Calibration of high accuracy radial velocity spectrographs: beyond the Th-Ar lamps

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ABSTRACT

Since its first light in 2003, the HARPS radial velocity spectrograph (RVS) has performed exquisitely well on the 3.6m ESO telescope at La Silla Observatory (Chile). It now routinely exhibits a measurement noise of 0.5 m/s or 1.7 10^{-9} on a relative scale. Despite innovative work by Lovis and colleagues [14] to improve the accuracy obtained with the calibration lamps used, there is evidence that still better performance could be achieved by using more stable wavelength standards. In this paper, we present two methods are aim at overcoming the shortcoming of present day calibrators and that could satisfy the need for a cm/s –level calibrator like we are planning on using on the 2nd generation instruments at the VLT and on the ELT instrumentation. A temperature-stabilized Fabry-Perot interferometer has the promise of being stable to a few cm/s and has very uniform line levels and spacings, while a laser comb has already achieved a precision better than 15 cm/s, despite using only one of the 72 orders of the spectrographs.

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

1. INTRODUCTION

The wavelength calibration process where the each pixel of the spectrograph detector is associated with a wavelength is an important step of the data reduction of a radial velocity spectrograph. The noise associated to this process can be a significant contributor to the total error budget, depending on what ultimate precision is targeted.

Currently, on the HARPS RVS, the calibration is done with a Thorium Argon (ThAr) lamp. The accuracy of this calibration is showing it limits and leads us to investigate other calibrators both for the current RVs and the future ones that target better accuracies.

In this paper, we report on two parallel developments toward wavelength calibration systems for high resolution spectrographs: a Fabry Perot Calibration system (FPCS) and the Laser Frequency Comb (LFC) demonstrator program.

The Fabry Perot Calibration system is being developed at the Observatory of Geneva as an attempt to have a simple, rugged, mostly passive system easy to operate at the telescope. Its advantage over the ThAr lamp it that by principle it produces spectral lines equidistant in the frequency domain and this distance can be chosen. Carefull desing of the system allows to produce a spectrum where the line depth is constant.

A wavelength calibration system based on a Laser Frequency Comb is being developed under agreement between the Max Planck Institut für Quantenoptik (MPQ) and the European Organizations for Astrophysical Research in the Southern Hemisphere (ESO). The absolute reference is provided by an atomic clock which guarantees long term stability and reproducibility over the decades required for some of the measurements. Advantages of the LFC over other

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wavelength calibration standards are discussed by Murphy *et al.* [15]; its potential use in astronomy has been shown in the laboratory [17], [18] and proof in the infrared at a telescope [19].

2. ASTRONOMICAL RATIONALE

The advent of Very and Extremely Large Telescopes is opening new exciting avenues for precision spectroscopy in astrophysics. The discovery of Neptune mass planets requires a Radial Velocity accuracy of better than 1 m/s [3], which can be obtained with dedicated spectrographs, such as HARPS [4]; the study of the variability of the fine structure constant calls for a precision of a few m/s for lines which are many nanometers apart, and it is pursued by using spectrographs such as UVES at the VLT or HIRES at Keck [5], [6], [7].

The need for improving by a large factor the present spectrographs performance is pressing: the discovery of earth-mass planets in the habitable zones of solar mass stars needs a precision of a few cm/s, the dispute on the variability of the fine constant requires a perfect control of the systematic effects and a factor 100 improvement in precision, to remove the present uncertainties and to reach the accuracy expected by future space missions.

The variability of other constants, such as the electron to proton mass ratio, can also be studied [8] and measuring the evolution of these two constants with redshift could prove the presence of a scalar field and determine the equation of state of dark energy [9], [10].

Finally, with a precision of 2 cm/s it would be possible to perform a direct measurement of the expansion of the Universe by observing Lyα clouds in the line of sight of QSOs [11].

