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Calibration of an echelle spectrograph with an astro-comb: a laser frequency comb with very high repetition rate

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ABSTRACT

Searches for extrasolar planets using precision radial velocity (PRV) techniques are approaching Earth-like planet sensitivity, however require an improvement of one order of magnitude to identify earth-mass planets in the habitable zone of sun-like stars. A key limitation is spectrograph calibration. An astro-comb, an octave-spanning laser frequency comb and a Fabry-Pérot cavity, producing evenly spaced frequencies with large wavelength coverage, is a promising tool for improved wavelength calibration. We demonstrate the calibration of a high-resolution astrophysical spectrograph below the 1 m/s level in the 8000-9000 Å and 4200 Å spectral bands.

Keywords: Precision radial velocity, optical wavelength calibration, laser frequency comb

1. INTRODUCTION

In recent decades, the discovery and characterization of exoplanets has progressed dramatically. Precision radial velocity (PRV) measurements are now widely used to determine oscillatory stellar motion about the barycenter of an exo-solar system. Encoded in the periodic variation of the Doppler shift of stellar spectral features measured with high resolution astrophysical spectrographs are the periods and lower limits on the masses of planets orbiting such stars. The current precision of such measurements has reached the 1 m/s level.¹ The detection of exo-Earths, Earth-mass planets in the habitable zone around Sun-like stars, however, will require an order-of-magnitude improvement in PRV measurement sensitivity to below 10 cm/s. A crucial technology for these investigations is an ultrastable, broadband, high line-density, bright wavelength calibrator that can be deployed flexibly and reliably.

An ideal wavelength calibrator provides a high density of bright, regularly-spaced optical lines optimized for the resolution of an astrophysical spectrograph used for PRV (typical resolving power $R = \lambda/\Delta\lambda \approx 100\,000$). The calibrator's spectrum should be broad (> 1000 Å) and stabilized to an atomic clock for long-term stability and accuracy, and the instrument should be robust and suitable for long-term operation in the environment of an astronomical telescope. At present, the best PRV measurement^{2,3} (precision > 50 cm/s), is substantially limited by the thorium argon (ThAr) emission lamp used as the wavelength calibrator for the spectrograph. Such emission lamps suffer from uneven line spacing, blended atomic lines from a diversity of ionic states and long-term spectral drift. A promising candidate for an ideal wavelength calibrator is the astro-comb, which consists of an octave-spanning laser frequency comb locked to an atomic clock for long-term stability, a Fabry-Pérot filtering cavity to create the appropriate line-density for use with an astrophysical spectrograph (Fig. 1),

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Figure 1. Schematic representation of astro-comb spectrum. (a) Source comb spectrum with line spacing of 1 GHz ($\approx 0.02 \text{ \AA}$ at $8000 \text{ \AA}$) and a diode laser spectral line which provides a fiducial reference to determine the absolute frequency of the comb spectrum. (b) Fabry-Pérot Cavity (FPC) transmission spectrum spaced by 50 GHz. (c) Resultant astro-comb spectrum showing exaggerated unsuppressed comb lines (referred to as “side modes” in the text).

and potentially a wavelength shifting mechanism such as a frequency doubling crystal or nonlinear optical fiber to match the desired spectral band for calibration. In previous work we developed astro-combs operating in the deep red⁴ ($\sim 8000 \text{ \AA}$) and in the blue⁵ ($\sim 4100 \text{ \AA}$). We deployed and successfully operated these red and blue astro-combs at the Tillinghast Reflector Echelle Spectrograph⁶ (TRES) and 1.5 m telescope at the Fred Lawrence Whipple Observatory (FLWO) on Mt. Hopkins in Arizona. Here we review the results of wavelength calibrations of the TRES spectrograph using the red and blue astro-combs, highlighting both spectrograph and calibrator performance near the photon-shot-noise limit,⁷ and realizing calibration precision and stability sufficient to enable PRV measurement sensitivity $< 1 \text{ m/s}$.

