Performance of a laser frequency comb calibration system with a high-resolution solar echelle spectrograph

H.-P. Doerr[a], T. J. Kentischer[a], T. Steinmetz[b,c], R. A. Probst[b,c], M. Franz[a], R. Holzwarth[b,c], Th. Udem[c], T. W. Hänsch[c] and W. Schmidt[a]

[a] Kiepenheuer-Institut für Sonnenphysik, Schöneckstraße 6, Freiburg, Germany;
[b] Menlo Systems GmbH, Am Klopferspitz 19a, Martinsried, Germany;
[c] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, Garching, Germany

ABSTRACT

Laser frequency combs (LFC) provide a direct link between the radio frequency (RF) and the optical frequency regime. The comb-like spectrum of an LFC is formed by exact equidistant laser modes, whose absolute optical frequencies are controlled by RF-references such as atomic clocks or GPS receivers. While nowadays LFCs are routinely used in metrological and spectroscopic fields, their application in astronomy was delayed until recently when systems became available with a mode spacing and wavelength coverage suitable for calibration of astronomical spectrographs. We developed a LFC based calibration system for the high-resolution Echelle spectrograph at the German Vacuum Tower Telescope (VTT), located at the Teide observatory, Tenerife, Canary Islands. To characterize the calibration performance of the instrument, we use an all-fiber setup where sunlight and calibration light are fed to the spectrograph by the same single-mode fiber, eliminating systematic effects related to variable grating illumination.

Keywords: spectrograph calibration, wavelength calibration, laser frequency comb, solar spectroscopy

---

---

1. INTRODUCTION

Solar spectroscopy is often used to study plasma dynamics by means of the Doppler shift of spectral lines. In most cases, the processes involved are characterized relative to some arbitrarily chosen reference point, e.g., a spatial or temporal mean position of the spectral lines. Such relative measurements are insensitive against most systematic effects that influence the wavelength measured. This self-calibration method fails, as soon as the mean value itself is biased by a systematic effect in an unpredictable way. In those cases, absolute wavelength calibration is needed. A prominent example for a measurement is the so-called convective blueshift. This is a shift of spectral lines caused by solar surface convection.[1] It is strongest at the disk center and shows a center-to-limb variation, known as the "limb effect".[2] For a precise characterization of the limb effect, absolutely calibrated measurements are needed. To date, absolute measurements of the limb effect have been limited to a few lines where accurate wavelength references are available[3] and model computations are employed.[4] Another example for an absolutely calibrated measurement are sun-as-a-star radial velocity measurements as a function of solar activity. This is a long-term measurement, and an absolute, repeatable, and reliable wavelength standard is needed to detect and eventually remove time-dependent instrumental effects.

Further author information: (Send correspondence to H.P.D.)
H.P.D.: E-mail: doerr@kis.uni-freiburg.de, Telephone: +49 761 3198-0

Traditionally, in solar spectroscopy, iodine cells are used for an absolute calibration. This method provides an accuracy of about 10 m/s (0.02 pm), and is limited by the knowledge of the iodine wavelengths themselves, and by the convolution of the solar and iodine spectra.[5]

Laser frequency combs (LFCs) have been proposed as the ideal calibrator for astronomical spectrographs.[6] The comb modes are equidistant in frequency, the absolute frequencies are directly linked to a frequency standard such as an atomic clock. A laser comb-based calibration source can be exchanged without affecting the calibration. LFC calibrated spectra from different instruments, even recorded decades apart, could directly be compared on an absolute scale. Several successful demonstrations of so called "astro-combs" have been published in the last couple of years,[7–12] where some setups were already employed for scientific measurements.

In a cooperation between the Kiepenheuer-Institut für Sonnenphysik, Freiburg, Germany and the Max-Planck-Institut für Quantenoptik, Garching, Germany, a frequency comb based calibration system for the high-resolution Echelle spectrograph at the German Vacuum Tower Telescope (VTT) on Tenerife, Canary Islands, was developed and deployed to the observatory in October 2011.[13] In this work, we report on the current status of the VTT astro-comb and our ongoing efforts in making the system available for regular observations.