These and other applications, including stellar oscillations and measurement of isotopic ratios, will be pursued by the next generation of instruments, such as CODEX [12], and a fairly complete review of these topics can be found in [13]. A prerequisite for this research is the availability of a precise, stable and reliable source of wavelength calibration. The commonly used calibration sources, Th-Ar and Th-Ne lamps, have intrinsic limitations. New calibrations using many more lines than in the past provide a global precision about 20 cm/s and a precision on the single line about 10 m/s [14], but shortcomings such as: uneven presence of the lines, instability with time, unpredictability of the frequency of the transition, are intrinsic to the calibrations with lamps [15].

Research on novel wavelength calibration system which copes and addresses the limitation in current systems is necessary to meet new scientific challenges.

3. FABRY-PEROT CALIBRATOR PRINCIPLE AND DESIGN

Fabry-Perot interferometers are one of the most basic interferometric devices used in the lab and they have been already used in astronomical instruments, where their potential for imaging spectroscopy in interesting. The potential of FP in the calibration of RVS we recognized more than a decade ago by our institute [2], and we were just waiting for an opportunity to pu t the concept to test. The Fabry-Perot interferometer that we are using is an etalon type, meaning that it is has a fixed spacing between the 2 reflecting plates

The calibrator that we are developing is not only a Fabry-Perot interferometer but a complete *system*. It is made of the primary source, a temperature controlled vacuum cell, and glass work including the etalon, collimating and decollimating optics, optics fibers and a structure that hold all the optical components together.

Our goal is to push the limits of stability and for this purpose a number of design options have been chosen:

- The etalon operates in a vacuum environment. With a residual refractive index of 10^{-4} at atmospheric pressure, an operating pressure of 10^{-3} mBar is required to insure 10^{-10} stability. (a stability of 1cm/s correspond to relative variation of $3.3\ 10^{-11}$).
- The vacuum cell is thermally controlled. The thermal performance budget is addressed below
- The mechanical structure holding the optical components together is built in Zerodur ceramic-glass and it is entirely optically contacted except the cell holding the lenses.
- The etalon itself comes in 2 flavors: the baseline etalon is an air-spaced etalon, with thermally compensated spacers (see below). A second etalon has been produced with the same optical specifications but it uses a classical spacing ring made of grade 0 Zerodur ceramic-glass.

The thermally compensated etalon works in the following manner. The spacers are installed between two silica plates. Plate #1 has a wide band thin film coating mirror on it acting as one face of the etalon. Plate #2 supports another silica plate (#3) on which the second mirror is deposited (see figure below). The spacers are made of stack of zerodur and BK7 glass. The ratio of zerodur to BK7 is adjusted so that the temperature expansion of the spacer exactly matches that of plate #3. The limit of precision of this design is given by the dimensional errors to the 2 spacer parts and the silica plate #3. We are expecting a residual sensitivity of 10^{-9} /K The non compensated etalon has a thermal stability of 2 10^{-8} /K.

