Achieving a few cm/sec calibration repeatability for high resolution spectrographs: the laser frequency comb on HARPS

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ABSTRACT

The laser frequency comb, with its extreme precision, opens a new window for high precision spectroscopy for current facilities, as well as for the ELT's. We report on the latest performance of the laser frequency comb obtained in combination with the HARPS spectrograph, which allowed calibration with cm/sec repeatability. The laser frequency comb system developed is described. Details of its laboratory set-up, characterization and integration with HARPS are shown. The results of the recent test campaigns are presented, showing excellent performance in terms of repeatability as well as wavelength coverage. Preliminary on sky data and next activities to integrate such a system in HARPS are presented.

Keywords: spectroscopy, Laser Frequency Comb, radial velocity, HARPS

1. INTRODUCTION

The detection and characterization of extrasolar planets is a very hot topic, with big impact beyond the astronomical community. In this field, the Radial Velocity (RV) technique has demonstrated to be the most productive and has provided by far the largest number of detections, including most of the lower mass planets[1], being HARPS[2] so far the reference instrument in this field. The detection of Earth-like planets – low mass and ~ 1AU orbits – requires very high precision in the measurement of the RV. The Earth for example, impresses to the Sun a recoil motion with a semi-amplitude of only 9 cm/sec. Hollow cathode lamps, the baseline calibration sources of today, have lines spacing and intensities widely varying across the spectra, and are not adequate for precision better than ~ 30 cm/sec. The need for calibration sources, which guarantee centimeter per second repeatability in long term has been the driving reason to explore, develop, test and use laser frequency comb (LFC) techniques to addresses most of the limitations observed so far, when is compared to other classical calibration techniques[3].

A program to demonstrate the use of LFC as calibration source for high resolution astronomical spectrograph has been recently concluded. Started in 2007[4], a LFC prototype has been designed, developed and built[5,6,7,8] demonstrating, by testing it in the laboratory and in a number of missions at the observatory, the successful fulfilment of the requirements for this system. The system developed has been focused to become a turnkey unit, using where it was possible proven technical solutions. During the development phase four campaigns at the ESO 3.6m telescope on La Silla, using the HARPS spectrograph have been performed. Latest run on January 2011, demonstrated cm/sec calibration reproducibility; the developed system has used mode separation of 14 and 18 GHz, generating a spectra covering up more than 100 nm in the visible range with these mode separations. The challenging requirement specified at the starting of the program has been addressed. The successful conclusion of the development program brought to the conclusion that a turn key device, ready for routine operation with HARPS is necessary to maintain and enhance the instrument capabilities in the forthcoming years, making available this new calibration system to the ESO community. A new phase in this project just started lasting two years, in which the prototype developed is being engineered, tested and integrated in the HARPS operation scheme. The most recent run on HARPS took place in February 2012, confirming the successful progress for the development of the final system and the achievement of the performances achieved during the development phase.

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2. MOTIVATIONS FOR A LASER FREQUENCY COMB FOR HARPS

In more than eight years of operations HARPS has demonstrated its scientific value and excellent performances. Even in its field it is the world leader instrument, HARPS is far from exhausting its potential, and it is now entering in a very interesting phase, discovering an increasing number of multiple planetary systems and planets in long period orbits. Thanks to the high RV precision of HARPS, it was possible to detect 13 out of the 28 "super-Earth" extrasolar planets (masses below 10 times the mass of the Earth) discovered up to date by the radial velocity technique, and the lightest planet discovered so far by RV: 1.9 Earth masses, orbiting the star Gl581.

The RV precision of HARPS is estimated to be around 60 cm/sec on a single exposure[9]. The knowledge of the instrument has permitted to identify the instrumental causes that limit the RV precision: the light injection system and scrambling[10], the wavelength calibration system[11] and, to a lesser extent, the temperature variations of the detector[12]. A new injection system has been recently commissioned, which is improving the image stability at the fibre entrance[13]. Now the Th-Ar wavelength calibration system is the strongest limiting factor to the long term HARPS RV precision[10]. With the LFC, which has been shown to be as good as a few cm/sec, HARPS shall reach long-term RV precision below 30 cm/sec, giving access to the detection of Earth mass planets in close in orbits, tracing the path towards the detection of the Earth's twin. The expected RV precision to be achieved is mid-way between the current HARPS performance and the 10 cm/sec precision expected for ESPRESSO[14] at the VLT, planned to start operations in about five years, being the LFC calibration system one of the key components for ESPRESSO.