2. INSTRUMENTAL SETUP AT THE VACUUM TOWER TELESCOPE

2.1 The Echelle spectrograph

The spectrograph was the main instrument when the 70 cm Vacuum Tower Telescope (VTT) started its science operation in the 1980s.[14] It is a visible and near-IR, pre-dispersed Echelle spectrograph for high-resolution ($R = 1.2 \times 10^6$ or 500 MHz @ 500 nm) spectroscopy of single Fraunhofer lines in the solar spectrum.

The spectrograph is aligned vertically in a steel vessel which is rotatable such that the slit can be positioned in any desired orientation on the solar image in the primary focus of the telescope. The slit covers a field of view (FOV) of 300 arcseconds. Different slits can be used with widths varying between 40 µ and 150 µm. The full spectral resolution is only available with the 40 µm slit, which also matches the diffraction limited spatial resolution of the VTT (0.2 arcseconds). Masks can be placed in the focal plane of the pre-disperser to select one or several spectral ranges of interest. The Echelle grating has 79 grooves per mm with the blaze angle at 63.43 °.

The light from the telescope enters the spectrograph with a comparably slow $f/65$ beam, typical for solar tower telescopes. Originally, the spectrograph was designed to give an optimal image scale for photographic plates resulting in large dimensions with a height of approximately 15 m. Neither temperature nor pressure stabilization is easily possible with that a large instrument. However, since the spectrograph tank is mostly situated below ground level, passive stability is comparably good and so far has not been an issue for the kind of measurements the instrument was designed for. In 2002, the focal length of the camera system was adopted to match the typical pixel scale of CCDs. The focal plane cameras are not permanently attached to the spectrograph but can be arranged by the observer to match the spectral regions selected with the predisperser mask.

Total system throughput is sufficient for typical exposure times of the order of 100 ms. With such short exposure times, a reasonable duty cycle can only be obtained with interline CCD cameras which feature a virtually negligible read-out time. The current generation of cameras at the VTT spectrograph provide thermo-electrically cooled CCDs with 4008×2672 pixels at a pixel pitch of 9 µm. The cameras can be read out with two amplifiers at 8 MHz or 32 MHz with a RMS readout noise of $11\,e^-$ or $14\,e^-$, respectively. With these cameras, two-dimensional spectra can be obtained by scanning the solar image over the entrance slit of the spectrograph.

2.2 The laser frequency comb

The frequency $f_n = f_0 + nf_{\text{rep}}$ of the n-th mode of a laser frequency comb is solely determined by the repetition rate f_{rep} and the carrier envelope offset frequency $|f_0| < f_{\text{rep}}$ of the laser resonator. Both are radio frequencies that can be stabilized by a local RF reference oscillator. The laser repetition rate, that defines the mode separation of the comb in the frequency domain, is typically in the order of a few 100 MHz which can not be resolved even by a very high-resolution spectrograph. Most astro-comb systems proposed so far use Fabry-Pérot Cavities (FPCs) for spectral filtering of the comb modes to increase their mode separation.

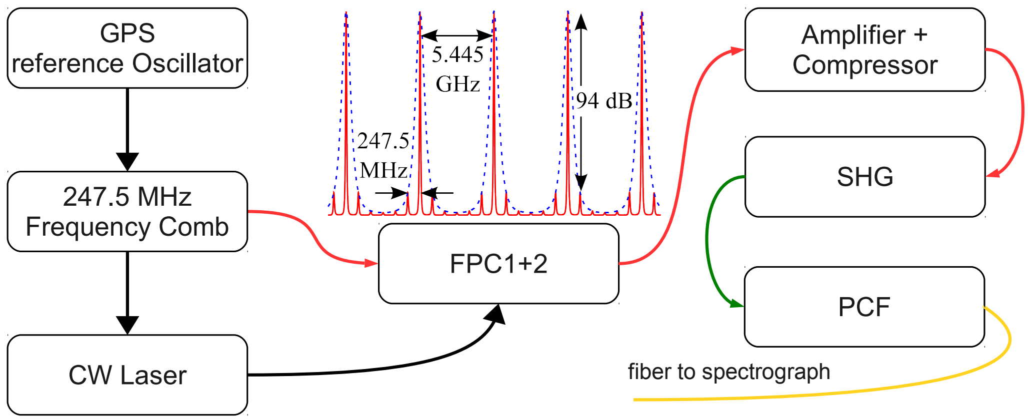

Figure 1. Schematic view of the VTT astro-comb. The comb laser (solid line) is filtered by two FPCs (dashed line). The filtered comb spectrum at 1060 nm is transferred to the visible via second harmonic generation and broadened in a photonic crystal fiber. Most components are fiber coupled which increases the stability of the optical alignment.

