A proposed laser frequency comb based wavelength reference for high resolution spectroscopy

Steve Osterman,[1*] Scott Diddams,[2] Matthew Beasley,[1] Cynthia Froning,[1]
Leo Hollberg,[2] Phillip MacQueen,[3] Vela Mbele,[2,4] Andrew Weiner[2,5]

[1] University of Colorado, Center for Astrophysics and Space Astronomy, Boulder, CO, USA
[2] National Institute of Standards and Technology, Time and Frequency Division, Boulder CO, USA
[3] University of Texas, McDonald Observatory, Austin, TX, USA
[4] National Metrology Institute of South Africa, Pretoria, SA
[5] Purdue University, School of Electrical and Computer Engineering, West Lafayette, IN, USA

ABSTRACT

High resolution spectroscopy is the foundation for many challenging astronomical observations. A highly precise, repeatable and stable wavelength calibration is especially essential for long term radial velocity observations. The two wavelength references in wide use for visible wavelengths, iodine absorption cells and thorium/argon lamps, each have fundamental limitations which restrict their ultimate utility.

We are exploring the possibility of adapting emerging laser frequency comb technology in development at the National Institute of Standards and Technology in Boulder, Colorado, to the needs of high resolution, high stability astronomical spectroscopy.[1,2] This technology has the potential to extend the two current wavelength standards both in terms of spectral coverage and in terms of long term precision, ultimately enabling better than 10 cm/s astronomical radial velocity determination.

Keywords: Frequency comb, optical spectroscopy, radial velocity, exoplanet

1. INTRODUCTION

High precision, high resolution spectroscopy has enabled many of the most challenging and productive of recent astronomical observations, including the search for extrasolar planets, constraining fundamental cosmological constants and perhaps even directly measuring the acceleration of the expansion of the Universe. Without a highly precise, repeatable and stable wavelength calibration, the ultimate success of these lines of inquiry will be compromised.

Modern astronomical observatories employ high resolution optical spectrographs operating at resolutions ($\lambda/\Delta\lambda$) between 50,000 and 300,000 which can resolve lines with equivalent Doppler widths on order 1km/s, and have monitored changes in radial velocity (RV) down to 1m/s over extended periods. This has resulted in the discovery of the majority of the known planets orbiting distant stars.[3] The best of these spectrographs could potentially monitor RV changes down to a few cm/s if a suitable wavelength reference can be obtained.[4,5] New astronomical telescopes in development such as the Thirty Meter Telescope and the Giant Magellan Telescope[6,7,8] will be host to high resolution optical spectrographs which will expand the boundaries of high precision spectroscopy. The performance of these new instruments will be limited by several factors, with the wavelength calibration source as one of the principal contributors to any error budget. An ideal wavelength standard would provide a high density array of uniformly spaced, uniformly bright emission lines which could be traced to fundamental constants or to the standard second. The precision and long term stability of this source should be sufficiently

* University of Colorado, Boulder , Center for Astrophysics and Space Astronomy, 1255 38th St Boulder CO 80305 Steve.Osterman@Colorado.Edu voice 1.303.492.3656 fax 1.303.492.5941

Techniques and Instrumentation for Detection of Exoplanets III, edited by Daniel R. Coulter
Proc. of SPIE Vol. 6693, 66931G, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.734193

high that these do not dominate the ultimate precision of the spectrograph ($\Delta\lambda/\lambda > 10^{-11}$). The laser frequency comb was considered as a calibration source by Murphy, et al., 2007,[5] and found to have many of the properties of an ideal spectral reference.

With a spectrograph and calibration system capable of achieving this level of precision and stability, a number of lines of enquiry become viable. These include

- The search for terrestrial mass planets in earthlike orbits. Such a planet would induce ~10cm/s radial velocity (RV) shifts in the host star over an orbit, requiring long term wavelength monitoring at the level of $\Delta\lambda/\lambda \sim 1\times10^{-10}$, far beyond the grasp of the most precise observations to date.
- Direct measurement of the acceleration of the universe. Loeb indicates that this should be detectable with 1-10 cm/s spectroscopy over a baseline of several decades.[9]
- Constrain variation of the fine structure constant using QSO spectra. While the current generation of spectrometers have sufficient resolution and long term repeatability to perform this measurement, there is too much uncertainty in the absolute wavelength of current calibration standards and of the laboratory values for the species of interest.[10]
- A single frequency comb could be used to increase the precision of current wavelengths standards such as Thorium/Argon (Th/Ar) lamps and iodine (I2) cells by providing a calibration traceable to the standard second. These lamps could in turn be used to increase the precision of observations made at remote facilities.

