire chain to have a fractional frequency stability $<10^{-11}$ over time scales from seconds to days. Heterodyne measurements with a narrowband diode laser at 408 nm reveal a maximum linewidth of the optical comb lines <5 MHz, limited by the linewidth of the diode laser.

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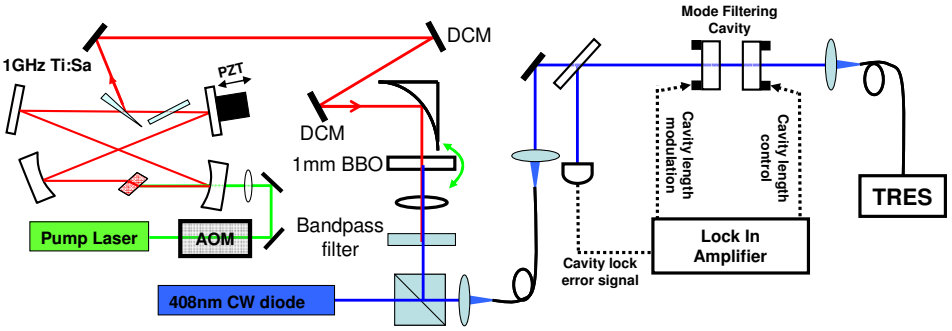


Fig. 2. Layout for visible wavelength astro-comb. Output from an octave-spanning 1 GHz Ti:Sapphire laser frequency comb is pre-chirped using two Dispersion Compensating Mirrors (DCM) and focused with an off-axis parabolic mirror into a BBO crystal. Single mode fiber between the Ti:Sapphire laser and the Fabry-Perot cavity filter ensures that the spatial profile of the beam entering the cavity is of lowest order (TEM_{00}), giving the best possible suppression of transmission by higher order transverse modes. A 408 nm external cavity diode laser allows for identification of the desired Fabry-Perot cavity length as well as side-mode suppression estimation. TRES – Tillinghast Reflector Echelle Spectrograph, AOM – acousto-optic modulator, PZT – piezo electric transducer.

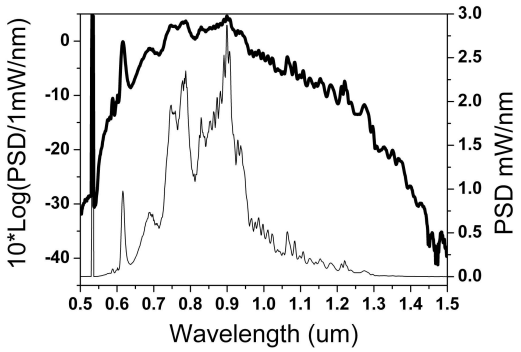


Fig. 3. Output spectrum of the 1 GHz laser used as the source comb for the visible wavelength astro-comb. The large peak at 532 nm is residual power from the pump laser.

The astro-comb system must be very robust and reliable over many hours for use in an observatory environment. We have, therefore, chosen to use a 1mm BBO crystal for frequency conversion rather than a photonic crystal fiber. Using 300 mW from the Ti:Sapphire laser as input to the BBO crystal, 18 mW average power and 15 nm FWHM spectrum centered at 420 nm is typically generated. Rotation of the BBO crystal in the laser focus allows tuning of the generated spectrum over a FWHM bandwidth of nearly 50 nm as measured directly after the BBO crystal. For reasons explained below, the tuning bandwidth is reduced to approximately 20 nm after transmission through the Fabry-Perot cavity, Fig. 4(A).

For optimal spectral filtering of the source comb, it is necessary to ensure that the intensity distribution of the beam sent to the Fabry-Perot cavity is well described by a fundamental order Hermite-Gaussian mode. Due to both the spatial chirp of the Ti:Sapphire laser output and spatial walk-off which occurs during second harmonic generation in the BBO crystal, the beam at the output of the BBO crystal contains many higher-order spatial terms. A single-mode fiber (mode field diameter ~2.9 μm) placed in the Fourier plane of a 4F lens system, leads to a transverse intensity distribution at the output of the 2nd lens which is approximately a lowest order Gaussian. While a using a single-mode fiber as a spatial filter reduces the power available after the doubling process by a factor of almost 5, the spatial profile of the

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output beam becomes a constant and only the spectral content and transmitted fraction can be affected by changes in beam pointing from the laser.