The VTT frequency comb system is similar in concept to setups published previously.[7,15] Figure 1 shows a sketch. The basis is a commercial Ytterbium fiber laser (Menlo Systems FC 1000) with a repetition rate of $f_{\mathrm{rep}} = 247.5\,\mathrm{MHz}$ operated in the near-IR at 1060 nm. Repetition rate and offset frequency are locked to a local GPS disciplined quartz oscillator with an accuracy and short-term stability of better than 10^{-12}. We employ two identical plano-concave high-finesse FPCs in series to filter out all but each 22nd comb mode to increase the mode separation to 5.445 GHz. The unusual value of the cavity free spectral range (FSR) and f_{rep} is a compromise solution to maximize the separation between the resonance frequencies of the TEM_{00} and higher-order cavity modes for the given curvature of the mirrors. Both cavities are locked with a modified Pound-Drever-Hall technique to a continuous wave (CW) laser which itself is locked to one of the transmitted comb lines. The frequency of the CW-laser is measured with a wavemeter to determine the offset frequency of the filtered comb spectrum. The FPCs were equipped with new mirrors in May 2012 to increase their finesses from previously 400 to a nominal value of 3000. The measured finesses of the cavities are now $\mathcal{F}_{\mathrm{FPC1}} = 3096$ and $\mathcal{F}_{\mathrm{FPC2}} = 2143$. The origin of the difference is not yet clearly identified. There are some manufacturing tolerances for the coatings but it could also stem from a slight contamination of one of the mirrors in FPC 2. To increase the servo bandwidth of the cavities, we cut down the plane mirrors before they are glued on a piezo tube. Nevertheless, the high finesse results in an excellent suppression of the nearest 247.5 MHz sidemodes of better than 94 dB. An efficient sidemode suppression is very important for the total system performance as the sidemodes will be re-amplified by non-linear processes and, since being unresolved by the instrument, would then slightly shift the centroids of the filtered comb modes in a non-predictable way.

Fiber amplifiers are inserted before each FPC to replenish the power that is lost due to spectral filtering and limited cavity transmission. A high-power amplifier boosts the laser power to about 1.5 W before it passes a pulse compressor with which we achieve pulse widths of about 120 fs. Short pulses are necessary for efficient second harmonic generation (SHG) in a 5 mm Lithium Borate (LBO) crystal and the following spectral broadening in a photonic crystal fiber (PCF). The PCF is tapered to enhance the non-linear effects that drive the spectral broadening.[16] The broadening characteristics depend very much on the actual PCF and the spectral power distribution of the incoming laser light. Typically, the usable bandwidth reaches from 480 nm to 640 nm. The spectral power distribution after the PCF is highly variable at a scale of a few nanometers, but this is not a major drawback so far since the spectral region recorded on the detector is only about 0.5 nm.

Compared with the nominal spectral resolution of the spectrograph of 500 MHz, 5.445 GHz is a rather large mode separation; the optimal spacing was found to be around three times the spectral resolution of the instrument.[6] However, for absolute wavelength calibration, the true mode numbers of the unfiltered comb need to be determined from the spectrum recorded on the CCD. To resolve the 5.445 GHz ambiguity of the filtered comb, it would be sufficient to use the known wavelengths of a spectral lamp superimposed on the comb. However, since the spectral bandwidth on the detector is very small, this would be practical only for a few selected spectral regions. Instead, we use the solar spectrum itself as a reference. This is possible, because the wavelengths of most solar lines are known with an accuracy of a few mÅ, corresponding to a few 100 MHz. But effects like solar oscillations, granulation etc. easily introduce wavelength shifts of a few GHz which would require long averaging times if the separation of the comb modes was much narrower.