Beyond the compelling benefits in observational astronomy and cosmology, a laser frequency comb based calibration source could positively impact several other important applications that require robust frequency combs with 10-20 GHz mode spacing. These applications include direct frequency comb spectroscopy,[11,12] remote sensing, optical and microwave waveform synthesis,[13] high-speed coherent communications, and optical clock development.[14]

Our objective is to adapt the Nobel prize winning laser frequency comb technology[1,2] to the needs of high resolution, high stability astronomical spectroscopy, exploring techniques to produce frequency combs with 10-20 GHz mode spacing that span the visible and near-infrared spectral region (400-1100 nm).

2. INSTRUMENT OVERVIEW

Limitations of Existing Calibration Sources

While astronomical spectrographs could, in principal, monitor changes in RV down to a few cm/s, a highly stable and repeatable wavelength standard is needed in order to compare observations that occur days or months apart with the required precision. The two dominant wavelength calibration technologies, Th/Ar lamps and I2 cells, have enabled RV observations down to 1m/s, but are faced with fundamental limitations which restrict their utility for sub-m/s observations.[5,15]

Today, iodine absorption cells are standard wavelength references for high precision velocity observations (for planet searches) and have provided reliable and cross-system replicatable absorption spectra. However, this is achieve at best only between 490 and 640nm, leaving a substantial portion of the optical band uncalibrated, and at the expense of depressing throughput of the target continuum by as much as 50%. In addition, I2 cells require deconvolution of the stellar spectrum from the superimposed iodine absorption spectrum, requiring high signal to noise.[16]

Th/Ar and He/Ne/Th lamps are dim but well characterized and provide rich spectra in the region of interest. For example, Th/Ar lamps provide over 4000 stable, identified lines between 310 and 1100 nm, and have provided excellent reference spectra for many instruments. However, hollow cathode lamps have limitations to their long term stability. While the wavelengths of individual emissions do not change, uncertainties in the absolute wavelengths assigned to these lines can introduce significant systematic RV errors, and the relative line strengths from hollow cathode lamps can change with time and operating conditions, altering the centroid of unresolved line groups.[15,17]

Laser frequency comb technology provides a near perfect reference, generating a set of evenly spaced calibration lines whose separation and base wavelength can be anchored to a compact atomic oscillator.[18,19] This could provide precision better than one part in 10^{11}, which is sufficient for the requirements of cm/s spectroscopy. However, at visible wavelengths these combs typically create lines separated by a maximum of ~1 GHz, resulting in lines spaced at an equivalent resolution of 500,000 – unresolvable by typical astronomical spectrographs. Ideally, these lines would be spaced no more tightly than one per 2.5 resolution elements, or at about 12.5 GHz for a R=100,000 optical spectrograph.

Calibration System Concept

While there are several types of laser frequency combs covering differing spectral regions, this paper will concentrate on the Ti:Sapphire femtosecond frequency comb because of its high line spacing and broad coverage of the optical band. The Ti:Sapphire frequency comb produces a series of narrow lines evenly spaced in frequency. The line spacing and offset frequency can both be tied to atomic clocks and controlled to great precision. The optical linewidth of the comb elements can be at or below 1 MHz, with the exact value being dependent on the spectral purity of the reference oscillator that controls the mode spacing. These lines, if properly filtered to a spacing of >12.5GHz, could provide a nearly ideal calibration source. The line centers would be densely and uniformly packed, span much if not all of the optical band, have nearly uniform intensity,[*] have known wavelengths directly tied to the SI second, and maintain stability over long periods.

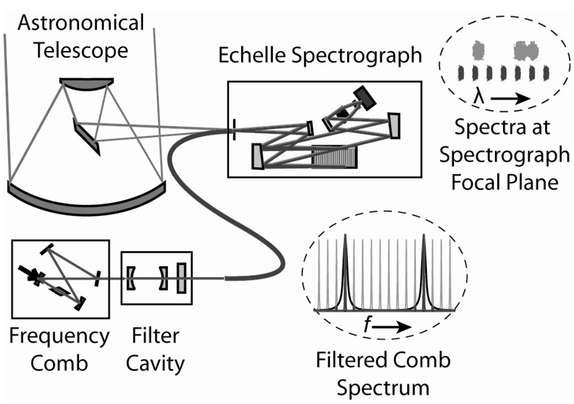

Figure 1. Light from the telescope and from the filter comb are fed to the spectrograph entrance aperture, employing an optical fiber for the LFC feed. The raw output of the frequency comb (grey in lower right balloon) is filtered so that only 1/10 teeth are fed into the spectrograph. The image at the spectrograph focal plane shows the science (above) and the calibration spectra (below) with a fixed offset between the two in the cross-dispersion direction.