The step of moving from a laboratory prototype to a device to be operated at the telescope on an existing instrument will move us to the production phase, and will drive the development of an operational comb for the next high precision radial velocity instruments for the VLT[14] and the E-ELT[15]. The experience collected with the HARPS LFC will be invaluable for ESPRESSO and beyond.

While delivering top RV precision data for the ESO community, HARPS would be in addition, the test bench for the first plug and play, fully functional LFC for astronomy. This would permit an understanding of the long term systematic (if any) and the early optimization of the spectrograph including the comb operations and of the reduction software before ESPRESSO goes online, and well in advance of the preliminary design of any high resolution spectrograph for the E-ELT.

The frequency comb that was designed, developed and tested as prototype is now being developed by collaboration between ESO, MPQ, Menlo Systems GmbH, the Instituto de Astrofisica de Canarias and the Universidade Federal do Rio Grande do Norte. It will be installed for routine operations in HARPS in the near future after two telescope runs in which the system will be engineered, verified and integrated in the HARPS control system.

3. THE LASER FREQUENCY COMB FOR HARPS

The LFC for HARPS is based on the experience gained thorough the development program[5,6,7,8], where the prototype has successfully demonstrated to achieve the performance requirements for high resolution spectroscopy[3]. LFC technology has been successfully employed in experiments of fundamental tests of physics, such as the determination of the fine structure constant, Lamb-shift and Rydberg constant, so the optical frequency comb is an enabling technology for a variety of other precision measurements and now specifically for astronomy. The experience gained during the development program has allowed identify three key parts for implementing successfully a laser frequency comb system as calibrator for HARPS: the LFC itself, the light injection system to the spectrograph and the data analysis. In the following subsections those are described.

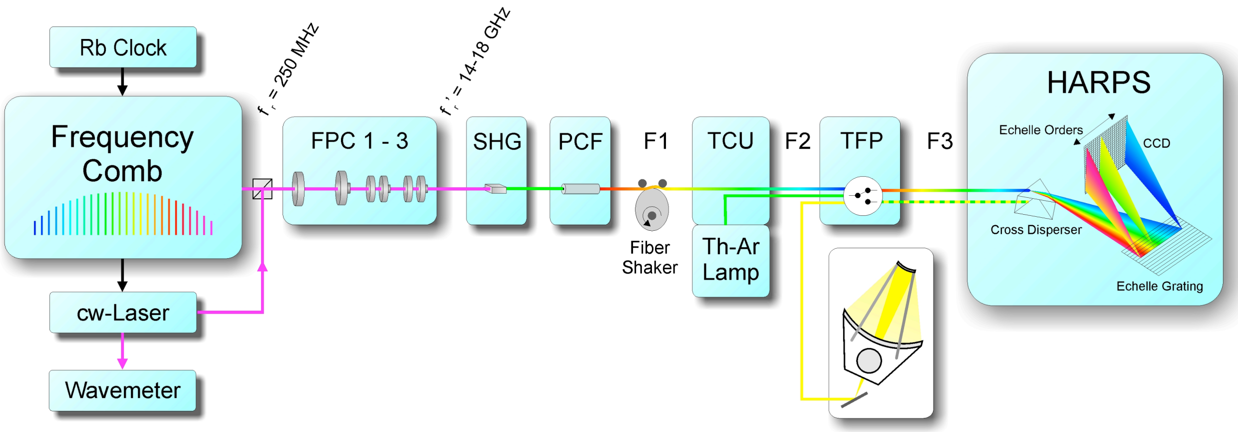

Figure 1: Experimental set-up. An Yb-fibre-based laser frequency comb is filtered with three Fabry-Perot cavities (FPC 1+2+3), which results in a mode spacing of f_r = 14 - 18 GHz. In the following second harmonic generation stage the centre wavelength frequency is doubled to 530 nm. Traversing a fibre shaker, the comb light is fed together with light from a conventional Th–Ar calibration lamp via the HARPS calibration unit (TCU) through the telescope focal plane (TFP) to the HARPS spectrograph. F1, F2 and F3 refer to the fibres between the different units, having a core diameter of 1 mm, 300 µm and 70 µm, respectively. At the TFP, apertures can be set, such that light coming from any of the F2 fibres or the telescope can be coupled to any of the two F3 fibres connected to HARPS spectrograph. Fibre 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.

