High-precision calibration of spectrographs using laser frequency combs

Tobias Wilken[a], Christophe Lovis[b], Antonio Manescau[c], Tilo Steinmetz[a,d], Luca Pasquini[c], Gaspare Lo Curto[c], Theodor W. Hänsch[a], Ronald Holzwarth[a,d], Thomas Udem[a]
[a]Max Planck Institut für Quantenoptik, Hans Kopfermann Strasse 1, 85748 Garching
[b]Observatory of Geneva, 51 ch des Maillettes, 1290 Sauverny, Switzerland;
[c]European Southern Observatory, Karl Schwartzschild Strasse 2, 85748 Garching, Germany
[d]Menlo System GmbH, Am Klopferspitz 19, 82152 Martinsried, Germany

ABSTRACT

We present the first stringent tests of a novel calibration system based on a laser frequency comb (LFC) for radial velocity measurements. The tests were obtained with the high resolution, optical HARPS spectrograph. Photon noise limited repeatability of 9 cm s^{-1} was obtained, using only little more than one of 72 echelle orders. In the calibration curve CCD inhomogeneities showed up and could be calibrated, which were undetectable with previous Th-Ar calibrations. To obtain an even higher repeatability and lower residuals, a larger spectral bandwidth is necessary. An improved version of the LFC is currently under development. The results of the latest tests will be presented.

Keywords: exo-planet search, radial velocity measurement, high resolution spectrograph, laser frequency comb

1. INTRODUCTION

Measuring the drifting redshift of cosmological objects - watching the Universe's expansion in real time - is the cleanest, most direct way to chart its global history. No cosmological assumptions or priors are required whatsoever. It is entirely model-independent - not even a theory of gravity is required - and is unique in being a dynamical rather than geometrical method. The suggestion that the so-called Lyman-α "forest" seen in high-redshift quasar spectra is the best target for this [6] was recently confirmed using cosmological hydrodynamical simulations [29]. The forest of absorption lines is caused by the Lyman-α transition arising in neutral hydrogen gas clouds at different redshifts along the quasar sight-lines. Detailed calculations using simulated quasar spectra show that the planned 42-m European Extremely Large Telescope (E-ELT), equipped with the proposed Cosmic Dynamics Experiment (CODEX) spectrograph[7], could detect the redshift drift convincingly with 4000 hrs of observing time over a ~20 yr period[29]. It is tempting to assume GR and calculate the likely constraint this might place on particular cosmological parameters, such as the dark energy density, but they are only about as strong as recent geometrical experiments have achieved. But to focus on this is to miss this experiment's more fundamental nature. Indeed, given its uniqueness, it is clearly desirable that it will be conducted at some stage.

Therefore, overcoming the many practical challenges in realizing the redshift drift experiment is imperative. Important astrophysical and technical requirements have been considered and do not seem difficult to surmount[29]. However, one extremely important requirement is that the astronomical spectrographs used to record the quasar spectra must have their wavelength scales calibrated accurately enough to record ~1 cm s^{-1} velocity shifts (~ 25 kHz frequency shifts). Moreover, this accuracy must be repeatable over ~ 20 yr timescales. LFCs offer a solution because they provide an absolute, repeatable wavelength scale defined by a series of laser modes equally spaced across the spectrum. Each modes' frequency is known to a precision limited only by the precision of the clock controlling the LFC. For this reason comb calibration data are easily exchanged among different instruments and readily conserved for comparisons. With current limits on the signal-to-noise ratio (SNR) imposed by the dynamic range of charge coupled devices (CCDs), LFC calibration can achieve the required precision[1] even with a moderately accurate clock.

Precisely calibrated astronomical spectrographs have several other important applications. For example, Jupiter- and Neptune-mass extra-solar planets have been discovered by the reflex Doppler motion of their host stars[22][8][21], but

Ground-based and Airborne Instrumentation for Astronomy III, edited by Ian S. McLean,
Suzanne K. Ramsay, Hideki Takami, Proc. of SPIE Vol. 7735, 77350T · © 2010
SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.857248

detecting Earth-mass planets around Solar-mass stars will require ~ 5 cm s^{-1} precision maintained over several-year time-scales. Another example is the search for shifts in narrow quasar absorption lines caused by cosmological variations in the fundamental constants of nature[9][10][11]. Recent measurements[12][13][14] achieve precisions of ~ 20 m s^{-1} but disagreements between the different constraints, and the increased photon collecting power of future ELTs, warrant much more precise and accurate calibration over the widest possible wavelength range.