A frequency comb can be used on an astronomical telescope either as a stand alone calibration source or in parallel with other calibration sources or absorption cells. Light from the frequency comb is first fed into a filter cavity to increase the effective mode spacing.[†] From here, light enters the spectrograph via a scrambled fiber optic feed. The feed is offset from the science spectrum in the cross dispersion direction so that simultaneous science and calibration spectra can be obtained. Alternatively, the output of a frequency comb is sufficiently bright that the light could be fed to the spectrograph via an integrating sphere in order to match the illumination of the spectrograph entrance slit by the science spectrum as accurately as possible.

Because of possible fixed dispersion direction offsets between the science and calibration spectra in a fiber fed system, an independent calibration source such as an absorption cell may be required to establish an absolute wavelength scale for the science spectrum, but no such external scale is needed to monitor relative changes over time.

Overview of Frequency Comb Technology

The use of a mode-locked laser as a tool for optical frequency metrology was first demonstrated with picosecond lasers in the late 1970's.[20] The concept lay largely dormant for two decades before being re-introduced by

[*] The comb output is many orders of magnitude brighter than needed for astronomical calibrations so that the spectrum can be flattened without any loss of capability.

[†] It is unlikely that a single cavity will be able to cover more than 15% of the optical band, so several cavities will be used in parallel.

Hänsch and co-workers.[21] The basic idea is to use the comb of frequencies emitted from a mode-locked laser as a precise "optical frequency ruler". Two microwave frequencies (f_r and f_0, see Fig. 2) are related to the n^{th} mode of the optical frequency comb by the simple expression

$$f_n = f_0 + nf \tag{1}$$

The repetitive pulse train $E(t)$ in the top panel of Fig. 2 can be written as

$$E(t) = \mathrm{Re}\left(A(t)\exp(-i2\pi f_c t)\right) = \mathrm{Re}\left(\sum_n A_n \exp(-i2\pi(f_0 + nf_r)t)\right) \tag{2}$$

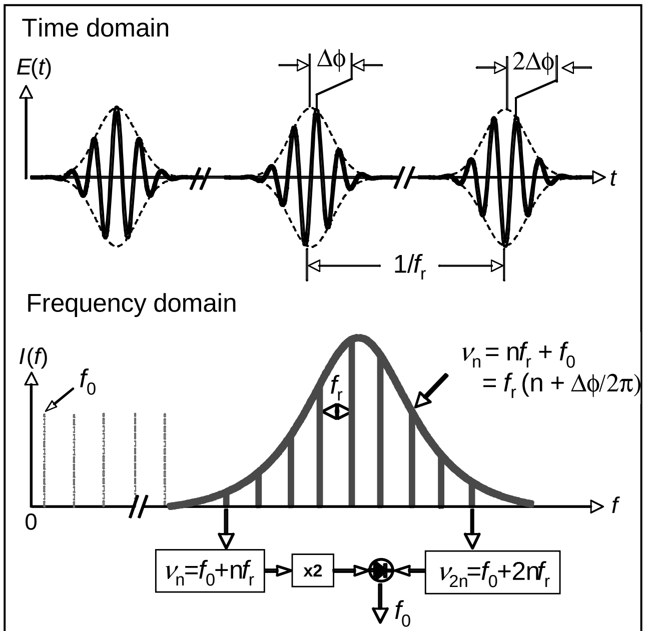

Figure 2. The time- and frequency-domain rep-representations of the output of a mode-locked femtosecond laser: Pulses are emitted at the rate f_r, but, because of dispersion in the laser cavity, the carrier advances with respect to the envelope by $\Delta\varphi$ from one pulse to the next. In the frequency domain, the result of this phase slip is an offset common to all modes of $f_0 = f_r\Delta\varphi/(2\pi)$. The lower half of this figure also shows the "f-2f" technique of self-referencing, whereby the offset frequency is measured.