3.1 The laser frequency comb system

A LFC is formed by a pulsed femtosecond laser that emits light at many frequencies (up to 10^6 lines). The frequency difference between two neighboring lines corresponds to the repetition frequency f_{rep} of the pulsed laser and is therefore constant across the comb spectrum. The frequency f_n of each line is characterized by a unique integer n such that $f_n = nf_{rep} + f_0$ with f_0 being the so-called carrier-envelope offset frequency[16]. Since both f_{rep} and f_0 are radio frequencies, they can be stabilized to an atomic clock using well established electronic phase locking techniques. In this way, each optical frequency obtains the accuracy and long-term stability of the atomic clock. While there are several frequency comb systems proposed to match the criteria for a spectrograph calibrator[17,18,19,20], our choice[5] is to use a fiber-laser-based LFC as fiber lasers are technically mature and turn-key systems - including complex wavelength conversions - are commercially available.

All relevant components of the system are depicted in Figure 2, most of them have been specifically developed for this system keeping in mind that a latter objective was to get an integrated turnkey unit, which can be used on the telescope. The first component developed was a high repetition rate oscillator, which is based on an Yb-doped femtosecond fiber-laser, capable of generating sub-100 fs pulses. Different microstructured fibers were tested to obtain an octave-spanning spectrum and to set up a *f*-2*f* interferometer for the detection and stabilization of the offset frequency. Both core-pumped amplifiers and double-clad amplifiers were developed. Core-pumped amplifiers provide moderate powers below 1 W for the *f*-2*f* interferometer and the Fabry-Pérot cavities (FPC). Double-clad amplifiers generate high powers above 10 W for the frequency conversion steps. Transferring fibers amounting to a total length of more than 30 m requires that the pulses be recompressed after passing through the amplifiers and FPCs. Pulses should be as short as possible to efficiently drive the subsequent nonlinear processes. The light is then doubled in its frequency in a selected crystal. Subsequently, tapered photonic crystal fibers (PCFs) were studied that exhibits enough nonlinearity to broaden the spectrum. Finally, to eliminate the strong intensity modulations after the PCF, a spatial light modulator has been set up to act as a high-resolution, adaptive spectral filter.

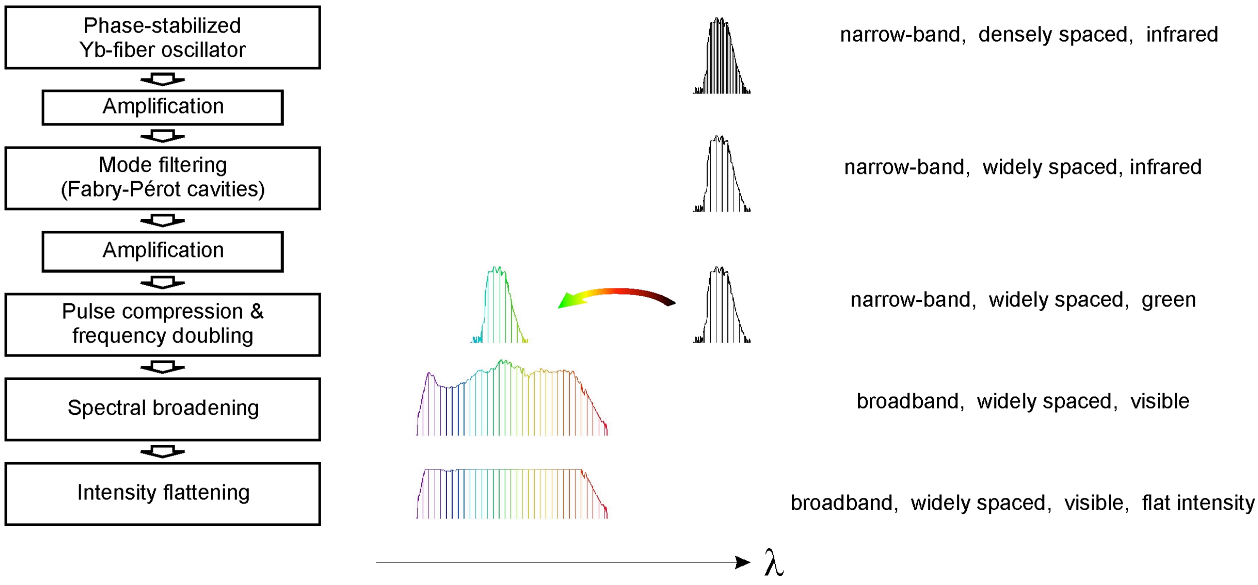

Figure 2: Schematic of the frequency comb system developed. The individual steps from the oscillator to the final calibration comb and their effect on the spectrum are depicted.