2. ASTRO-COMB AND SPECTROGRAPH HARDWARE AND OPERATION

An astro-comb^{4,5,8–14} consists of a high repetition-rate, octave-spanning femtosecond laser frequency comb¹⁵ (“source comb”) with a filter cavity to match the laser comb line spacing^{16,17} to the spectrograph resolution (see schematic shown in Fig. 2). In our work, The red source-comb is a pulsed titanium sapphire (Ti:Sapph) laser with a pulse repetition rate of 1 GHz (corresponding to $0.02 \text{ \AA}$ line spacing at $8000 \text{ \AA}$) and a pulse width of < 6 femtoseconds, which produces light from $7000 \text{ \AA}$ to $10000 \text{ \AA}$ in the deep red range of the optical spectrum.¹⁸ The light may be frequency doubled to around $4000 \text{ \AA}$ in the blue, *e.g.*, using a β -barium borate (BBO) crystal, to provide a blue source-comb.⁵ The 1 GHz source-comb (see Fig. 1(a)) is stabilized to a rubidium atomic clock providing reference lines spaced by $0.02 \text{ \AA}$ with optical frequencies given by

$$f = f_{\text{ceo}} + n \times f_{\text{rep}} \quad (1)$$

where f_{rep} is the repetition rate of the laser, f_{ceo} is the carrier envelope offset frequency, determined by intra-cavity dispersion, and n is an integer numbering the comb spectral lines (comb teeth).¹⁵ Both f_{ceo} and f_{rep} are radio-frequencies which are measured and stabilized to the atomic frequency reference. The central wavelength portion of the red or blue source-comb light is spatially overlapped with light from a single-mode diode laser, which is offset-locked to the source-comb at a frequency to optimize the Fabry-Pérot cavity (FPC) for maximum astro-comb bandwidth. The diode laser and source-comb are configured to provide light with orthogonal linear polarizations. The spatially overlapped light is sent to a single-mode, polarization maintaining (PM) optical fiber

Figure 2. Block diagram for the red and blue astro-combs operating around 8000 Å and 4000 Å, respectively. A 1-GHz repetition-rate Ti:Sapphire laser frequency comb (source comb), with a spectrum centered at 8000 Å and stabilized to a rubidium atomic clock, provides emission lines regularly spaced by 0.02 Å. Light from the source-comb, either directly or after frequency doubling in a BBO crystal to 4000 Å to provide the blue source-comb, is spatially overlapped with light from a single wavelength reference laser and sent via a single-mode optical fiber through a Fabry-Pérot cavity to create an astro-comb spectrum with an adjustable effective repetition rate up to 50 GHz (*i.e.*, spectral line spacing up to 1 Å). A multi-mode fiber, which can be physically shaken to produce optical mode scrambling, sends the astro-comb light to the wavelength calibration system of the TRES spectrograph.

to provide a clean spatial mode. After the fiber, the light is passed through a plane-mirror FPC (Fig. 1(b)) with modified quarter wave Bragg stack coatings to create a high repetition-rate astro-comb spectrum with adjustable frequency spacing up to 50 GHz. After the filter cavity, the transmitted astro-comb lines have frequencies, f_{AC} , given by

$$f_{AC} = f_{ceo} + (l + Kn')f_{rep} \quad (2)$$

where K is the integer line spacing multiplier determined by the ratio of the FPC's free spectral range (FSR) to the source-comb line spacing (f_{rep}); l is the offset of the astro-comb lines in the source-comb; and n' numbers the astro-comb teeth. Note that Eq. 2 gives the exact frequencies of the main astro-comb lines, without accounting for residual effects from source comb lines suppressed by the FPC ("side modes"). As these side modes are not resolved by the spectrograph, they can systematically shift the line centers recovered by the spectrograph if they are not sufficiently suppressed by the FPC. An electro-optic modulator (EOM) modulates the frequency of the single-mode laser and allows the FPC to be locked to the reference laser with a Pound-Drever-Hall¹⁹ style technique in transmission via a piezo electric transducer (PZT). Light from the reference laser is separated from the comb light after the FPC for stabilization of the cavity, while the astro-comb light is propagated by a multi-mode optical fiber to the calibration system of the astrophysical spectrograph. The multi-mode optical fiber may be physically shaken to produce mode and phase scrambling and thus reducing modal noise (see Fig. 3).

3. ASTRO-COMB WAVELENGTH CALIBRATION OF SPECTROGRAPH

During two sessions at the Whipple Observatory in 2009 and 2010 we accumulated several weeks of astro-comb calibration spectra using the TRES spectrograph. These spectra were primarily acquired during the day or while the telescope dome was closed due to poor weather conditions, though some calibration spectra were acquired during observing hours. We used standard techniques to acquire and reduce astro-comb calibrations from the TRES spectrograph into one dimensional (1-D) spectra.²⁰ At the beginning of each calibration sequence, we took

Figure 3. Images of a 100 μm multi-mode optical fiber with mechanical shaker (a) off and (b) on, showing reduced intensity variation across the fiber surface in the presence of shaking, observed with a laboratory CMOS camera. (c) Cross section showing both the shaker on and off and the reduction by a factor of 4 of the intensity variation.