The offset frequency f_0 and pulse repetition frequency f_r are illustrated in the lower panel of Fig. 2, and f_c is the carrier frequency. What Eqs. 1 and 2 indicate is that the output of the laser cavity is a series of ultrashort (~ 10fs) pulses uniformly separated in time. Note that in so far as f_0 and f_r can be stabilized, Eq. 1 is an exact relationship, which has been found to be valid with precision reaching one part in 10^{19}.[22]

While the repetition frequency f_r is the pulse rate of the pump laser and is easily accessible and controllable, the offset frequency f_0 is less readily determined. The offset frequency f_0 arises from dispersion in the cavity components and without active control will drift at random.

While it is possible to stabilize the offset frequency by monitoring the difference between some mode n of the laser and the output of a stabilized laser, a more direct solution takes advantage of the broad band nature of the output from the laser, which in the most advanced femtosecond sources spans more than an octave. This in turn makes it possible to readily measure and control the offset frequency comb to itself. Light from the comb is split, with a portion of the light going directly into a spectrometer, and the rest first passing through a frequency doubler and then into the spectrometer. The output of the frequency doubler is $2f_1=2(n_1f_r+f_0)$. If the band width of the frequency comb is broad enough, then there will be some mode $f_2=n_2f_r+f_0 =2f_1$ with $n_2=2n_1$ and enough power to beat against the frequency doubled component. The observed beat frequency is then

$$f_{\mathrm{beat}} = 2(n_1 f_r + f_0) - n_2 f_r + f_0 = f_0 \;\text{ for }\; n_2 = 2n_1 \tag{3}$$

This radio frequency beat can be directly measured and used to adjust the cavity dispersion to stabilize f_0 to the same precision as f_r. With f_0 and f_r tied to a stable atomic source, the optical frequency comb can be stabilized well beyond the needs of optical astronomy. The validity of the comb concept has been tested at

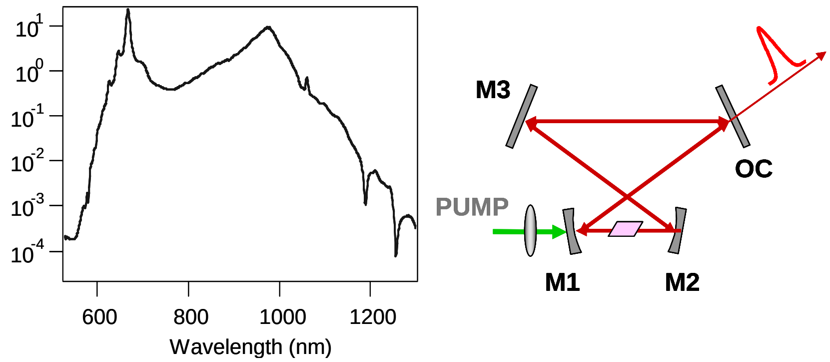

Figure 3. Spectrum from an octave spanning Ti:sapphire femtosecond ring laser with repetition rate of 1 GHz: Cavity mirrors M1, M2 and M3 are broad bandwidth dispersion compensating chirped mirrors, while the output coupler (OC) reflects nominally 1% from 700-900 nm. The spectral envelope shown was acquired with a low resolution spectrometer, so individual modes are unresolved.[19]

levels approaching 1×10^{-19} (e.g. a residual uncertainty of ~100 μHz on an optical frequency of 500 THz). Moreover, due to the simplicity and relatively low cost, the femtosecond comb techniques and tools can be implemented in university and industrial research labs.

A schematic of a Ti:sapphire femtosecond laser frequency comb with 1 GHz repetition rate is illustrated in Fig. 3, along with a measurement of its spectral envelope.[18] Among femtosecond lasers, the spectrum shown in Fig. 3 is notable in two aspects: (1) the 1 GHz repetition rate is ~10x higher than typical solid-state femtosecond lasers and provides more power per comb mode, and (2) the extremely broad spectrum of the laser provides sufficient bandwidth to directly measure f_0, as described above. Additional broadening of the optical spectrum down to 400 nm can be achieved via nonlinear self-phase modulation in novel microstructured nonlinear optical fibers. For the purposes of this work GPS or a compact rubidium atomic reference could be used to stabilize the comb and would provide sufficient accuracy (~10^{-11} level).[18]

Mode Filtering

While the 1 GHz repetition rate of the laser shown in Fig. 3 is quite high compared to other mode-locked femtosecond solid-state lasers, it is still too low compared to the resolution of typical high resolution astronomical spectrographs. Ideally, for such spectral calibration one would prefer a mode spacing on the order of 10-20 GHz.[5] However, a 10 GHz mode-locked laser only has enough nonlinearity to generate pulses of several picoseconds in duration, which is insufficient to make the octave-spanning spectrum required for stabilization. Moreover, existing 10 GHz mode-locked lasers typically operate in the 1-1.5 micron regime, which would then require nonlinear frequency conversion to reach the spectral range of interest.