3.2 Coupling the frequency comb to HARPS

The light of our frequency comb system was coupled to HARPS via the fibers (Figure 1), which in normal operation of the instrument are used to deliver the calibration light of the thorium lamp to the spectrograph. After the LFC the comb light was coupled to a multimode fiber (F1, with 1mm core diameter). Either a collimating lens is used to focus the light directly onto the fiber input facet or the fiber is attached to an integrating sphere that is fed with the comb light. In the F1 fiber the light is guided to the calibration unit of HARPS (TCU in Figure 1). This is a rack, in which several lamps are installed, e.g. thorium lamps for calibration or white light sources for taking flat fields. At the calibration unit, optics with a 10:1 demagnification are installed that are designed to focus the light of two lamps onto two fibers (F2, 300 µm core diameter), bringing the calibration light to the telescope's focal plane (TFP). The same optics were used to couple the comb light from F1 to F2, projecting the comb light onto a 100 µm spot on the input facet of the F2 fibers. Each of these then projects a spot of 750 µm diameter on the TFP. The projected light is collected by one or both of the two fibers (F3 with 70 µm core diameter) that bring the light to the spectrograph. At the TFP, light from each of the F2 fibers or starlight from the telescope can be coupled to any of the F3 fibers. The images of the two fibers on the CCD are termed channel A and B respectively. In the path to the spectrograph, a static optical scrambler exchanges the F3 fibers near-field and far-field to reduce the effect of an inhomogeneous illumination of the input facet of F3. For our calibration tests, a dynamic scrambler was attached to F1, which actively shook the fiber to increase the occupancy of spatial modes in the fiber[6].

3.3 Data analysis

A plot of the raw data from part of the two CCD chips is shown in Figure 3. Raw data are processed with the standard HARPS data reduction routine to obtain one-dimensional spectra. The dispersion on the CCD is roughly 1.6 GHz per pixel, corresponding to about one third of the spectrograph resolution. A single comb line is therefore projected onto ~ 3 pixels (FWHM) with a spatial distribution given by the instrumental profile (IP) of the spectrograph plus the input aperture. The center of the line and an estimate of its uncertainty can be derived from a fit to the data. A Gaussian is a good approximation of the IP and is thus chosen as fit function. Note that systematic effects due to projection and fitting are common mode for differential measurements and cancel to a high degree.