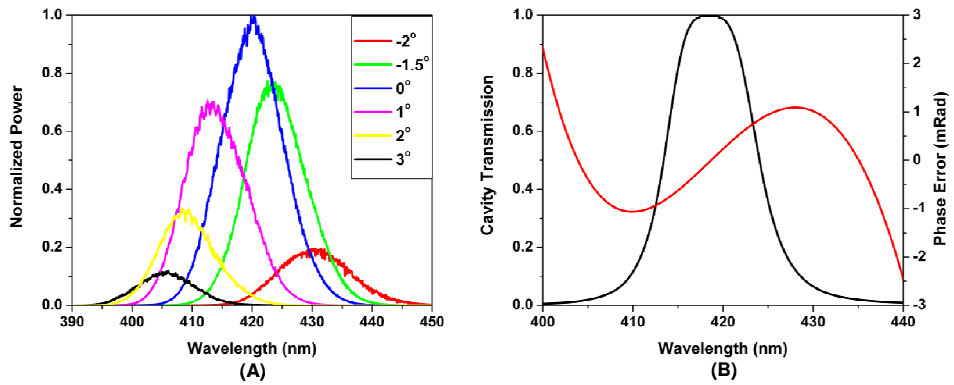


Fig. 4. (A) Measured optical spectra of the visible wavelength astro-comb, after the Fabry-Perot cavity filter, for several angles of the BBO crystal relative to the IR source comb beam. Integrated power for the central spectrum is 25 uW (~25 nW per astro-comb line). Filtered mode spacing is 22 GHz. (B) Calculated characteristics of the Fabry-Perot cavity filter using dispersion-optimized dielectric Bragg reflectors. Round-trip dispersion due to reflection from the Fabry-Perot cavity mirrors is plotted on the right axis, and cavity transmission for an input spectrum centered at 420 nm is plotted on the left axis taking into account air dispersion as well as mirror dispersion and reflectivity.

2.3 Spectral filtering

The highest precision of calibration occurs when the spacing between spectral features in the spectrum used to calibrate a spectrograph is approximately three times the resolution of the spectrograph [1], ensuring high contrast coverage of the spectrograph's CCD. Spectral filtering of the source comb is currently necessary to achieve this ideal spacing since the frequency spacing between comb lines of all current mode locked lasers suitable for spectrograph calibration is smaller than the resolution of most existing astrophysical spectrographs.

The most straightforward way to achieve this filtering is by using a two mirror Fabry-Perot cavity where the distance between the mirrors, L, is set such that the free spectral range of the filter cavity, $c/2L$, is an integer multiple of the source comb repetition rate, Fig. 1. Such a filter only transmits every m^{th} source comb line, suppressing the remaining source comb lines to varying degrees resulting in a transmitted spectrum which more closely approximates the ideal. Dispersion from air or mirror reflections causes a deviation from this integer spacing resulting in a change in amplitude of source comb line transmission. This difference in transmitted amplitude is generally small and is manifested primarily as an asymmetry in the suppression of the two source comb lines on either side of the m^{th} transmitted source comb line (astro-comb line), causing an apparent shift in the overall line center recovered by the spectrograph. This shift occurs because the spectrograph's limited resolution causes all three source comb lines to be recovered as a power-weighted sum rather than as individual lines. The shift in frequency of the recovered center of gravity caused by asymmetrical line suppression as $\Delta f = (P_{n+1}-P_{n-1})f_{Rep}/(P_{n-1} + P_n + P_{n+1})$ which is a truncated version of the formula described above in Fig. 1. A recently developed scanned cavity technique [16] can be used to identify and remove these systematic shifts from the final calibration which is critical since any dielectric mirror coating will contain both small errors and a systematic divergence of the dispersion at the edges of its working range.

In this work, plane parallel mirrors are used to construct the Fabry-Perot cavity filter to reduce distortion of the astro-comb caused by transmission of source comb light through the filter cavity as a result of excitation of higher order transverse modes (HOM) at frequencies

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far from the longitudinal, *c/2L*, resonances. The reduction in transmission via HOM is a result of three factors: First, the frequency offset for the higher order transverse modes is typically <100 MHz for plane parallel cavities. Second, due to the high source comb repetition rate of 1 GHz, transmission of a source comb line adjacent to a desired astro comb line, can only occur via transverse modes with very high mode order (10 or more). Third, the difference in nominal transverse mode size between the $TEM_{(0,0)}$ mode and higher order transverse modes prevents significant coupling into higher order transverse modes once the coupling is optimized for the $TEM_{(0,0)}$ mode. The combination of these three factors reduces the side mode transmission via higher order transverse modes to a level similar to what would be expected from a hypothetical cavity possessing only the longitudinal *c/2L* modes. To verify this chain of arguments experimentally, Fig. 5(A) shows the measured transmission of the Fabry-Perot filter cavity using a swept frequency laser diode. Asymmetry of the measured transmission, due to transmission via higher order transverse modes is clearly visible on the high frequency side of the transmission fringe in Fig. 5(A). However, we emphasize that the benefit of this approach is the elimination of transmission maxima in a similar sweep spanning the full 22 GHz free spectral range, Fig. 5(B). The broadening of the main transmission fringe in Fig. 5(A) occurs mainly because the flatness deviations are not spherical, though this type of asymmetry can be compensated using the technique described in [16].