Rather than increasing the inherent line spacing of the frequency comb, it is possible to use Fabry-Perot (FP) optical cavity to filter unwanted modes.[23] The basic scheme is illustrated in Fig. 1. In the example shown, the FP cavity spacing would be ~1.5 cm such that every 10^{th} mode of the original frequency comb is transmitted. As required, the cavity length of the FP can readily be changed to provide filtered outputs at any harmonic of f_r up to a limit determined by the reflectivity and dispersion of the FP mirrors. In any case, filtering to any spacing between 2 and 30 GHz should be achievable, with servo control employed to lock the length of the FP cavity on resonance with the 1 GHz femtosecond comb spacing. This could also provide the flexibility of changing the filtered mode spacing across the optical spectrum to appropriately match the spectrograph resolution.

The transmission through a plane-parallel FP cavity composed of two identical mirrors, each having power reflectivity R, is given by

$$T_{FP} = \frac{(1-R)^2}{1+R^2-2R\cos(\delta)}. \qquad (4)$$

where $\delta = 4\pi nt/\lambda$ (for example, see Saleh, 1991[24]) The spacing between the mirrors is given by t, n is the index of refraction of the intervening medium (assumed to be 1 for the following), and λ is the wavelength. Using this expression, one can choose the mirror reflectivity which results in the appropriate attenuation of the off-resonant modes. For example, with a 10 GHz filter cavity consisting of two R=99% reflectors spaced by 1.5 cm, the unwanted modes 1 GHz away from the FP transmission peaks are attenuated by 35 dB. This attenuation increases to about 45 dB at 5 GHz from the FP transmission peaks. Higher reflectivity mirrors would provide still greater attenuation of unwanted modes, but would have the possible disadvantage of increased sensitivity to fluctuations in cavity length.

An important detail that was neglected in the discussion surrounding Eq. 4 is that in contrast to the frequency comb produced by the femtosecond laser, the "comb" associated with the Fabry-Perot optical cavity is not strictly uniform. This is because of dispersion in the cavity mirror coatings as well as the medium between the mirrors. A practical consequence of this dispersion is that effective filtering cannot likely be achieved over the full bandwidth of the femtosecond laser frequency comb with a single FP cavity. Several approaches could be taken to correct this shortcoming. First, the optical bandwidth over which the cavity effectively filters can be maximized by employing specially designed low-dispersion mirror coatings. Our estimates indicate that it should be possible to filter fractional bandwidths on the order of 15% (120 nm at the center wavelength of 800 nm). Evacuating the FP cavity or backfilling with He, or another noble gas, may also be useful to eliminate residual dispersion associated with oxygen and water resonances while also providing some fine-tuning of the effective cavity length and dispersion.

Also note that while the mode spacing of the Fabry-Perot cavity can on average be made to match a harmonic of the repetition rate, the optical offset of the cavity modes requires an independent degree of control. For example, this application will require that we unambiguously know the value of n when the FP cavity is locked to modes n, n+10, n+20, … A straightforward approach to the determination of n is to employ a stable optical reference, such as provided by a frequency-stabilized helium-neon laser. The heterodyne beat between the filtered comb and the stable optical reference then identifies n. With different FP cavities employed in different spectral regions, a heterodyne beat between the transmitted modes of adjacent cavities can be used to verify the relative offset of the different FP cavities, provided there is at least some small spectral overlap between the transmission of adjacent FP cavities.

Current State of Development

In Fig. 4, we present preliminary results on the filtering of a portion of the spectrum from a 1 GHz Ti:sapphire with a 10 GHz filter cavity consisting of two 99% reflectors. For these tests, an optical bandpass filter first selected ~60 nm of spectrum emitted by a laser similar to that shown in Fig. 3. This light was then sent to the 10 GHz FP cavity filter, and the length of the FP was controlled via a piezoelectric transducer (PZT) such that maximum power was transmitted when the FP was matched to 10× the 1 GHz laser mode spacing. A low resolution grating-based spectrometer was used to acquire the optical spectra before and after the 10 GHz filter cavity. These spectra, which are shown in Fig. 4(a) are nearly identical in shape, indicate that the filter cavity is functioning over the entire 60 nm bandwidth. The total average power that is transmitted is 4.6 mW out of the 80 mW incident on the cavity. The deviation from the expected transmission is attributed to imperfect matching of the laser's spatial mode to the lowest order spatial mode of the filter cavity. Nonetheless, from the 4.6 mW of average power we can infer approximately 1 microwatt per 10 GHz mode.