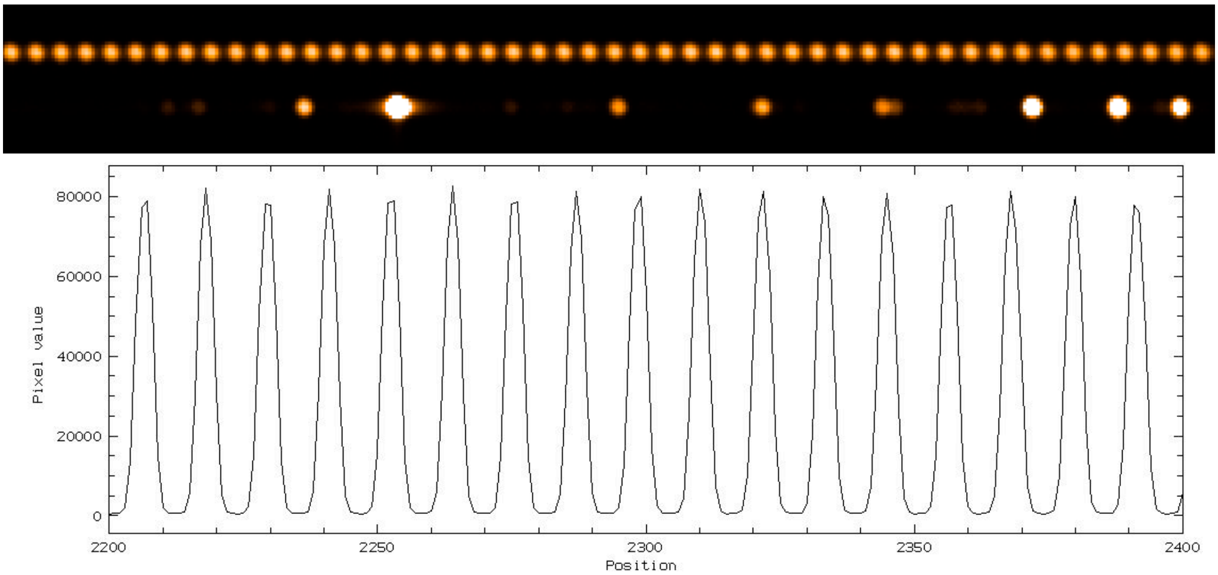

Figure 3: Raw data of one spectral order acquisition with HARPS for the fibers illuminated with the LFC (upper) part and Th-Ar lamp (lower). With a line separation of 18 GHz, the comb lines are densely spaced but do not overlap. The lower plot represents the extracted spectra showing that LFC lines are separated about 12 pixels, i.e. about 3 resolution elements.

The repeatability of the calibration is determined by taking a long series of subsequent acquisitions in which both fibers are illuminated and computing the standard deviation of the differential drift between the two independent fibers. In this way instrument induced drifts are subtracted at first order. According to the known frequency of each line, the pixel difference is converted into a shift in units of radial velocity. The algorithm to compute the LFC's calibration repeatability from the extracted and flat-fielded one-dimensional spectra was developed specifically for case.

The LFC spectrum generated has the potential to achieve repeatability at the photon noise limit of 2 cm/sec in a single acquisition, provided that the spectrum is flattened in intensity at -20 dB below the peak by using the spatial light modulator. To demonstrate this, photoelectrons of consecutive acquisitions have been added before computing the drift, the number of accumulated photons can be increased and the photon noise limit is lowered. A measure to quantify the stability of an observable, in this case the average line position, over time is the Allan deviation. The Allan deviation $\sigma_y(\tau)$ is defined as the square root of the average quadratic difference of two subsequent measurements of an observable y after a time interval τ.

$$\sigma_y(\tau) = \sqrt{\frac{1}{2}\left\langle \left(y_k - y_{k+1}\right)^2 \right\rangle}$$

where < > denotes an infinite time average and there is no dead-time between the measurement of y_k and y_{k+1}. As usual, the Allan deviation is the square root of the Allan variance. A generalized version of the Allan deviation is the 2-sample deviation, which allows for a dead-time between two subsequent measurements as it is the case for the spectrograph calibration data due to the read-out time. When no change to the comb's intensity is made during one series the 2-sample deviation can be plotted versus the accumulated number of photons instead of the acquisition time. In this way, series with different intensity are easily compared, because the number of accumulated photons uniquely determines the photon noise limit. During the latest test run on HARPS it has been achieved routinely photon noise limited repeatability. When adding several exposures, we could decrease the scatter of the calibration down to 2.5 cm/sec, after which adding more exposures do not improve the scatter and systematics limit the precision. The origin of these systematics is still unknown but likely originates from the spectrograph or the interface between the LFC and the spectrograph (Figure 4).