“biases,” zero-time exposures with the shutter closed, to determine the zero value of each CCD pixel and “flats,” exposures of the spectrograph to a continuum halogen lamp. Lastly, we acquired a series of 2-D astro-comb image, which required 300 seconds when using the red astro-comb due to the presence of an integrating sphere in the TRES calibration system reducing the calibration throughput by more than 10^6 and 10 seconds when using the blue astro-comb as the integrating sphere was not present. 1-D spectra for each spectrograph order were extracted from the 2-D spectral image and properly normalized using the biases and flats.

Figure 4 shows example astro-comb spectra acquired using the TRES spectrograph. The blue astro-comb covers about 100 $\text{\AA}$ and centered around 4100 $\text{\AA}$ (Fig. 4(a)) and the red astro-comb spans 1100 $\text{\AA}$ centered on 8300 $\text{\AA}$ (Fig. 4(b)). With the greater optical throughput from the blue astro-comb to the spectrograph (because the integrating sphere was removed), each 1-D spectral peak reaches a maximum of 40 000 – 60 000 counts per 1-D point in a 10 s exposure.

The expected frequency uncertainty, $\delta\nu$, from photon shot-noise, in determining the centroid of a single astro-comb 1-D spectral peak^{8,21} is

$$\delta\nu = A \frac{\text{FWHM}}{S/N \times \sqrt{n}} \quad (3)$$

where A is a normalization constant of order unity, FWHM is the peak width, S/N is the peak signal-to-noise ratio, and n is the number of 1-D points sampling the peak. For the TRES spectrograph with an instrument profile dominated by the fiber profile, we find from simulations that $A \approx 0.4$. The resulting sensitivity from a photon-shot-noise limited measurement for one red astro-comb peak of width 10 GHz, spanning 6 pixels, and with 50 000 counts is then 7 MHz (PRV sensitivity ≈ 7 m/s). In the ideal case of no systematic effects, the shot-noise-limited precision of a wavelength calibration improves as $N^{1/2}$, where N is the number of astro-comb spectral peaks leading to 50 cm/s PRV sensitivity for 200 peaks spanning one full echelle order in the center of the astro-comb spectrum and below 30 cm/s when all six orders of the red astro-comb are combined. For the blue astro-comb, the photon-shot-noise limit is 16 MHz (PRV sensitivity ≈ 6 m/s at 4100 $\text{\AA}$) sensitivity for one peak of width 20 GHz and spanning 6 pixels. With roughly 600 astro-comb lines in the calibration spectrum (Fig. 4(a)), the expected photon-shot-noise limit for the wavelength calibration sets an ideal PRV sensitivity of 50 cm/s in a single calibration exposure.

3.1 Fitting astro-comb spectra

To calibrate the spectrograph we fit a measured astro-comb 1-D spectrum to extract a “frequency solution”: an assignment of frequency (and thus wavelength in vacuum) to each CCD pixel. Each astro-comb spectral peak (*i.e.*, calibration line) is separated from its neighbor by a constant frequency determined by Eq. 2 with at least 10

Figure 4. Example astro-comb spectra. (a) Spectrum of the blue astro-comb, acquired with the TRES spectrograph. FWHM of the spectrum is approximately 100 Å with 40000 to 60000 peak counts acquired in a 10 s exposure with the astro-comb light attenuated by a factor of 10. Inset: five peaks from the central region of the blue astro-comb spectrum. (b) Spectrum of the red astro-comb spanning 1100 Å from 7700 Å to 8800 Å with 50000 peak counts.