Except for a free space section for the SHG and PCF, all components of the comb system are fiber coupled. This ensures a very stable alignment of the optics which is important for our application as the system will be operated by non-experts during the regular observing campaigns.

2.3 Single-mode fiber coupling system

Calibration and sunlight is coupled in the spectrograph with single-mode fibers. By using the same single-mode fiber, a perfect mode match between object and calibration light can be guaranteed, and we may assume that any systematic effects related to varying illumination of the spectrograph optics are avoided that way. Light from the telescope can currently efficiently be coupled to the single-mode fiber from a circular aperture with a FOV of approximately 6 arcseconds which is sufficient for many applications and will be further decreased in the future. With this setup, the spectrograph camera saturates with exposure times of two seconds (@ 550 nm) which is acceptable for most applications also. The position of the aperture in the solar focal plane image is tracked with a CCD camera so that the actual FOV observed by the fiber can be reconstructed for each spectrum later. A second fiber collects light from the robotic full-disk telescope ChroTel[17] which is attached to the VTT building. This can be used for sun-as-a-star spectroscopy with integrated sunlight, complementing the spatially resolved measurements with the VTT. Sunlight and calibration light from the laser comb is then combined in another single-mode fiber that finally feeds the spectrograph. A computer controlled chopper allows one to switch between the sun and laser channels, or to use both simultaneously. Light from a halogen lamp is coupled in another single-mode fiber that is used instead of the sunlight fiber for flatfielding. Efficiency is very low here, but a single flatfield spectrum can be recorded in about 40 seconds.

We developed a slitless fiber unit to couple the light in the spectrograph. The fiber's exit facet is imaged to a spot of about 10 µm at the focal plane of the telescope where normally the entrance slit defines the light beam that enters the spectrograph. The f-ratio of the fiber beam is matched to that of the telscope so that the collimating mirrors and the grating are illuminated in the same way as if using the slit. The spectrograph suffers from a slight astigmatism so that a compromise between spatial and spectral resolution has to be found for normal observations with the slit. With the fiber setup however, we can readjust the camera to the best spectral focus and compensate for the distorted PSF by vertical binning. An extended fiber unit with a second single-mode fiber channel that would allow for simultaneous calibration is currently in preparation.

Originally, it was foreseen to illuminate a small fraction of the entrance slit with light from the frequency comb calibrator such that most of the FOV could still be used for solar spectra and a simultaneous calibration with the laser comb would be possible. For a stable calibration, the laser beam needs to be extremely precisely aligned with the optical axis of the telescope. Permanent monitoring of the alignment would be necessary to guarantee the stability of the absolute calibration. While this should be possible in principle, we decided to test the complete system with the all-fiber setup first.

3. TEST MEASUREMENTS

LFCs are valuable tools for spectrograph characterization not only in terms of wavelength calibration. Since the line width of the laser lines is much narrower than the spectrograph resolution, in a fiber fed spectrograph, the laser acts as a spatial and spectral point source and can be used to determine the point spread function (PSF) of the instrument very precisely. This can also be done with any stabilized single-mode laser of course, but the LFC covers a much wider wavelength range and the PSF is available for each science exposure without additional effort. Knowledge of the instrument PSF is especially important when spectra obtained from numerical computations are to be compared with measured data as the computed spectra need to be convolved with the instrumental PSF to be meaningful.