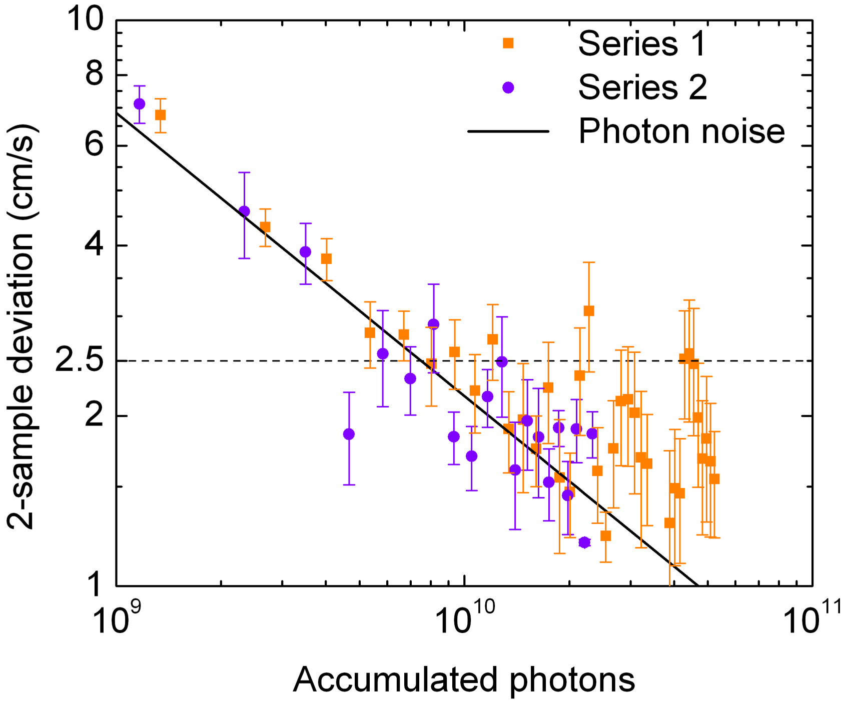

Figure 4. 2-sample deviation of the lines position in cm/sec, as function of the number of accumulated photons for two independent acquisition series (Series 1 in November 2010 and Series 2 in January 2011, see Figure 5). The solid line is not a fit, and corresponds to the $\sqrt{N}$ trend. After accumulating 10^{10} photons a floor of 2.5 cm/sec is reached, and the RMS does not diminish anymore. At this point systematics such as e.g. light injection may enter into play.

Executing different tests, performed with different LFC configurations, we have observed dependence, at the level of several cm/sec, of the line positions on the signal intensity injected into the HARPS fibers. This effect is particularly noticeable when comparing data taken with and without an integrating sphere (see Figure 5): in this case the position of the lines changes by up to ~ 1 m/sec. The light injection is indeed an area that needs further improvement, for example via the construction of a more stable injection stage. Another potential cause for the small measured lines drift is a flux dependent Charge Transfer Efficiency (CTE) in the detector. Although such an effect has never been measured on the HARPS detectors, and there is not yet strong evidence from the LFC tests, it is certainly a possibility to be considered. The CTE effect on the measured line positions is easy to calibrate[21].

In Figure 5 is shown the measured lines displacement ("Computed velocity difference") relative to the first acquired spectrum as a function of time, for two weeks of tests in November 2010 and February 2011[8]. The first and the second week were separated by forty days, and the system underwent a major overhaul in the meantime. Despite this, the RMS over the entire data set is of the order of 1 m/sec, including the large deviation measured during the integrating sphere acquisitions, presumably due to the different light injection. During the tests the system was perturbed in many ways, in order to better understand its behavior. Even the detector cooling was momentarily switched off. Nevertheless deviations measured on the spectra from the two HARPS fibers cancel each other generally very well, demonstrating the stability of both the LFC and the spectrograph.