digit accuracy, as both the repetition rate and offset frequency are locked to a rubidium atomic clock. Therefore, the centroids of astro-comb lines are spaced evenly in the frequency domain. A smoothly varying polynomial then provides a reliable frequency solution accounting for dispersion in the spectrograph. Importantly, astro-comb calibration lines are much narrower than the response of the spectrograph - effectively frequency delta functions - allowing the spectrograph response to be determined directly. We model the 1-D instrument profile of each astro-comb line as the convolution of a modified half circle, representing the optical fiber output bringing the astro-comb light into the spectrograph and a sum of Hermite-Gaussian modes, representing contributions from the spectrograph optics (Fig. 5). This convolved profile is then integrated across each 1-D pixel for fitting to the 1-D astro-comb spectrum. Achieving near photon-noise sensitivity in the fits of astro-comb spectra requires the spectrograph optical response to include 16 orders of Hermite-Gaussian modes, including both symmetric and anti-symmetric terms. To apply this multi-parameter model to the astro-comb spectrum in which each peak covers six pixels on the spectrograph, the parameters of the fit model are assumed to vary smoothly across each spectrograph order, and thus may be re-parameterized by a series of polynomials.

All the parameters describing the instrument profile for an individual astro-comb line along with the frequency solution and the background due to read noise and scattered light are re-parameterized as smoothly varying polynomials across each order of the spectrograph, with the amplitudes of each line allowed to vary independently. Resulting fit parameters for both red and blue astro-comb data confirm expectations based on the spectrograph's physical properties: we find that the spectrograph instrument profile is dominated by the half-circle component representing the 100 micron optical fiber along with a 15 micron width from the Hermite-Gaussian modes representing the spectrograph optics. Our fits yield slow variation with wavelength in the astro-comb spectral peak width from both the half-circle and Hermite-Gaussian components of roughly 20%. These results are consistent with models of the spectrograph focus, anamorphism, and variable dispersion showing roughly 1 pixel variation across an echelle order, with the spot size becoming larger at shorter wavelength on the blue end of the spectrograph.⁶

A key requirement for achieving photon-shot-noise limited spectrograph calibration is scrambling of the coherence of the input astro-comb light to prevent unwanted optical interference patterns on the spectrograph CCD, which leads to added intensity noise in the measured astro-comb spectrum. Individual transverse modes of the optical fiber, used to transport the astro-comb light to the spectrograph, have differing path lengths, leading to non-trivial optical interference patterns on the focal plane of the CCD²² if the input astro-comb light is coherent. We reduce the optical interference using an optical fiber shaker (Fig. 3) to scramble the amplitudes and phases in each mode of the multi-mode fiber. To study the noise properties of the blue astro-comb as measured by the spectrograph with the mechanical shaking of the fiber turned off and on, we normalized the heights of all astro-comb 1-D spectral lines provided by the data fit procedure described above. We then folded all

Figure 5. Representation of the components of the function fit to each astro-comb spectral peak: (a) filtered spectrum of the comb, (b) 1-D integrated profile of the optical fiber, (c) instrument profile of the spectrograph optics, and (d) the discretization of CCD pixels.

normalized astro-comb lines on top of each other with their peak centers aligned and widths normalized so as to create a single peak. Comparing such normalized and folded astro-comb spectra with fiber shaking off and on, we find that shaking improves the calibration signal-to-noise ratio by a factor of 3-5. Using the fit model described above with blue astro-comb spectra acquired with active mode scrambling, we realized near photon-shot-noise limits on the fit to one echelle order from the TRES spectrograph, with residuals within 10% of photon-shot-noise near the folded line center and growing somewhat in the wings, as determined point-by-point directly from the measured line profile with a noise model including photon-shot-noise as well as read noise and in good agreement with Eq. (3).

3.2 Spectrograph stability

To characterize the stability of the TRES spectrograph, we performed repeated wavelength calibrations using the red astro-comb over a week. We injected light into two channels of the spectrograph: the “science” fiber, which when not being calibrated is guided on a target star; and a “sky” fiber used to measure background light (*e.g.*, scattered moonlight). We evaluated overall changes in the frequency solution of the spectrograph by calculating the central frequency of each spectrograph order and determining the average change of all calibrated orders. The results of a night of such calibrations are summarized in Fig. 6(a), showing changes in the frequency solution of several hundred m/s, corresponding to several hundred MHz changes in the mean optical frequency. Over the course of a full week of such calibrations, we observed comparable variations in the frequency solution, with maximum variations in the frequency solution < 250 m/s. These results are consistent with expectations of the TRES spectrograph’s performance as observed with ThAr wavelength calibrations.⁶ The standard error in PRV precision ≈ 1 m/s for the red astro-comb of the frequency solution (corresponding to roughly 1 millipixel on the CCD) for the full six spectrograph orders. This standard error is approximately a factor of 2 above expectations from photon shot-noise, limited by excess noise caused by (i) spatial variations in the intensity profile of astro-comb light leaving the fiber (as the shaker was not used with the red astro-comb) and (ii) by fringing at the red end of the CCD. Nevertheless, our fit model successfully recovered red astro-comb spectra in the presence of this excess noise at the 1 m/s level.