A simple means to assess the level of suppression of unwanted modes is to detect the transmitted light from the FP cavity with a high speed photodetector. The resulting photocurrent is measured as the power across the 50Ω input of a microwave spectrum analyzer, which yields the data shown in Fig. 4(b). The microwave

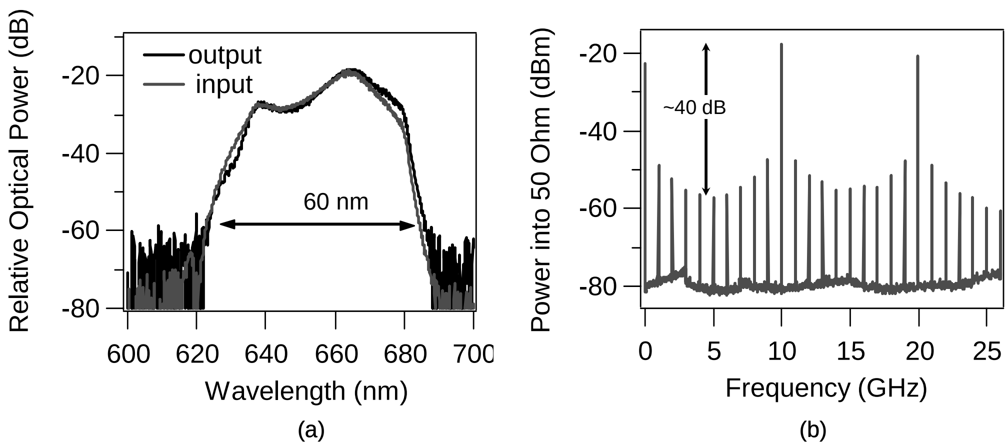

Figure 4. (a) Optical spectra input to (red) and output from (black) the 10 GHz filter cavity. For ease of comparison, the two spectra are given arbitrary vertical offsets. (b) Measured RF spectrum of the transmitted light as detected with a 25 GHz photodetector. The original 1 GHz repetition rate harmonics are suppressed by -30dB to as much as -40dB below the 10 GHz carrier.

spectrum bears strong resemblance to the shape the optical spectrum. However, it is important to note that the microwave spectrum arises from heterodyne beats between numerous optical modes leading to more power in the suppressed modes relative to the 10 GHz harmonic. Calculations indicate that the off-resonant (filtered) modes of the optical spectrum are in fact suppressed an additional 6 dB below what is shown in Fig. 4(b). Thus, the measured 40 dB suppression of the mode at 5 GHz in the microwave spectrum corresponds to a suppression of approximately 46 dB in the optical domain, which is in agreement with the prediction of Eq. 4.

3. Future Work

Mode Filtering

Mode filtering, while straightforward in principal, represents a considerable technical challenge. Small changes in the cavity free spectral range could compromise the reliability of the calibration source. If the finesse of the cavity (the finesse $\mathcal{F}$ is the ratio of the cavity free spectral range to the FWHM of each transmission peak) allows contributions from adjacent frequency comb modes (which cannot be resolved from the desired mode) then changes in the free spectral range will result in a change in the apparent line center of the calibration line as discussed in Schmidt, et al.[25]

While we have demonstrated filtering approaching the levels required for R = 100,000 spectroscopy, we still need to expand the band pass of the filters and demonstrate sufficient finesse and stability to support cm/s observations. We are currently funded to study FP cavity design and operation in detail and will explore the following:

1. Demonstrate mode filtering at the 10-30GHz level.
2. Determine the requirements placed on the cavities by the need to support cm/s spectroscopy, both in terms of finesse and in terms of cavity FSR stability.
3. Explore strategies to reduce the effects of dispersion and to increase bandwidth.
4. Develop techniques for phase locking cavities, and characterize the degree to which the cavity can be stabilized.
5. Identify factors that will impact the long term stability of the cavities and develop strategies for controlling these factors.

Future telescope applications

One of the design teams participating in the initial instrument feasibility studies for the Thirty Meter Telescope has proposed to include an optical frequency comb as part of the calibration suite for the High Resolution Optical Spectrograph.[8] The combination of large focal length and aperture makes the standard echelle prohibitively expensive, so the Colorado team explored design alternatives. In place of the two arm echelle, the instrument calls for an array compact, nearly identical first order spectrographs fed by a dichroic tree which performs a binary sort on the light so that each spectrograph can be optimized for a narrow band. The spectrograph is fed by a fiber optic IFU and the design places the bulk of the spectrograph in a vacuum chamber to increase vibration and thermal isolation.