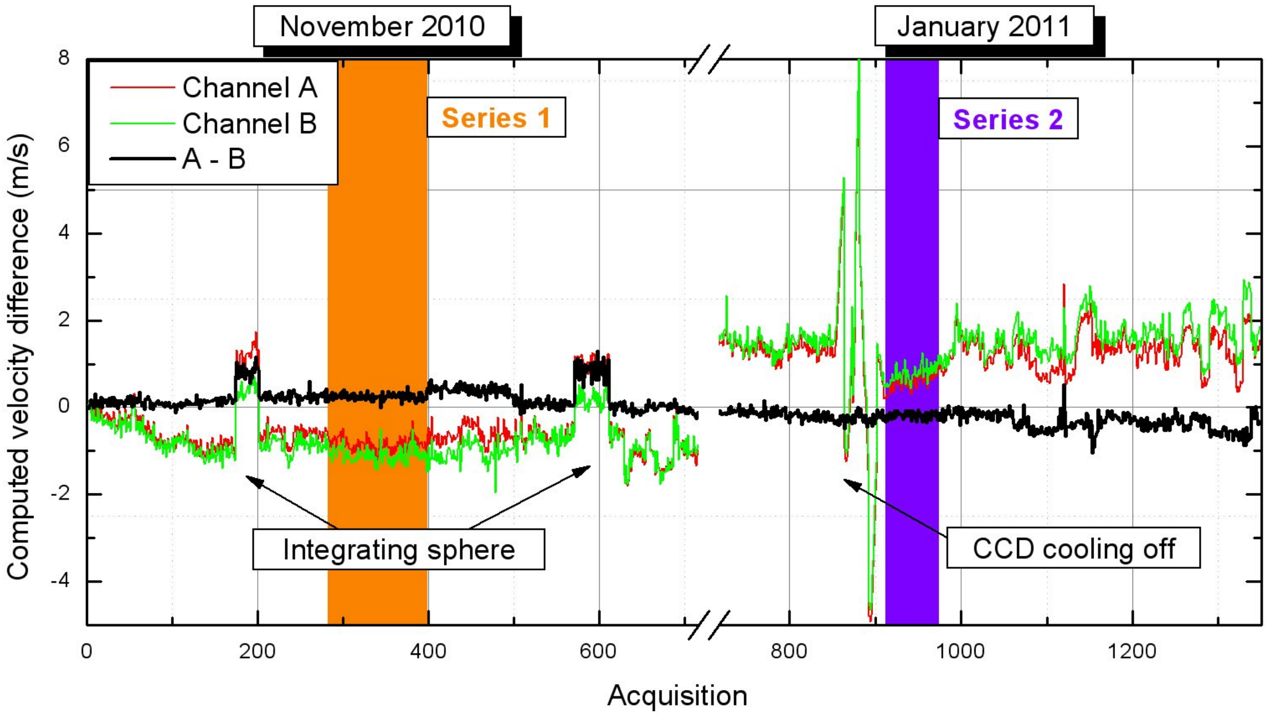

Figure 5: lines displacement (expressed in velocity drift) as a function of acquisition number[8]. The green and the red lines refer to the two different HARPS fibers (see legend), while the black line displays the differential displacement. Between the November and the January data set several components (e.g. the FPCs) were disassembled. The major events are indicated in the plot. The orange and the blue strip indicate the two series that were used in the generation of the plot in Figure 4.

FIRST ON SKY RESULTS OF THE LFC FOR HARPS

The last campaigns on HARPS have been focused not only on the technical integration of the system but to estimate its performance with astronomical measurements comparing results with known targets. The star HD75289 is an inactive 6 Gyr old dwarf star, in the constellation of Vela. Its mass and luminosity are slightly larger than solar, and it belongs to the G0 spectral class. In the year 2000, an orbiting planet was detected via the radial velocity method using the CORALIE spectrograph installed at the Euler Swiss telescope in La Silla Observatory in Chile[22]. As for other stars hosting giant planets in tight orbits, HD75289 is richer in metal than the Sun. The planet has a period of 3.51 days, a projected mass m sin(i) of 0.4 times the mass of Jupiter, and zero eccentricity. Orbiting at a distance of 0.046 AU from its parent star, it belongs to the class of "hot jupiters" giant planets strongly irradiated by their star.

During our observing campaign we have collected eight radial velocity measurements of this star, obtained both with the LFC and with the thorium calibrations. The radial velocity data obtained with both calibrations are shown in Table 1 (Figure 5). We used three more data points from the HARPS archive and fit an orbit to the entire set of radial velocity data in our possession. The root mean square of the residuals around the keplerian fit is of 6.1 m/sec for the thorium calibrated data and of 5.8 m/sec for the LFC calibrated data, indicating that the two measurements are consistent, although the LFC data seem to have residuals which are marginally smaller than the thorium data.

We expect that the measured residuals originate mostly from stellar activity or from a possible other body orbiting the star, and not from the calibration source.