Despite the 1 m/s sensitivity of the red astro-comb frequency solutions, the solutions for the science and sky channel wavelength solutions diverge by 6 m/s over the course of one night (Fig. 6(b)). This is likely caused by the off-axis positioning of the sky channel,⁶ which is therefore not illuminated uniformly by the calibration light. Significant re-engineering of the calibration unit at the TRES spectrograph has recently been implemented which should reduce such drifts.

Using the blue astro-comb we demonstrated near photon-shot-noise limited wavelength calibration of the TRES spectrograph. At the shorter blue wavelengths the silicon of the CCD is strongly absorbing, which greatly suppresses fringing. Additionally, we implemented the mechanical shaker described above to eliminate interference between modes in the optical fiber coupling light from the blue astro-comb to the spectrograph. We repeatedly calibrated the spectrograph over several consecutive nights using the blue astro-comb. Figure 7(a)

Figure 6. (a) Measured drift over six hours of the TRES spectrograph frequency solution from red astro-comb calibrations in the 8000-9000 Å spectral range, expressed as an effective PRV shift. Results are shown for calibrations using two input optical channels to the spectrograph: the science and sky fibers. Across five nights of calibrations, the frequency solution never drifted by more than 250 m/s from the initial frequency solution. (b) Difference in the frequency solution between the two fibers showing drift of ≈ 8 m/s. Over the course of a week of calibrations, the difference between the wavelength solutions for the two fibers was never larger than 10 m/s. Uncertainties in the data points of (a) and (b) ≈ 1 m/s.

Figure 7. Measured drift over about one hour of the TRES spectrograph frequency solution from blue astro-comb calibration. (a) Frequency solution (expressed as an effective PRV shift) from averaging four spectrograph orders of blue astro-comb data between 4000 and 4200 Å. Error bars indicate the standard deviation of the averaged orders. Observed PRV variations ~ 30 m/s over spans of several minutes are consistent with known drift rates of the TRES spectrograph.⁶ (b) For each spectrograph order, variations of frequency solutions from the average solution (expressed as effective PRV shifts) ≈ 1 m/s.

shows a sample of the measured drift in the spectrograph wavelength calibration over a period of about one hour, consistent with the spectrograph's sensitivity to changes in the ambient environment. Because of improved coupling of the blue astro-comb light to the spectrograph compared to the earlier red astro-comb measurements, much larger optical throughput was achieved in the blue astro-comb measurements, and hence much faster spectrograph calibrations, such as the 10 s exposures reported here. Note, however, that readout of the spectrograph CCD took close to one minute, limiting the calibration speed. Typical measured spectrograph drift during the readout period was near 1 m/s. Residuals in the frequency solutions provided by the blue astro-comb were ≈ 1 m/s in each spectrograph order (Fig. 7(b)), and within 10% of that expected from photon shot-noise as verified with Monte Carlo simulations of the astro-comb spectrum using a noise model including photon-shot-noise and read noise. This enables 50 cm/s calibration of the TRES spectrograph using the full spectrum of the blue astro-comb across four spectrograph orders.

4. CONCLUSIONS

We used two astro-combs, each consisting of a laser frequency comb integrated with a Fabry-Pérot filtering cavity, to calibrate the absolute frequency (or wavelength) of a high-resolution astrophysical spectrograph over a 1000 Å band in the deep red and over 200 Å in the blue. We reliably operated the astro-combs over several weeks in 2009 and 2010 at the Fred Lawrence Whipple Observatory (FLWO) on Mt. Hopkins in Arizona, and repeatedly calibrated the TRES spectrograph. Expressed in terms of measurement sensitivity to changes in the precision radial velocity (PRV) of stellar sources, relevant to searches for small exoplanets, the astro-combs provided spectrograph calibration sensitivity < 1 m/s, limited primarily by the environmental sensitivity of the TRES spectrograph.