One challenge in reaching such calibration precision will be the measurement and, eventually, mitigation and/or modeling/removal of systematic effects in astronomical spectrographs and detectors. For typical high-resolution spectrographs, a ~ 1 cm s^{-1} shift corresponds roughly to the physical size of a silicon atom in the CCD substrate. Only with the statistics of a very large number of absorption or emission lines one can hope to achieve the required sensitivity provided that systematic shifts can be controlled accordingly. For example, even in a highly stabilized, vacuum-sealed spectrograph, small mechanical drifts will slightly shift the spectrum across the CCD. While, as we demonstrate here, this can easily be tracked to first order, CCD intrapixel sensitivity variations might be important for higher precision. Testing LFCs on astronomical spectrographs and CCDs is therefore imperative for the long-term goal of accurate calibration.

2. LASER FREQUENCY COMB SYSTEM

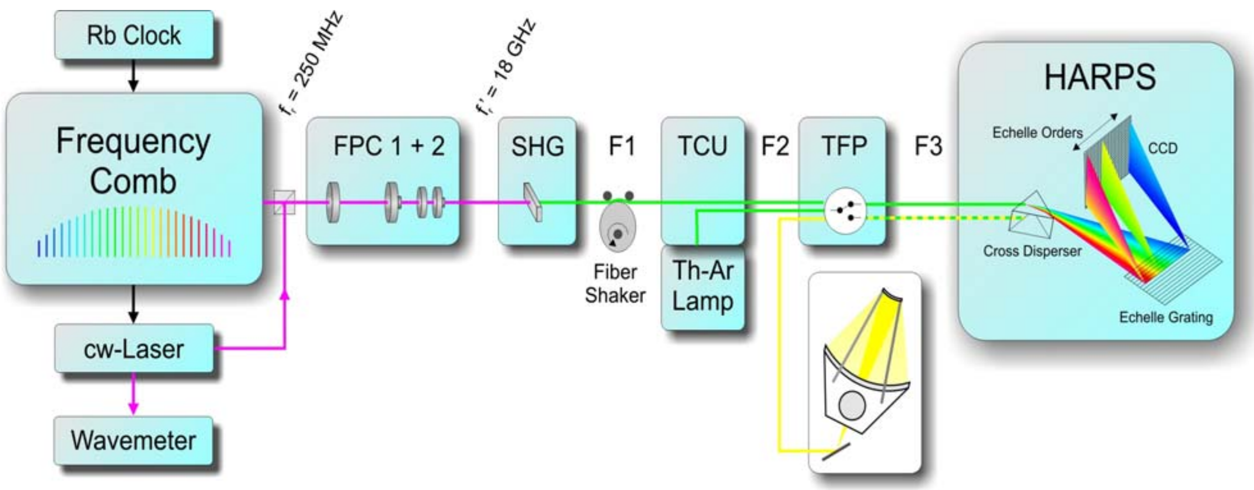

Figure 1. Experimental set-up [5]. An Yb-fiber-based laser frequency comb was filtered with two Fabry-Perot cavities (FPC 1+2),which results in a mode spacing of f_r' = 18 GHz. In the following second harmonic generation stage the centre wavelength frequency was doubled to 515 nm. Traversing a fiber shaker, the comb light was fed together with light from a conventional Th–Ar calibration lamp via the telescope's calibration unit (TCU) through the TFP to the HARPS spectrograph. F1, F2 and F3 refer to the fibers between the different units, having a core diameter of 1 mm, 300µm and 70µm, respectively. At the telescope's focal plane (TFP), apertures can be set, such that light coming from any of the F2 fibers or the telescope can be coupled to any of the F3 fibers. Fiber amplifiers situated before, between and directly after the FPCs are not illustrated. They compensate for the power losses due to the rejected modes of the filter stages.

The LFC, we have constructed to calibrate astronomical spectrographs, is based on a mode-locked Yb-doped fiber laser with a repetition rate of f_r = 250MHz and a central wavelength of 1030 nm [5]. The optical frequencies of the LFC modes are given by $mf_r + f_0$, where m is a large integer (of the order 10^6) and $f_0 < f_r$ is a radio frequency comb offset [33]. Two FPCs with free spectral ranges of $m_1 f_r$ and $m_2 m_1 f_r$ are used in series to suppress the unwanted LFC modes [1] (see Fig. 1). The modes transmitted by the FPCs are then given by $f_n = n\, m_1\, m_2\, f_r + f_0' = n\, f_r' + f_0'$, with the larger mode spacing $f_r' = m_1\, m_2\, f_r$ and the integer filter ratios m_1 and m_2. The comb offset after filtering is $f_0' < f_r'$ and might differ from f_0 by a multiple of f_r. Just like f_r, the common LFC offset frequency f_0 is controlled by a Rb atomic clock with an accuracy of 5×10^{-11} (1.5 cm s^{-1}). The mode number n which resolves the remaining 250MHz ambiguity was determined by comparison with the Th–Ar calibration curve of the CCD. Using more than one filter cavity has the advantage of achieving a higher suppression of the unwanted modes [34]. The cavities were tilt-locked to the reflection signal of a continuous wave laser [35], which was locked to the LFC and whose frequency was monitored with a wavemeter. This ensures that the same comb modes were continuously transmitted by the FPCs. With $m_1 = 8$ and $m_2 = 9$, we provide an LFC with a mode spacing of 18 GHz for calibration, which is 3.4 times the resolution of HARPS and slightly above the theoretical optimum [1]. Calibration at 12 GHz was tested, but we opted for a slightly larger mode spacing, which minimizes the overlap between the wings of adjacent modes, to facilitate the analysis. The cavity mirrors have a reflectivity of 99.2 per cent, resulting in a finesse of ~400. Both cavities are plano-concave, where the radii of curvature of the concave mirrors are chosen to minimize the transmission of higher order spatial modes as described by [34]. The suppression of the unwanted modes is calculated to be better than 50 dB, which was confirmed by radio frequency spectra. Three fiber amplifiers (before, between and after the filter FPCs) provide enough power for frequency doubling in a periodically poled potassium–titanyl–phosphate crystal. The calibration light generated is centered at around 514.9 nm with a full width at half maximum of 2.1 nm. The spectrum covers one echelle order with 362 modes, and its width is presently limited by the crystal's phase matching bandwidth. In future, this will be improved by broadening the spectrum in a highly non-linear fiber.