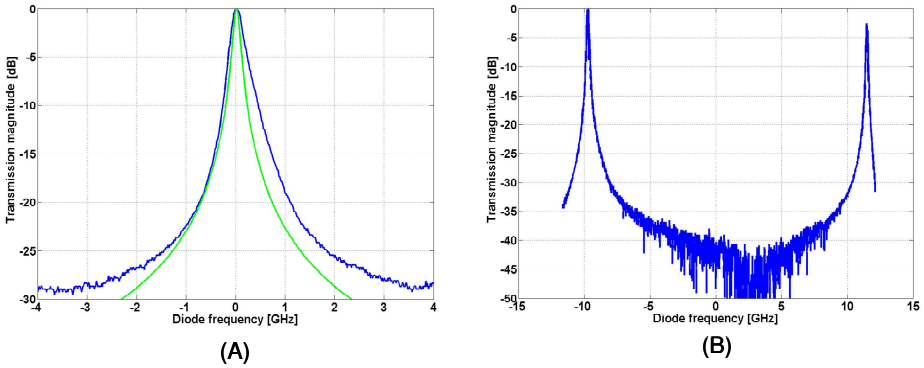


Fig. 5. Transmission of the Fabry-Perot cavity filter measured with a swept frequency laser diode. (A) Comparing measured transmission (blue) and calculated transmission assuming R = 98.2% and a free spectral range of 22 GHz (green) shows the asymmetric observed line shape. Coupling of the diode laser into the cavity is identical to that of the frequency comb. (B) No higher order peaks are visible in a sweep spanning the full 22 GHz free spectral range.

Misalignment in the frequency domain of the Fabry-Perot cavity filter's transmission resonances and the source comb lines caused by air and mirror dispersion is also a limiting factor for the bandwidth of the source comb which can be successfully filtered. The mirrors used here are dielectric Bragg reflectors with slightly modified layer thicknesses using the numerical routine described in [20]. The layer thicknesses are optimized for minimum accumulated phase on reflection over most of the high reflectivity bandwidth of the initial Bragg layer stack. The resulting phase from reflection as a function of wavelength is plotted in Fig. 4(B) with the portion due to a constant group delay removed. Due to the fast variation of round trip phase mainly due to air dispersion [13] at the edges of the reflectivity bandwidth, the bandwidth over which the input comb lines and the Fabry-Perot cavity's transmission resonances are well aligned is limited, reducing the overall transmission and resulting in an astro-comb bandwidth of ~20 nm, Fig. 4(A).

2.4 Astro-comb operation

Initially, alignment of the comb lines from the source comb with the transmission resonances of the Fabry-Perot cavity filter is achieved by maximizing the transmission of the source

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comb through slow change of the filter cavity length. Once the cavity is set to the nominally correct length, the cavity length is modulated by ~3 pm at a rate of 100 kHz, causing modulation of the power transmission of the cavity. Demodulating the detected transmission using a lock in amplifier, the resulting signal is used to control the length of the cavity using a second piezo mounted mirror. Two piezos are used so that one of the piezos can be optimized for generating a high frequency modulation allowing a higher feedback bandwidth. The second piezo can then be of slightly larger physical size enabling larger deflection and thus correction of larger amplitude cavity length errors at the cost of much larger piezo capacitance and longer response time.

For calibration of an astrophysical spectrograph, it is not strictly necessary that the absolute frequency of each astro-comb line to be known before the astro-comb light is sent to the spectrograph. The astro-comb spectrum as measured on the spectrograph can be compared to the spectrum from an iodine cell or a thorium argon lamp, the emission lines of which are well tabulated and known to better than 1 GHz. Once one line of the filtered astro-comb is identified by this method, all of the other lines in that spectrograph order can be identified and the full accuracy of each individual astro-comb line can be exercised. In our previous NIR (near infrared) astro-comb studies [11], a single fiducial reference laser was used as a frequency marker to identify the frequency of all astro-comb lines recorded by the spectrograph. However, because the frequency difference between spectrograph orders is not constant, and for some orders the dispersed spectrum extends beyond the collection area of the CCD, the loss of information between orders can prevent indexing of astro-comb lines from one order to the next. Thus in general a fiducial wavelength marker is required for each order of the spectrograph, which an iodine cell or thorium argon lamp can easily provide.