In ongoing work, we are preparing both to calibrate broader, visible wavelength bands and to apply the obtained sub-m/s calibration sensitivity to stellar PRV observations. To this end we have assembled and are presently characterizing a “green astro-comb” comprising a 1 GHz repetition rate Ti:Sapphire laser, a coherent wavelength shifting element based on a short, tapered photonic-crystal fiber (PCF),²³ and a broadband Fabry-Pérot filter cavity based on zero dispersion group delay mirror sets.^{24,25} Improved spectrograph wavelength calibration is not limited to exoplanet research — a broad cross section of astrophysical problems may be addressed, perhaps including the nature and dynamics of dark energy,^{26,27} and the constancy of fundamental constants over cosmological time scales.

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REFERENCES

- [1] Pepe, F., Lovis, C., Ségransan, D., Benz, W., Bouchy, F., Dumusque, X., Mayor, M., Queloz, D., Santos, N. C., and Udry, S., “The HARPS search for Earth-like planets in the habitable zone,” *Astron. Astrophys.* **534**, A58, 1–16 (2011).
- [2] Lovis, C., Mayor, M., Pepe, F., Alibert, Y., Benz, W., Bouchy, F., Correia, A. C. M., Laskar, J., Mordasini, C., Queloz, D., Santos, N. C., Udry, S., Bertaux, J., and Sivan, J., “An extrasolar planetary system with three Neptune-mass planets,” *Nature* **441**, 305–309 (2006).
- [3] Udry, S., Bonfils, X., Delfosse, X., Forveille, T., Mayor, M., Perrier, C., Bouchy, F., Lovis, C., Pepe, F., Queloz, D., and Bertaux, J.-L., “The harps search for southern extra-solar planets,” *Astron. Astrophys.* **469**, L43–L47 (2007).
- [4] Li, C., Benedick, A. J., Fendel, P., Glenday, A. G., Kärtner, F. X., Phillips, D. F., Sasselov, D., Szentgyorgyi, A., and Walsworth, R. L., “A laser frequency comb that enables radial velocity measurements with a precision of 1 cm s^{−1},” *Nature* **452**, 610–612 (2008).
- [5] Benedick, A. J., Chang, G., Birge, J. R., Chen, L.-J., Glenday, A. G., Li, C.-H., Phillips, D. F., Szentgyorgyi, A., Korzennik, S., Furesz, G., Walsworth, R. L., and Kärtner, F. X., “Visible wavelength astro-comb,” *Opt. Express* **18**, 19175–19184 (2010).
- [6] Furesz, G., “Design and application of high resolution and multiobject spectrographs: Dynamical studies of open clusters,” Ph. D. thesis, University of Szeged, Hungary (2008).
- [7] Phillips, D. F., Glenday, A. G., Li, C.-H., Cramer, C., Furesz, G., Chang, G., Benedick, A. J., Chen, L.-J., Kärtner, F. X., Korzennik, S., Sasselov, D., Szentgyorgyi, A., and Walsworth, R. L., “Calibration of an astrophysical spectrograph below 1 m/s using a laser frequency comb,” *Opt. Express* **20**, 13711–13726 (2012).
- [8] Murphy, M. T., Udem, T., Holzwarth, R., Sizmann, A., Pasquini, L., Araujo-Hauck, C., Dekker, H., D’Odorico, S., Fischer, M., Hänsch, T. W., and Manescau, A., “High-precision wavelength calibration of astronomical spectrographs with laser frequency combs,” *Mon. Not. R. Astron. Soc.* **380**, 839–847 (2007).
- [9] Osterman, S., Diddams, S., Beasley, M., Froning, C., Hollberg, L., MacQueen, P., Mbele, V., and Weiner, A., “A proposed laser frequency comb-based wavelength reference for high-resolution spectroscopy,” in “Techniques and Instrumentation for Detection of Exoplanets III,” SPIE, 66931G, 1–9 (2007).
- [10] Steinmetz, T., Wilken, T., Araujo-Hauck, C., Holzwarth, R., Hänsch, T. W., Pasquini, L., Manescau, A., D’Odorico, S., Murphy, M. T., Kentischer, T., Schmidt, W., and Udem, T., “Laser frequency combs for astronomical observations,” *Science* **321**, 1335–1337 (2008).
- [11] Braje, D. A., Kirchner, M. S., Osterman, S., Fortier, T., and Diddams, S. A., “Astronomical spectrograph calibration with broad-spectrum frequency combs,” *Euro. Phys. J. D* **48**, 57–66 (2008).
- [12] Wilken, T., Lovis, C., Manescau, A., Steinmetz, T., Pasquini, L., Lo Curto, G., Hänsch, T. W., Holzwarth, R., and Udem, T., “High-precision calibration of spectrographs,” *Mon. Not. R. Astron. Soc. Lett.* **405**, L16–L20 (2010).