3. CALIBRATING THE HARPS SPECTROGRAPH

For testing our frequency comb as a spectrograph calibrator, we employ the High Accuracy Radial Velocity Planet Searcher (HARPS) spectrograph, fed by the ESO 3.6m telescope at La Silla observatory. The instrument has a resolving power R = 115000, corresponding to 5.2GHz at 515nm, and has been especially designed for superior stability [22]. Thanks to a crossdisperser design, it covers 380-690nm simultaneously, collecting the light over 72 dispersed echelle orders onto a mosaic of two 2K x 4K CCD detectors. The majority of neptunian exo-planets and super-earths have been discovered with this instrument, and a repeatability below 1m s^{-1} (3×10^{-9}) has been demonstrated for several years [21].

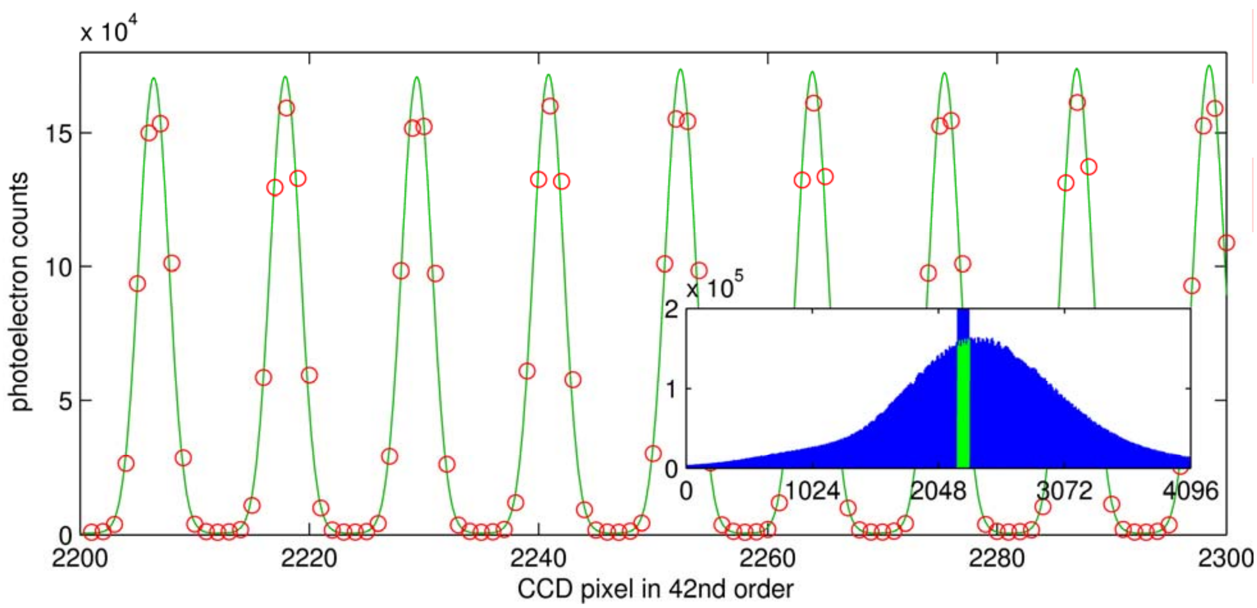

Figure 2. Laser frequency comb calibration spectrum. A part of the extracted comb spectrum (red) is shown together with a sum of Gaussians fitted to the data (green). A single, 80 s exposure was integrated to arrive at the given photoelectron count rates. The inset shows one full echelle order (out of 72) with the LFC's spectral envelope. The range of the zoomed region is highlighted..