The fiber feed incorporates several calibration fibers in the scrambled bundle, simplifying the injection of an external calibration spectrum, either from a conventional line source, or from an optical frequency comb. Because of anticipated gains in instrument stability, the design team felt that this instrument would be able to take advantage of the capabilities of the optical frequency comb calibration standard.

A second instrument which has discussed the possibility of including a frequency comb as part of the calibration suite is the ESO HARPS instrument.[4] HARPS is a R=110,000 spectrograph on the 3.6m telescope at La Silla Observatory. The spectrograph is maintained in a vacuum chamber giving rise to very high mechanical and thermal stability (fluctuations < 10mK), with overnight instrumental drifts consistently less than 1m/s. All this gives rise to an instrument which has a published long term precision of 1m/s, with the goal of pushing this to 1cm/s as a pathfinder for the CODEX (Cosmic Dynamics Experiment) project for the European Extremely Large Telescope.

Improved wavelength calibration is of central importance to achieving this goal. Scatter in Th/Ar spectra has been limited to no better than 1.5m/s, suggesting that the use of an emission line lamps as a calibration source may limit the ultimate performance of HARPS to roughly 1m/s. The use of a frequency comb is seen as one path for overcoming the limitations of the Th/Ar calibration lamps.

In addition to directly supporting astronomical observations, the optical frequency comb could support ground based spectroscopy that would in turn help to advance astronomy. First, a frequency comb wavelength standard could be used to increase the accuracy of line lists for Th/Ar calibration lamps, decreasing the scatter from the tens to hundreds of m/s found in current line lists.[14] Less directly, the precise wavelength knowledge of the frequency comb could increase the accuracy of published wavelengths for atomic transitions of astronomical interest. Berengut, et al. have published a shopping list of transitions of astronomical interest to the search for time space variations of the fine structure constant for which accurate wavelength values are urgently needed.[26] A majority of the 87 transitions cited are at FUV to NUV wavelengths, but roughly 12% fall within the frequency comb's spectral range.

4. Conclusion

A laser frequency comb adapted to the needs of optical spectroscopy could provide a high density array of uniformly spaced, uniformly bright emission lines which can be traced to the standard second to a precision of much better than one part in 10^{-11}. While more complex than the current optical wavelength standards, I2 cells and Th/Ar lamps, the laser frequency comb is not subject to the limitations of either of these calibration sources. As a result, the laser frequency comb represents an attractive avenue for advancing the precision and repeatability of high resolution astronomical spectroscopy.

REFERENCES

1. J. L. Hall. Nobel Lecture: Defining and measuring optical frequencies. *Rev. Mod. Phys.* **78**, 1279-1295 (2006).
2. T. W. Hänsch, Nobel Lecture: Passion for precision. *Rev. Mod. Phys.* **78**, 1297-1309 (2006).
3. R.P. Butler, J.T. Wright, G.W. Marcy, D.A. Fischer, S.S. Vogt, C.G. Tinney, H.R.A. Jones, B.D. Carter, J.A. Johnson, C. McCarthy, and A.J. Penny, "Catalog of nearby exoplanets," AJ, **646**, 505 (2006).