- [13] Redman, S. L., Ycas, G. G., Terrien, R., Mahadevan, S., Ramsey, L. W., Bender, C. F., Osterman, S. N., Diddams, S. A., Quinlan, F., Lawler, J. E., and Nave, G., “A high-resolution atlas of uranium-neon in the h band,” *The Astrophysical Journal Supplement Series* **199**:2, 1-11 (2012).
- [14] Ycas, G. G., Quinlan, F., Diddams, S. A., Osterman, S., Mahadevan, S., Redman, S., Terrien, R., Ramsey, L., Bender, C. F., Botzer, B., and Sigurdsson, S., “Demonstration of on-sky calibration of astronomical spectra using a 25 GHz near-ir laser frequency comb,” *Opt. Express* **20**, 6631–6643 (2012).
- [15] Cundiff, S. T., and Ye, J., “Colloquium: Femtosecond optical frequency combs,” *Rev. Mod. Phys.* **75**, 325–342 (2003).
- [16] Steinmetz, T., Wilken, T., Araujo-Hauck, C., Holzwarth, R., Hänsch, T., and Udem, T., “Fabry–Pérot filter cavities for wide-spaced frequency combs with large spectral bandwidth,” *Appl. Phys. B* **96**, 251–256 (2009).
- [17] Kirchner, M. S., Braje, D. A., Fortier, T. M., Weiner, A. M., Hollberg, L., and Diddams, S. A., “Generation of 20 GHz, sub-40 fs pulses at 960 nm via repetition-rate multiplication,” *Opt. Lett.* **34**, 872–874 (2009).
- [18] Benedick, A., Birge, J., Ell, R., Mucke, O. D., Sander, M., and Kärtner, F. X., “Octave spanning 1 GHz Ti:sapphire oscillator for HeNe CH₄-based frequency combs and clocks,” in “Lasers and Electro-Optics, 2007 and the International Quantum Electronics Conference,” (CLEOE-IQEC 2007).
- [19] Drever, R. W. P., Hall, J. L., Kowalski, F. V., Hough, J., Ford, G. M., Munley, A. J., and Ward, H., “Laser phase and frequency stabilization using an optical resonator,” *Appl. Phys. B* **31**, 97–105 (1983).
- [20] Piskunov, N. E. and Valenti, J. A., “New algorithms for reducing cross-dispersed echelle spectra,” *Astronomy and Astrophysics* **385**, 1095–1106 (2002).
- [21] Brault, J. W., “High precision Fourier transform spectrometry: The critical role of phase corrections,” *Microchimica Acta* **93**, 215–227 (1987).
- [22] Baudrand, J. and Walker, G. A. H., “Modal noise in highresolution, fiberfed spectra: A study and simple cure,” *Publ. Astron. Soc. Pac.* **113**, 851–858 (2001).
- [23] Chang, G., Li, C.-H., Phillips, D. F., Walsworth, R. L., and Kärtner, F. X., “Toward a broadband astro-comb: effects of nonlinear spectral broadening in optical fibers,” *Opt. Express* **18**, 12736–12747 (2010).
- [24] Chen, L.-J., Chang, G., Li, C.-H., Benedick, A. J., Philips, D. F., Walsworth, R. L., and Kärtner, F. X., “Broadband dispersion-free optical cavities based on zero group delay dispersion mirror sets,” *Opt. Express* **18**, 23204–23211 (2010).
- [25] Li, C.-H., Chang, G., Glenday, A. G., Philips, D. F., Kärtner, F., Szentgyorgyi, A., and Walsworth, R. L., “Conjugate Fabry–Pérot cavity pair for astro-combs,” submitted to *Opt. Lett.* (2012).
- [26] Sandage, A., “The change of redshift and apparent luminosity of galaxies due to the deceleration of selected expanding universes,” *Astrophys. J.* **136**, 319–333 (1962).
- [27] Loeb, A., “Direct measurement of cosmological parameters from the cosmic deceleration of extragalactic objects,” *Astrophys. J. Lett.* **499**, L111–L1114 (1998).