3. Astro-comb system characterization

We have installed a second astro-comb system nearly identical to the one described above at the Fred Lawrence Whipple Observatory (FLWO). Using a Menlo Systems 1 GHz octave spanning Ti:Sapphire laser as the source comb source as well as a BBO crystal, Fabry-Perot filter cavity, and filter cavity stabilization scheme identical to that described above, we are typically able to generate an average output power from the astro-comb of 10-30 μW (~10-30 nW per astro-comb line) with a line spacing of 51 GHz. The TRES spectrograph [21] has a resolving power of $R = \lambda/\delta\lambda$ = 40,000 and spectral coverage from 390 to 900 nm. A 100 um multimode step-indexed fiber couples light from the calibration system where astro-comb light is injected to the spectrograph optical bench to where it is dispersed by an echelle grating and a prism to produce a 2 dimensional spectrum consisting of 51 orders of approximately 10 nm each. The dispersed light is then re-imaged onto a two dimensional CCD array with a resolution of ~0.01 nm, sampled by ~6 pixels in the dispersion direction. The CCD (E2V 42-90) is read out with added noise of less than 3 counts per pixel. Spectra are arranged as 1 dimensional data through the use of a halogen flat-fielding lamp which maps the spectrograph orders and compensates for pixel to pixel gain variations. Approximately six pixels in the cross-dispersion direction orthogonal to the grating dispersion direction contained counts from each order which are added together to produce one dimensional spectra. In the data presented in Fig. 6, the wavelength calibration was provided by a standard thorium argon calibration lamp also attached to the spectrograph calibration system. For exposure times compatible with the spectrograph control software (~30 sec), the output of the astro-comb was attenuated by 20 dB to avoid saturating the CCD.

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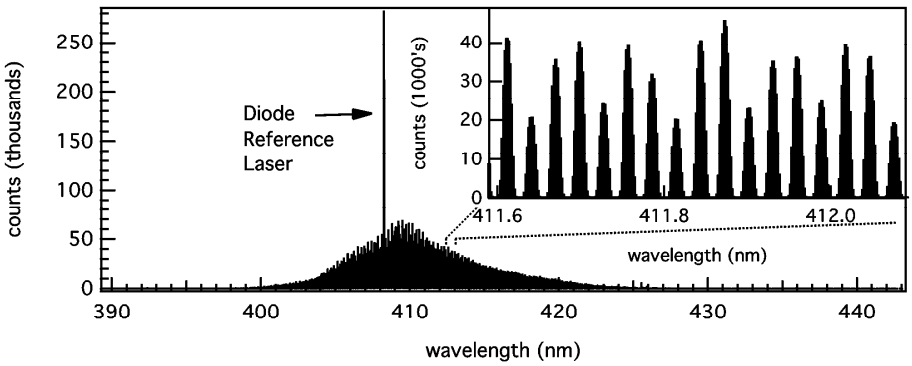


Fig. 6. Extracted one dimensional spectrum of full astro-comb spectrum. The FWHM of the spectrum is approximately 10 nm, with approximately 50,000 peak counts in 10 seconds on the spectrograph. Inset: example of filtered comb lines with mode spacing of 51 GHz. The diode reference laser is used for characterization of the filter cavity transmission profile described in the text.

To achieve ~10 cm/s precision required for detection and characterization of Earth-like exoplanets over several year observation times, an in situ technique may be used to characterize the cavity filter [16] and determine the apparent shift in the center of gravity of each astro-comb line from its nominal position caused by cavity dispersion and transmission resonance asymmetry and thus recover accurate astro-comb calibrations. Briefly, this technique uses a diode laser phase locked to the stabilized source comb to which the cavity filter is then locked using the Pound-Drever-Hall technique. After initially aligning the comb lines from the source comb and the transmission resonances of the cavity filter, the offset frequency between the diode laser and frequency comb is changed in discrete steps and the spectrum transmitted through the cavity is recorded. This type of broadband characterization of an astro-comb system is necessary to ensure the astro-comb spectrum is fully understood prior to its use as a calibrator.