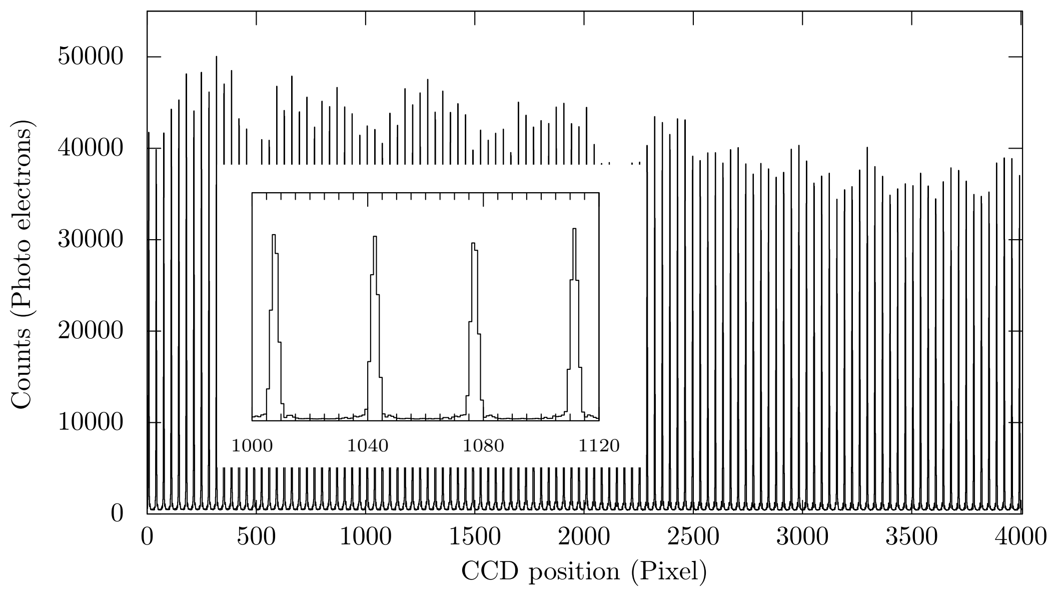

Figure 2. Calibration spectrum from the first exposure of the test data-set. The spectral window of approximately 0.6 nm is centered on 543.4 nm. The inset shows a close-up of four laser lines at around pixel 1050.

3.1 Calibration accuracy

The dense grid of equidistantly spaced emission lines of a laser comb calibrator makes it very straightforward to establish a pixel-to-wavelength map from a calibration exposure. Individual Gaussians are fitted to each of the laser lines to find their line centroids in terms of pixel position on the CCD. A polynomial is then fitted to the line positions to derive the relation between pixels and the known frequencies of the laser modes. A common measure for the calibration accuracy is the standard deviation of the residuals when the calibration curve is subtracted from the fitted line positions.

The photon noise limited accuracy δv_{rms} when estimating the centroid of a single Gaussian profile with a full-width-at-half-maximum (FWHM) of Δv m/s, sampled with n pixels at a given peak signal-to-noise-ratio (SNR) can be computed by[6]

$$\delta v_{\mathrm{rms}} = 0.41 \frac{\Delta v}{\mathrm{SNR}\sqrt{n}}. \quad (1)$$

With the VTT Echelle, at a typical SNR of 150, this yields an error of about 40 cm/s for the position of a single comb line.

In the following, we report some results from a preliminary analysis of a series of 1000 calibration exposures that were recorded on June 2, 2012, 21:42 UT. The exposure time was 30 ms with a cadence of 10 Hz. The spectral window on the CCD was centered at 543.4 nm. The leftmost and rightmost comb lines were clipped out in the fitting procedure and a total of 114 lines for each calibration exposure was used for the analysis.

Figure 2 shows the calibration spectrum from the first exposure in the data-set. From the Gaussian fits to the comb lines, a mean FWHM of 2.82 pixels can be derived which corresponds to a spectral resolution of $R = 1.24 \times 10^6$. The mean SNR of 200 of the comb spectrum yields a photon noise limited error of 30 cm/s for a single comb line. For the calibration curve, we use a sixth-order polynomial resulting in a significant lower scatter when compared with lower-order polynomial fits. Figure 3 shows the residuals of the calibration curve for the spectrum in Figure 2. The mean calibration error as measured by the standard deviation of the residuals is 65 cm/s. For the complete sample of 1000 exposures the mean, the minimum and the maximum calibration errors are 66 cm/s, 49 cm/s and 170 cm/s, respectively. In general, we find a higher scatter in the upper 2000 pixels of the calibration spectra of this data-set. In Figure, 4 the calibration accuracy for the pixels #0 − #2003