3.1 Calibration repeatability

A crucial component for the calibration repeatability was the interface between the LFC and the spectrograph (see fig. 1). We used two multi-mode fibers (F1, 1mm core diameter) to couple our LFC light to the HARPS calibration unit which also contained the Th-Ar lamp. The output facet of one fiber F1 was positioned at the focal plane of a lens system that illuminates one out of two multi mode fibers (F2, 300 µm core). The lens system was designed for the Th-Ar lamps and has a demagnification of 10:1, projecting the LFC light onto a 100 µm spot on the input facet of the F2 fibers. Each fiber then projects a spot of 750 µm diameter on the telescope focal plane. The projected light is collected by one out of two fibers (F3, 70 µm core) that bring the light to the spectrograph. At this point light from each of the F2 fibers or starlight from the telescope can be coupled to any of the F3 fibers. In the path to the spectrograph, a passive optical scrambler exchanges the F3 fiber near field and far field. At the spectrograph's entrance the F3 fibers are displaced along the direction of the grating rules such that their images are ~15 pixels apart in the cross-dispersed direction on the CCD. After the SHG stage, the comb light was split and coupled independently to the two F1 fibers. In this way we were able to monitor drifts of the spectrograph independently with both fiber channels A and B. The comb calibration is determined by fitting modes individually with Gaussians, which serve as a good approximation of the instruments point spread function. We determine the drift of the spectrograph through the mean shift of the observed line positions between different acquisitions, weighted with the uncertainty of each line position, derived from the fit (see fig. 2). The ultimate calibration limit is given by the photon noise and can be calculated from the total number of photons collected from all LFC modes in use. Taking ever longer series of acquisitions, other noise sources besides photon noise will dominate and may reveal the dominating systematic effects.