We have employed this calibration technique with the system installed at the FLWO, Fig. 7. From this data we find good agreement between the measured group delay dispersion (GDD) and that expected from the mirrors, Fig. 3(B), along with few mrad oscillations in the recovered offset due to weak etalon effects between the mirror substrates. Because this etalon effect can be straightforwardly circumvented by using wedged substrates for the cavity filter mirrors, we have chosen to low pass filter the offset data in Fig. 7. A four point binomial filter with a cut off frequency of 0.1 nm^{-1} was chosen for removal of the high frequency oscillations to reveal the true potential of the system. Incorporation of the calibration data into astronomical observations will also require a robust model of the cavity transmission asymmetry, which was not accounted for in Fig. 7, as well as the line to line amplitude variation of the source comb.

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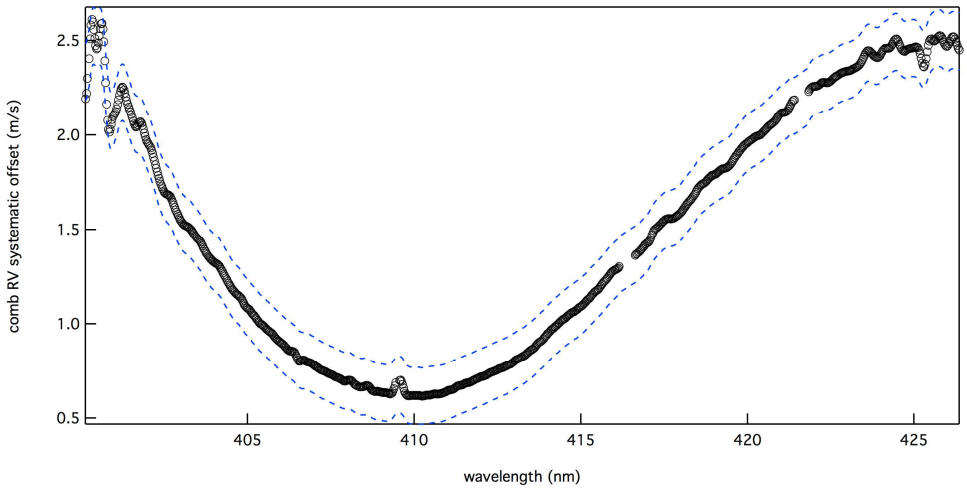


Fig. 7. Offset of recovered astro-comb line center caused by misalignment of filter cavity transmission maximum and the source comb lines as measured by the TRES spectrograph (black circles). Error bars at +/–15 cm/s on the recovered offset correspond to the uncertainty of the laser diode frequency used to lock the filter cavity and astro-comb (blue dotted lines). Breaks in the data set at 417 nm and again at 422 nm correspond to transitions between spectrograph orders as recovered from the CCD. The glitch at 408 nm is caused by amplitude to phase conversion by slight saturation of the CCD by the laser diode. Increased fluctuation in the trace above 424 nm and below 402 nm is due to the reduced signal to noise ratio at the edges of the astro-comb spectrum. The offset of recovered astro-comb lines has been low pass filtered to remove oscillations caused by mild etalon effects from the mirror substrates, see text above.

Straightforward summation of this solution to the wavelength to pixel mapping for the spectrograph will allow sub meter per second accuracy calibration of the TRES spectrograph, to be reported in an upcoming publication. An estimate of the lower bound for calibration precision can be made using (1.2) which gives precision of ~30cm/s for the signal to noise ratio of 200 observed in fits to comb spectra.

4. Conclusion

Development of visible wavelength frequency combs with wide mode spacing will have broad applicability as high-accuracy and high-stability wavelength calibrators for astrophysical spectrographs. The absence of broadband laser materials in the 400-600 nm range leaves nonlinear frequency conversion as the means to realize such wavelength calibrators. We frequency-doubled a Ti:Sapphire laser frequency comb to provide a tunable visible wavelength astro-comb operating near 420 nm, with a spectral line spacing variable over tens of GHz (up to 51 GHz in the present demonstration), a usable spectrum of 15 nm, and an output power of up to 20 nW per line. Systematic shifts in the resulting astro-comb will not limit the final calibration accuracy [16]. Using astro-combs as calibration sources, instability in spectrographs used for radial velocity spectroscopy such as the TRES spectrograph at the Fred Lawrence Whipple Observatory can be reduced to below the 1m/s level to enable high-resolution exoplanet studies. In principle, this approach could be adapted to other wavelengths within the Ti:Sapphire lasers' frequency-doubled spectrum, potentially covering the wavelength range 370-550 nm, depending on the properties of the spectrograph in question.

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