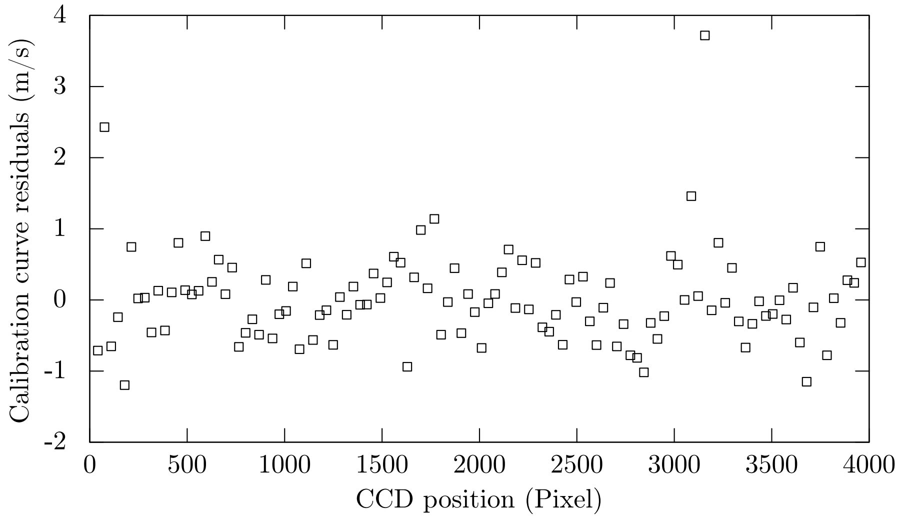

Figure 3. Residuals from a sixth-order polynomial calibration curve computed from exposure #0 in the test data-set. The standard deviation is 65 cm/s with a photon noise of 30 cm/s.

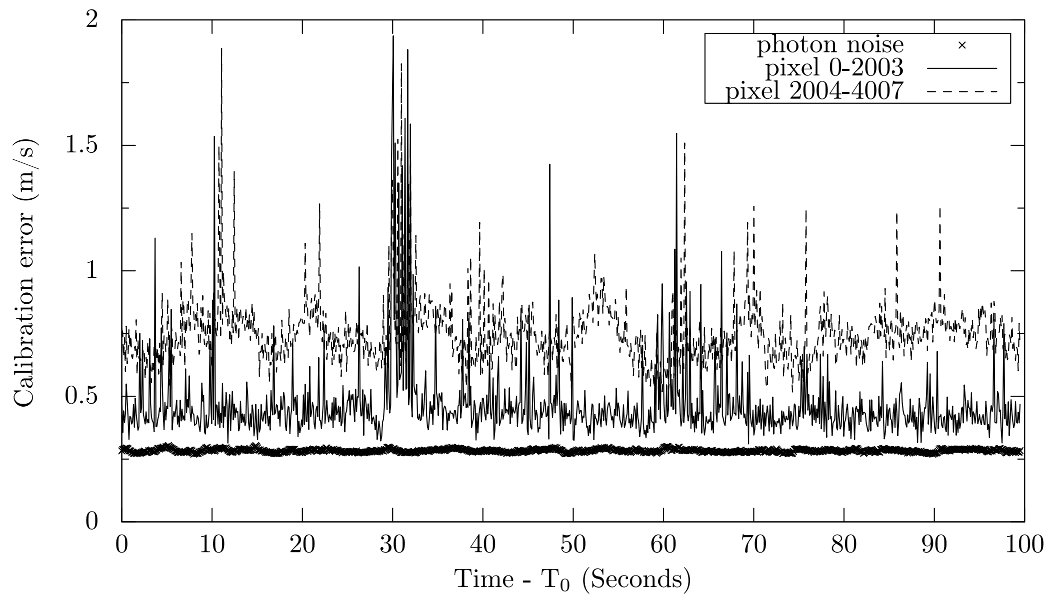

Figure 4. Calibration errors for the complete sample of 1000 exposures from the test data-set. The spikes at T=30 seconds exceed 3 m/s for the dashed line. The mean values of the solid line and dashed lines are 47 cm/s and 75 cm/s, respectively.

and #2004 – #4007 is computed separately. Compared to the right CCD section (75 cm/s), the calibration error in the left section is significantly smaller (47 cm/s) and close to the limit set by photon statistics (30 cm/s).