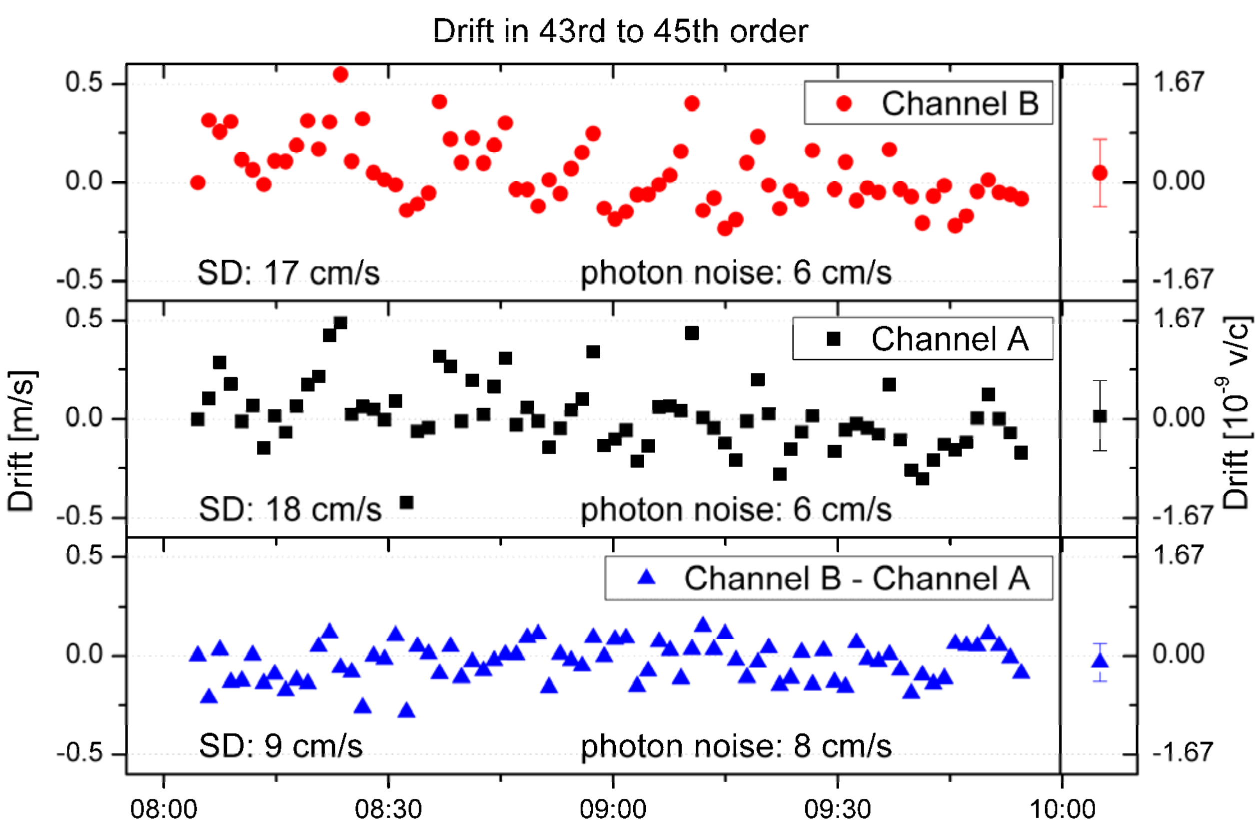

Figure 3. Calibration repeatability. Top panel: average line shift data for LFC calibration in fiber channel B as a function of time. The data are measured with respect to an arbitrarily selected reference acquisition (recorded at 08:04 h). Mean and SD are shown separately on the right-hand side. Middle panel: the same for fiber channel A. Bottom panel: the difference of both calibrations. This results in a cancellation of common fluctuations of instrumental origin, which leads to a reduced SD of these data as compared to the individual channels. By eliminating the instrumental drift, the calibration is at the photon noise limit of 8 cm s^{-1}.

The latest data is from our run in January 2010, where we have changed our fiber amplifiers, which lead to a broader spectrum of ≈10 nm FWHM, centered at 532 nm. We determine the calibration repeatability by computing the mean difference of the fitted line positions relative to an arbitrarily selected reference acquisition for both fiber channels. The upper panel of fig. 3 shows a series of 75 acquisitions (80 s exposure time each, using one complete echelle order and the wings of the spectrum in the two adjacent orders) with a measured standard deviation of the comb calibration of 17 cm s^{-1}. The central panel shows the same data for the second fiber channel giving a standard deviation of 18 cm s^{-1}. There is a clear indication of partial correlation of the data, reflecting instrumental drifts. An even lower standard deviation of 9 cm s^{-1} of the difference of both channels, which is close to the calculated photon noise, is shown in the lower panel. For comparison, a calibration with Th-Ar, using all 72 echelle orders, would only give a 15 cm s^{-1} calibration, when computing the difference between both fiber channels. Using only a little more than one echelle order, a LFC calibration is thus already superior to a Th-Ar lamp.

3.2 Multimode Fiber issues

To provide reproducibility for the ambitious long-term projects in astronomy, calibration relative to an absolute frequency scale seems to be the best solution. For this purpose we have identified the largest systematic calibration shift which is due to an incomplete wavefront matching between the star light and the calibration light. Lacking a workable scheme for adaptive optics that compensates atmospheric turbulences in the visible, multimode fibers have been thus far. This leads to two effects that can induce systematic calibration shifts. First, the inhomogeneous illumination will be partly preserved through the fiber and result in an inhomogeneous output pattern [17]. Second, for each frequency component, spatial fiber modes can interfere producing inhomogeneous output patterns [18] and spectral modulations that vary with fiber bending, temperature or air pressure. Consequently the barycenter of the beam entering the spectrograph may shift. The spectrograph's imaging system can not perfectly compensate for this effect. With the image size of the fiber output facet of about 3 CCD pixels a calibration stability of 10 cm s^{-1} requires a stability of this image of 2×10^{-4} pixels. Note that this stability is required only as an average over the full spectrum. While we cannot differentiate the two effects, they could be reduced by moving and bending the fiber during one exposure with a fiber shaker. The device actively scrambles the fiber modes on a time scale much shorter than the exposure time. Tests with different mode field diameters for fiber F1 showed best performance when using the largest core available. Without the fiber shaker, instead of the 9 cm s^{-1} photon noise limited repeatability we obtained a value of 30 cm s^{-1}. Thus our method suppresses this effect below detectability. Our results show that the design of future high precision instruments should incorporate optimized fiber mode scrambling or single mode fibers that require effective coupling with adaptive optics. This is especially challenging for fibers guiding starlight. When calibrating an observation of a stellar object, blurring effects of the atmosphere lead to a varying illumination of the input pupil at the focal plane of the telescope. The resulting line shift cannot be monitored in this simultaneous calibration scheme [19] and thus must be minimized or best prevented beforehand.

3.3 Absolute Calibration

If one wants to determine the center of a line to 10^{-4} of a pixel or better, one obviously must characterize the pixel to frequency map very well. So far, only estimations could be made concerning which imperfections a CCD can have and what impact those will have on the calibration. By fitting a 4th-order polynomial to our pixel to line center distribution, CCD inhomogeneities could be seen for the first time in a calibration curve. The residuals of this fit plotted against the line position (fig. 4) show jumps every 512 pixels. These derive from the manufacturing process of the CCD which is written with a 512 pixel mask, leading to variations in size or sensitivity at the edges of the mask. Including the jumps in the calibration curve and increasing the polynomial order leads to a 2.4 m s^{-1} standard deviation of the residuals from the calibration curve. This value is significantly above the photon noise and measures the unmodeled pixel inhomogeneities and flatfielding uncertainties. Comparing with the usual 4th order Th-Ar calibration [32] (blue curve in fig.4), one finds large local deviations of up to 60 m s^{-1}. Those can now be modelled using the LFC which significantly improves the absolute calibration of HARPS. An upper limit for the absolute frequency uncertainty can be given by measuring the Th-Ar line positions with the comb calibration curve and comparing the results with the published values [20]. Unfortunately the absolute Th-Ar frequencies are only known with an uncertainty of about 50 m s^{-1}, however, our much more accurate measurements are consistent within this limit. Assuming that the fiber coupling has an effect of probably less than 1m/s (which can be concluded from the repeatability without mode scrambler), we are confident that the absolute calibration of the spectrograph can be improved by at least one order of magnitude. As a by-product, a corresponding improvement in the Th-Ar line list can be obtained from our data