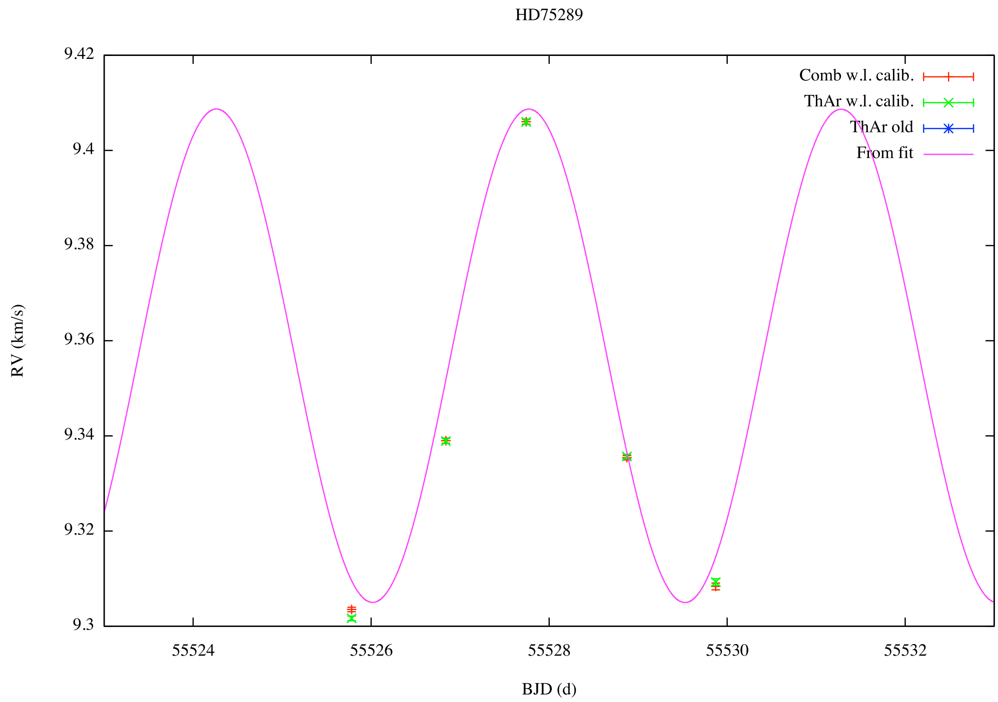

Figure 6. The orbital fit (solid line) together with the LFC calibrated data and the Th-Ar calibrated radial velocity data of the star HD75289. The Th-Ar and the LFC calibrated data are consistent. Deviations from the fit could be due to an additional companion or to the star itself. More data would be able to disentangle its origin. The measurement uncertainties are displayed in the plot, but the error bars are within the point markers. This is the first LFC-assisted measurement of the orbital motion of a star.

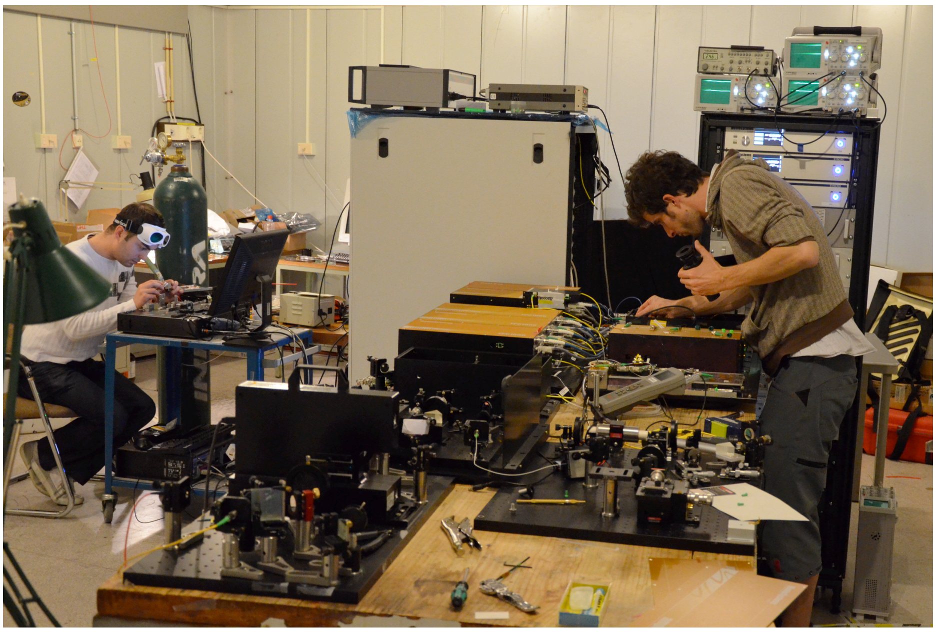

Figure 7. Laser Frequency Comb whiles the last test run of the turnkey system at HARPS in February 2012.

4. CONCLUSION AND NEXT ACTIVITIES

Laser Frequency Comb has demonstrated to improve the calibration repeatability comparing actual system and has shown to fulfill most of the expectations to become the most reliable calibration source for high resolution spectrograph, overcoming most of the limitations of current standards and achieving unprecedented repeatability. A turnkey LFC system is being in development for HARPS. The first test of this new unit took place on February 2012, after complete assessment it will be offered as standard calibration tool of the instrument to the ESO community by 2014. In long term, the experience acquired with the use of the LFC on HARPS is fundamental for the successful implementation of the new generations of high resolution spectrograph at the VLT as ESPRESSO and for the E-ELT High Resolution Spectrograph.

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