3.2 Spectral drift of the system

We measure the spectral drift of the system by subtracting the fitted comb line positions in each exposure from an arbitrarily chosen reference exposure (exposure #0). Figure 5 shows the drift measured that way. The short-term drift oscillates with an amplitude of about 30 m/s at a timescale of 15 seconds. We also find a very-high frequency jitter with an amplitude of a few m/s whose timescale is unresolved by the current measurement.

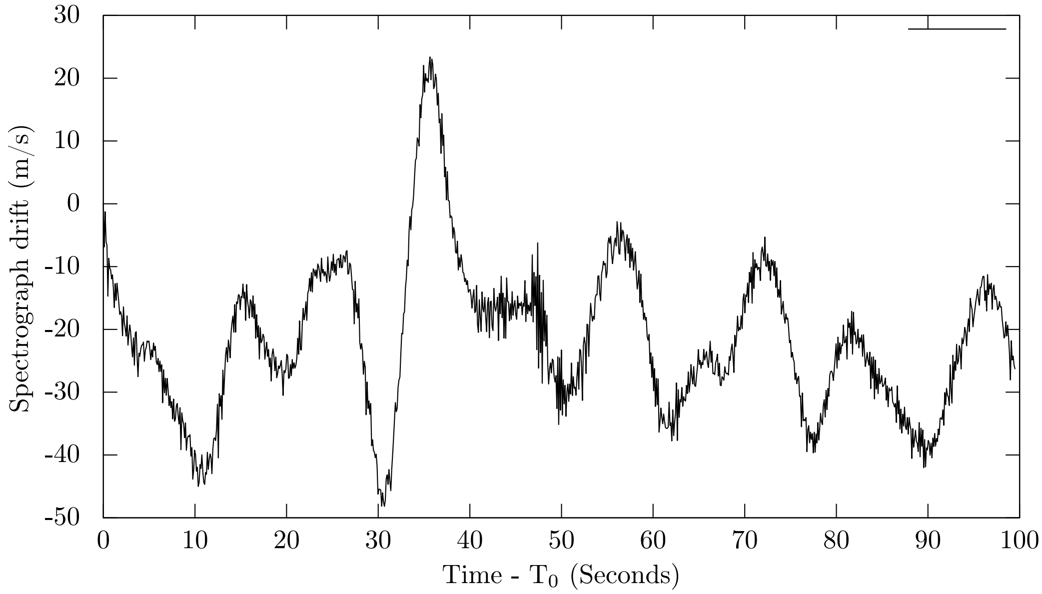

Figure 5. Total system spectral drift as measured from the test data-set.

3.3 Discussion

The spectral instrument PSF obtained from both data-sets is not purely Gaussian as it features weak sidelobes and a slight asymmetry (Fig. 2). For demonstration of the calibration accuracy this is not critical. For the purpose of absolute calibration at sub m/s precision however, a study on the impact of different fit functions and varying lineshapes needs to be carried out.

From the data we analyzed so far, we find a large variation in the calibration accuracy depending on the row on the CCD. Even when there are no visible flatfield contaminations or hotpixels, a systematic variation can be identified in most data sets. We attribute this to the microlens array that is used by the interline CCDs. While these cameras are needed for typical solar spectroscopy applications (section 2.1), they are clearly not perfectly suited for spectroscopy at this level of accuracy. Tests with a full-frame CCD camera are planned for the coming campaigns. Since with the fiber setup, spatial resolution is lost anyway, the slow read-out time of full-frame CCDs can be compensated by sub-region read-out and vertical binning without decreasing the duty cycle.

The reason for the high temporal variability in the calibration performance and the spectral drift of the system is not identified yet. The shape of the PSF changes strongly with slight detuning of the fiber coupling optics which will be made more stable in the future. The camera suffered from vibrations from the cooling fan; this could not be solved on-site during the campaign. A Doppler shift of 80 cm/s corresponds to 1/100 of a pixel or 0.1 µm on the CCD and mechanical vibrations could easily introduce displacements of much larger magnitude. The impact of vibrations from control motors, cooling fans etc. will be studied in more detail during the the next campaigns. The impact of the short-term oscillations on the calibration repeatability will be mitigated by simultaneous calibration with a second fiber which will also improve the duty cycle.