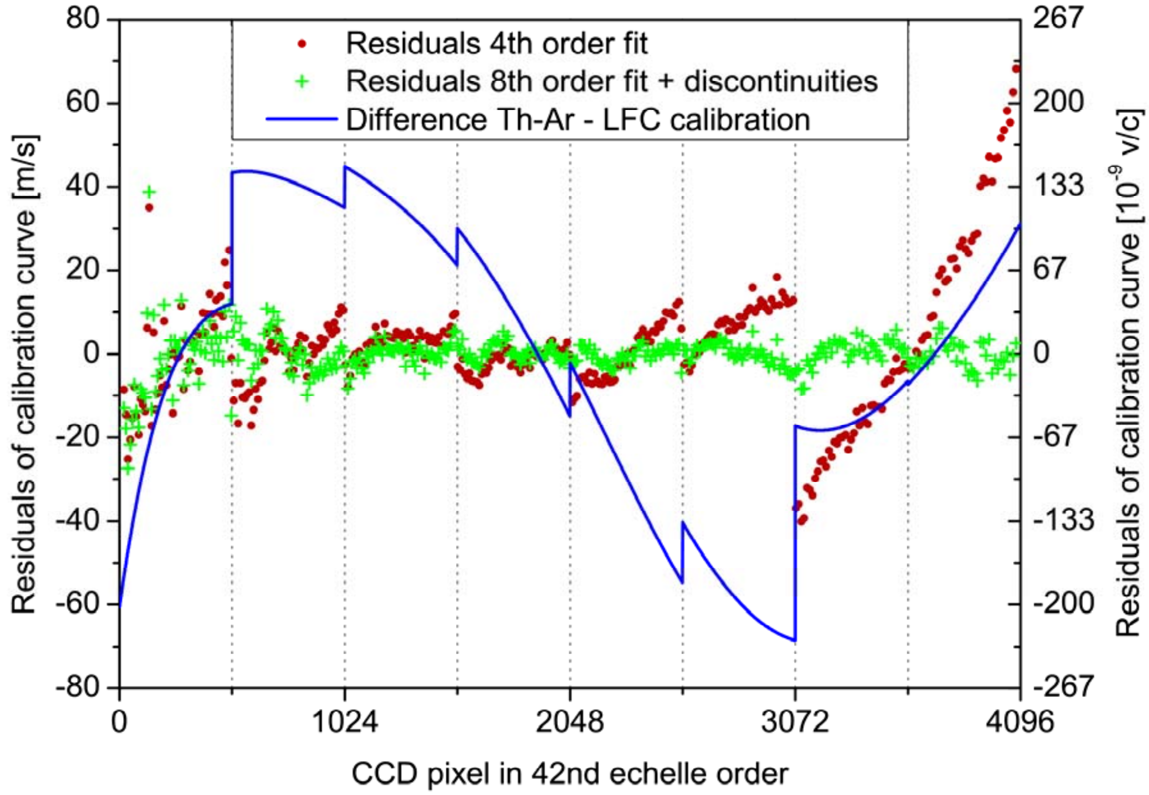

Figure 4. Detector inhomogeneities unveiled by residuals of the calibration curve. Polynomials are fitted to the pixel versus frequency distribution and the residuals are plotted. Fitting functions to the LFC data are a global-fourth order polynomial (red dots) and eight piecewise eighth-order polynomials (green crosses) that cover 512 pixels each (72 parameters). Variations in pixel size, shape, position etc. which have their origin in the manufacturing process lead to the pattern with this period. The solid blue line shows the difference between the usual Th–Ar calibration curve (global fourth-order polynomial) and the LFC calibration curve (including the discontinuities). Due to the low line density of a Th–Ar lamp its calibration curve deviates strongly from the LFC calibration curve and discontinuities could previously not be detected.