4. C. Lovis, F. Pepe, F. Bouchy, G.L. Curto, M. Mayor, L. Pasquini, D. Queloz, G. Rupprecht, S. Udry, and S. Zucker, “The exoplanet hunter HARPS: unequalled accuracy and perspectives toward 1 cm s^{-1} precision”, Proc. SPIE, **6269**, 62690P-1-9 (2006).
5. M.T. Murphy, T. Udem, R. Holzwarth, A. Sizmann, L. Pasquini, C. Araujo-Hauck, H. Dekker, S. D’Odorico, M. Fischer, T.W. Hänsch, A. Manescau, “High-precision wavelength calibration with laser frequency combs,” ArXiv:astro-ph0703622v1, Submitted to MNRAS (2007).
6. J. Nelson, G.H. Sanders, “TMT Status Report,” Proc SPIE **6267**, 626728 (2006).
7. M. Johns, R. Angel, S. Schectman, R. Bernstein, D. Fabricant, P. McCarthy and M. Phillips, “Status of the Giant Magellan Telescope (GMT) Project,” Proc SPIE, **5489**, 441 (2004).
8. S. Osterman, C. Froning, M. Beasley, J. Green, and S. Beland, “A high-resolution optical spectrograph for the Thirty Meter Telescope: design and performance”, Proc SPIE, **6269**, 626930 (2006).
9. A. Loeb, “Direct Measurement of Cosmological Parameters from the Cosmic Deceleration of Extragalactic Objects,” AJ Lett., **499**, L111 (1998) .
10. J.K. Webb, V.V. Flambaum, C.W. Churchill, M.J. Drinkwater, J.D. Barrow, “Search for Time Variation of the Fine Structure Constant,” Phys Rev Lett., **82**, 884 (1999).
11. M.C. Stowe, M.J. Thorpe, A. Pe'er, J. Ye, J. Stalnaker, V. Gerginov, and S.A. Diddams, “Direct Frequency Comb Spectroscopy,” to appear in Advances in Atomic, Molecular and Optical Physics (2007).
12. S. Diddams, L. Hollberg, and V. Mbele, “Molecular fingerprinting with spectrally-resolved modes of a femtosecond laser frequency comb,” Nature **445**,627 (2007).
13. Z. Jiang, D. E Leaird, and A. M. Weiner, “Line-by-line pulse shaping control for optical arbitrary waveform generation,” Opt. Express **13**, 10431 (2005).
14. S.A. Diddams, Th. Udem, J.C. Bergquist, E.A. Curtis, R.E. Drullinger, L. Hollberg, W.M. Itano, W.D. Lee, C.W. Oates, K.R. Vogel, and D.J. Wineland, “An Optical Clock Based on a Single Trapped Hg+ Ion,” Science **293**, 825 (2001).
15. M.T. Murphy, P. Tzanavaris, J.K. Webb, C. Lovis, “Selection of ThAr lines for wavelength calibration of echelle spectra and implications for variations in the fine-structure constant,” ArXiv: astro-ph/0703623v1, accepted for publication in MNRAS (2007).
16. H. Dekker, S. D'Odorico, A. Kaufer, B. Delabre, H. Kotzlowski, “Design, construction, and performance of UVES, the echelle spectrograph for the UT2 Kueyen Telescope at the ESO Paranal Observatory,” Proc. SPIE **4008**, 534 (2000).
17. F. Kerber, G. Nave, C.J. Sansonetti, P. Bristow, A. Rosa, H-U Käufl, M.R. Rosa, “The Spectrum of Th-Ar Hollow-cathode Lamps in the 900–4500 nm region: Establishing Wavelength Standards for the Calibration of VLT Spectrographs”, Proc SPIE, **6266**, O1 (2006).
18. R. Fox, S.A. Diddams, A. Bartels, and L. Hollberg, “Optical frequency measurements with the global positioning system: tests with an iodine-stabilized He-Ne laser,” Apl. Opt. **44**, 113 (2005).
19. T. Fortier, A. Bartels, S.A. Diddams, “A high repetition rate octave-spanning Ti:sapphire laser for optical frequency measurements and comparisons,” Opt. Lett. **31**, 1011 (2006).
20. J. Eckstein, A. Ferguson, and T. Hänsch, "High-resolution 2-photon spectroscopy with picosecond light- pulses", Physical Review Letters **40**, 847 (1978).
21. T. Udem, R. Holzwarth, & T.W. Hänsch., "Optical frequency metrology", *Nature* **416**, 233 (2002).
22. L.-S. Ma, Z. Bi, A. Bartels, L. Robertsson, M. Zucco, R. S. Windeler, G. Wilpers, C. Oates, L. Hollberg, S. A. Diddams, “Optical frequency synthesis and comparison with uncertainty at the 10^{-19} level,” *Science*, **303**, 1843 (2004).
23. S. Diddams, A. Weiner, V. Mbele and L. Holberg, “Increasing the Mode-Spacing of Sabilized Frequency Combs with Optical Filter Cavities,” IEEE LEOS Summer Topical Meeting, Portland (2007).
24. B. Saleh, M. Teich, *Fundamentals of Photonics*, New York: John Wiley & Sons, p.316-317 (1991).
25. P. Schmidt, S. Kimeswenger and H. Käufl, “A new generation of spectrometer calibration techniques based on optical frequency combs”, ArXiv:astro-ph0705.0763v1 (2007).
26. J. Berengut, V. Dzuba, V. Flambaum, M. Marchenko, J. Webb, “Laboratory Spectroscopy and the search for space-time variation of the fine structure constant using QSO spectra”, ArXiv: physics/0408017v3.