4. CONCLUSION

With the laser frequency comb calibrator at the VTT spectrograph, we can achieve a precise absolute calibration which is mainly dominated by photon statistics. Once the setup is completely tested, scientific measurements, both spatially resolved, and unresolved (sun-as-a-star) will be carried out.

ACKNOWLEDGMENTS

This project is in part funded by the Leibniz-Gemeinschaft within the "Pakt für Forschung und Innovation". A. Fischer, K. Gerber, T. Sonner, M. Weissschädel and T. Keller provided invaluable technical support for the setup at the VTT. We would like to thank S. Stark, H. Hundertmark and P.S.J. Russell for supplying us with the tapered PCF. HPD would like to thank R. Schlichenmeier, N. Bello González and R. Rezaei for very helpful discussions.

REFERENCES

[1] Beckers, J. M. and Nelson, G. D., "Some comments on the limb shift of solar lines. II - The effect of granular motions," *Solar Phys.* **58**, 243–261 (July 1978).

[2] Balthasar, H., "Asymmetries and wavelengths of solar spectral lines and the solar rotation determined from Fourier-transform spectra," *Solar Phys.* **93**, 219–241 (July 1984).

[3] Kentischer, T. J. and Schroeter, E. H., "Interferometric measurements of the solar line Fe I 5576.1 A and its centre-to-limb variation," *Astron. Astrophys.* **245**, 279–284 (May 1991).

[4] de la Cruz Rodríguez, J., Kiselman, D., and Carlsson, M., "Solar velocity references from 3D HD photospheric models," *Astron. Astrophys.* **528**, A113 (Apr. 2011).

[5] Koch, A. and Woehl, H., "The use of molecular iodine absorption lines as wavelength references for solar Doppler shift measurements," *Astron. Astrophys.* **134**, 134–138 (1984).

[6] 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. Roy. Astron. Soc* **380**, 839–847 (2007).

[7] 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– (2008).

[8] 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. Roy. Astron. Soc* **405**, L16–L20 (June 2010).

[9] 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," *Optics Express* **181**, 19175 (Aug. 2010).

[10] 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," *Optics Express* **20**, 6631 (Mar. 2012).

[11] Wilken, T., Curto, G. L., Probst, R. A., Steinmetz, T., Manescau, A., Pasquini, L., González Hernández, J. I., Rebolo, R., Hänsch, T. W., Udem, T., and Holzwarth, R., "A spectrograph for exoplanet observations calibrated at the centimetre-per-second level," *Nature* **485**, 611–614 (May 2012).

[12] 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," *Optics Express* **20**, 13711 (June 2012).

[13] Doerr, H.-P., Steinmetz, T., Holzwarth, R., Kentischer, T., and Schmidt, W., "A Laser Frequency Comb System for Absolute Calibration of the VTT Echelle Spectrograph," *Solar Phys.* , 59 (Mar. 2012).

[14] Schroeter, E. H., Soltau, D., and Wiehr, E., "The German solar telescopes at the Observatorio del Teide," *Vistas in Astronomy* **28**, 519–525 (1985).

[15] Wilken, T., *Calibrating Astronomical Spectrographs with Frequency Combs*, PhD thesis, LMU München (2010).

[16] Stark, S. P., Steinmetz, T., Probst, R. A., Hundertmark, H., Wilken, T., Hänsch, T. W., Udem, T., Russell, P. S. J., and Holzwarth, R., "14 ghz visible supercontinuum generation: calibration sources for astronomical spectrographs," *Opt. Express* **19**, 15690–15695 (Aug 2011).

[17] Kentischer, T. J., Bethge, C., Elmore, D. F., Friedlein, R., Halbgewachs, C., Knölker, M., Peter, H., Schmidt, W., Sigwarth, M., and Streander, K., "ChroTel: a robotic telescope to observe the chromosphere of the Sun," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7014** (Aug. 2008).