4. CONCLUSION

In summary, we have set up a frequency comb system with a mode separation and spectral bandwidth adequate for calibrating ≈ 2 echelle orders of the HARPS spectrograph. We could demonstrate a repeatability of 9 cm s^{-1}, compatible with the computed photon noise and already better than a Th-Ar calibration, which needs to use all 72 orders. By using the LFC we could measure the contribution of the CCD pixel irregularities to the calibration curve for the first time. This leads to an unprecedented low scatter of the residuals. Applied to the measurement of absolute Th-Ar frequencies we could exceed the accuracy of the published values. After spectrally broadening our LFC in a highly nonlinear fiber we hope to cover the whole visible range in future. By using an adjustable spectral filter the comb modes will also have about equal intensity. This system will reduce the photon noise by more than an order of magnitude which is expected to enable Doppler shift measurements at the cm s^{-1} level.

Acknowledgments

The authors would like to thank the staff at La Silla Observatory for their support during our campaign. T.W.H. gratefully acknowledges support by the Max-Planck Foundation.

REFERENCES

[1] M. T. Murphy, Th. 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 of astronomical spectrographs with laser frequency combs", MNRAS, 380, 839, 2007

[2] 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, 610, 2008

[3] 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, 57, 2008

[4] 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, Th. Udem, "Laser Frequency Combs for Astronomical Observations", Science 321, 1335, 2008

[5] T. Wilken, C. Lovis, A. Manescau, T. Steinmetz, R. Holzwarth, L. Pasquini, G. Lo Curto, T.W. Hänsch and Th. Udem, "Frequency Combs for High Precision Spectrographs in Astronomy", Mon. Not. R. Astron. Soc. 405, L16–L20 (2010) .

[6] Loeb, A. "Direct Measurement of Cosmological Parameters from the Cosmic Deceleration of Extragalactic Objects." Astrophys. J. 499, L111 (1998).

[7] Pasquini, L. et al. CODEX: measuring the acceleration of the universe and beyond. In Whitelock, P., Dennefeld, M. & Leibundgut, B. (eds.) Scientific Requirements for Extremely Large Telescopes, vol. 232 of IAU Symp. Ser., 193–197 (Cambridge Univ. Press, Cambridge, UK, 2006).

[8] Marcy, G. W. & Butler, R. P. "A Planetary Companion to 70 Virginis." Astrophys. J. 464, L147 (1996).

[9] Bahcall, J. N. & Salpeter, E. E. "On the Interaction of Radiation from Distant Sources with the Intervening Medium." Astrophys. J. 142, 1677 (1965).

[10] Webb, J. K., Flambaum, V. V., Churchill, C. W., Drinkwater, M. J. & Barrow, J. D. "Search for Time Variation of the Fine Structure Constant." Phys. Rev. Lett. 82, 884–887 (1999).

[11] Thompson, R. I. "The determination of the electron to proton inertial mass ratio via molecular transitions." Astron. Lett. 16, 3 (1975).

[12] Murphy, M. T., Webb, J. K. & Flambaum, V. V. "Further evidence for a variable fine-structure constant from Keck/HIRES QSO absorption spectra." *Mon. Not. Roy. Soc.* 345, 609–638 (2003).

[13] Chand, H., Srianand, R., Petitjean, P. & Aracil, B. "Probing the cosmological variation of the fine-structure constant: Results based on VLT-UVES sample." *Astron. Astrophys.* 417, 853–871 (2004).

[14] Levshakov, S. A. *et al.* "Most precise single redshift bound to $\Delta\alpha/\alpha$." *Astron. Astrophys.* 449, 879–889 (2006).

[15] Reinhold, E. *et al.* "Indication of a Cosmological Variation of the Proton-Electron Mass Ratio Based on Laboratory Measurement and Reanalysis of H_2 Spectra." *Phys. Rev. Lett.* 96, 151101 (2006).

[16] Bouchy, F. et al., "Fundamental photon noise limit to radial velocity measurements" Astron. Astrophys., 374, 377–739 (2001)

[17] Baudrand, J. and Walker, G.A.H., "Modal Noise in High-Resolution, Fiber-fed Spectra: A Study and Simple Cure" Publ. Astron. Soc. Pac., 113, 851–858 (2001)

[18] Grupp, F., "The nature of the fiber noise with the FOCES spectrograph" Astron. Astrophys., 412, 897–902 (2003)

[19] Baranne, A. et al., "ELODIE: A spectrograph for accurate radial velocity measurements" Astron. Astrophys., 119, 373 (1996)

[20] Palmer, B. A. and Engleman, R., Los Alamos National Laboratory Report LA-9615 (1983).

[21] C. Lovis, M. Mayor, F. Pepe, , Y. Alibert, W. Benz, F. Bouchy, A. C. M. Correia, J. Laskar, C. Mordasini, D. Queloz, N. C. Santos, S. Udry, J.-L. Bertaux and J.-P. Sivan, "An extrasolar planetary system with three Neptune-mass planets", Nature, 441, 305, 2006,

[22] M. Mayor, F. Pepe, D. Queloz, F. Bouchy, G. Rupprecht, G. Lo Curto, G. Avila, W. Benz, J.-L. Bertaux, X. Bonfiils, Th. Dall, H. Dekker, B. Delabre, W. Eckert, M. Fleury, A. Gilliotte, D. Gojak, J.C. Guzman, D. Kohler, J.-L. Lizon, A. Longinotti, C. Lovis, D. Mégevand, L. Pasquini, J. Reyes, J.-P. Sivan, D. Sosnowska, R. Soto, S. Udry, A. Van Kesteren, L. Weber and U. Weilenmann, "Setting new standards with HARPS", The Messenger ,114, 20, 2003

[23] M. T. Murphy, J. K. Webb and V. V. Flambaum, "Revisiting VLT/UVES Constraints on a Varying Fine-structure Constant", in "Precision Spectroscopy in Astrophysics", N. C. Santos, L. Pasquini, A. C. M. Correia, M. Romaniello (eds.), p. 95, Springer, 2008

[24] H. Chand, R. Srianand, P. Petitjean and B. Aracil, “On the Variation of the Fine-structure Constant, and Precision Spectroscopy”, in “Precision Spectroscopy in Astrophysics”, N. C. Santos, L. Pasquini, A. C. M. Correia, M. Romaniello (eds.), p. 101, Springer, 2008
[25] S. A. Levshakov, P. Molaro, S. Lopez, S. D’Odorico, M. Centurion, P. Bonifacio, I. I. Agafonova and D. Reimers, “High-Precision Measurements of $\Delta\alpha/\alpha$ from QSO Absorption Spectra”, in “Precision Spectroscopy in Astrophysics”, N. C. Santos, L. Pasquini, A. C. M. Correia, M. Romaniello (eds.), p. 105, Springer, 2008
[26] E. Reinhold, R. Buning, U. Hollestein, A. Ivanchik, P. Petitjean and W. Ubachs, “Indication of a Cosmological Variation of the Proton-Electron Mass Ratio Based on Laboratory Measurement and Reanalysis of H2 Spectra”, Phys. Rev. Lett. 96, 151101, 2006
[27] P. P. Avelino, C. J. A. P. Martins, N. J. Nunez and K. A. Olive, “Reconstructing the dark energy equation of state with varying couplings”, Phys. Rev. D, 74, 083508, 2006,
[28] C. J. A. P. Martins, “Astrophysical Probes of Fundamental Physics”, in “Precision Spectroscopy in Astrophysics”, N. C. Santos, L. Pasquini, A. C. M. Correia, M. Romaniello (eds.), p. 89, Springer, 2008
[29] J. Liske, A. Grazian, E. Vanzella, M. Dessauges, M. Viel, L. Pasquini, M. Haehnelt, S. Cristiani, F. Pepe, G. Avila, P. Bonifacio, F. Bouchy, H. Dekker, B. Delabre, D. D'Odorico, V. D'Odorico, S. Levshakov, C. Lovis, M. Mayor, P. Molaro, L. Moscardini, M. T. Murphy, D. Queloz, P. Shaver, S. Udry, T. Wiklind and S. Zucker, “Cosmic dynamics in the era of Extremely Large Telescopes”, MNRAS, 386, 1192, 2008, DOI: 10.1111/j.1365-2966.2008.13090.x
[30] L. Pasquini, S. Cristiani, H. Dekker, M. Haehnelt, P. Molaro, F. Pepe, G. Avila, B. Delabre, S. D’Odorico, J. Liske, P. Shaver, P. Bonifacio, S. Borgani, V. D’Odorico, E. Vanzella, F. Bouchy, M Dessauges-Lavadsky, C. Lovis, M. Mayor, D. Queloz, S. Udry, M. T. Murphy, M Viel, A. Grazian, S. Levshakov, L. Moscardini, T. Wiklind and S. Zucker, “CODEX: Measuring the Expansion of the Universe (and beyond)”, The Messenger, 122, 10, 2005
[31] N. C. Santos, L. Pasquini, A. C. M. Correia and M. Romaniello, “Precision Spectroscopy in Astrophysics”, Springer, 2008
[32] C. Lovis and F. Pepe, “A new list of thorium and argon spectral lines in the visible”, Astron. Astrophys. 468, 1115, 2007
[33] Th. Udem, R. Holzwarth, T. W. Hänsch, “Optical frequency metrology”, Nature, 416, 233, 2002
[34] T. Steinmetz, T. Wilken, C. Araujo-Hauck, R. Holzwarth, T.W. Hänsch and T. Udem, “Fabry–Pérot filter cavities for wide-spaced frequency combs with large spectral bandwidth”, Appl. Phys. B, 96, 251, 2009,
[35] D. A. Shaddock, M. B. Gray and D. E. McClelland, “Frequency locking a laser to an optical cavity by use of spatial mode interference”, Opt. Lett. 24 1499, 1999