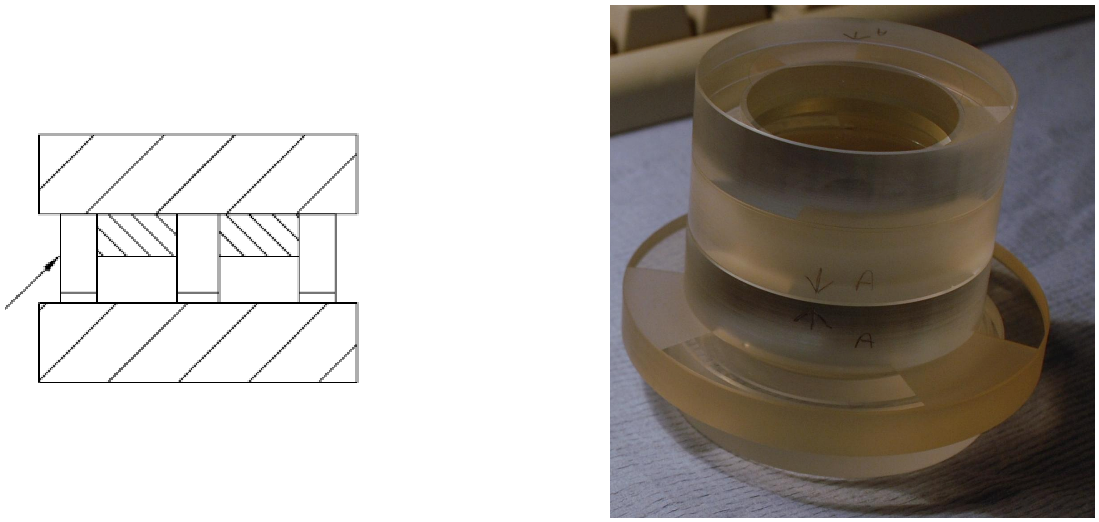

Fig 1: Plan of the compensated etalon. All dashed parts are fused silica plates. The vertical expansion of the center plate matches that of the 2-part etalon spacer (L/h). On the picture on the right, one can see that the etalon is already mounted on a structural zerodur plate that is part of the mechanical structure of the system.

The thin film mirror stack will also expand with temperature. While this is not expected to create noticeable changes in the spectral response of the mirrors, it will produce gap variations, which in first order we estimate to be proportional to the expansion of the stack. With a stack of 2 micron thickness and a CTE of 7 10^{-6}, the stability is 3.8 10^{-9} /K

With a final temperature stability estimated at a 5 10^{-3} K rms, the relative stability versus temperature is 2.4 10^{-11} and 2.0 10^{-10} for the compensated resp. uncompensated etalon.

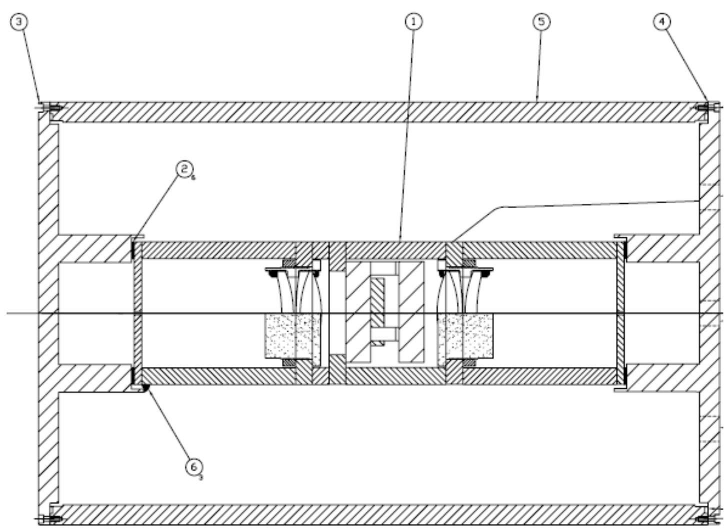

Fig 2: FCPS assembly. The outer structure is the aluminum vacuum cell. The internal closely dashed structure in the center is made of zerodur. It is optically contacted and hold all the optical components together. Light from an optical fiber enters on the L/h side, is collimated by the L/h triplet, goes through the etalon and is refocused by the R/h triplet on the fiber exiting on the R/h side. The assembly is meant to wok vertically unlike shown on this figure.

4. FABRY-PEROT TESTS

Test runs of the FPCS where scheduled on HARPS technical time in July 2009. Unfortunately, due to manufacturing delays it has not been possible to conduct them. We will use another window in early Sept this year.

Presently the system is undergoing a test phase in the laboratory. The vacuum system and the temperature control system are being checked and tuned. From the optical point of view, the global spectral response needs to be checked but the LSF cannot be measured until we have a very high resolution spectrograph (i.e. HARPS) at our disposal.

The temperature control shows already a performance better than 0.01 K and measures are being taken to reduce the time constant between heater and sensor so that a more aggressive controller setting can be used. The picture on the right shows the FPCS in its vacuum cell connected to the vacuum pump and the thermal control system. The input and output fibers are not connected to their corresponding feedthroughs

One of the potential limitations that we are most eager to test is the shrinkage of the Zerodur. This shrinkage has been documented to be roughly 10^{-7} /year [1], but certain Zerodur etalons working in the field for numerous years have not shown this behavior.

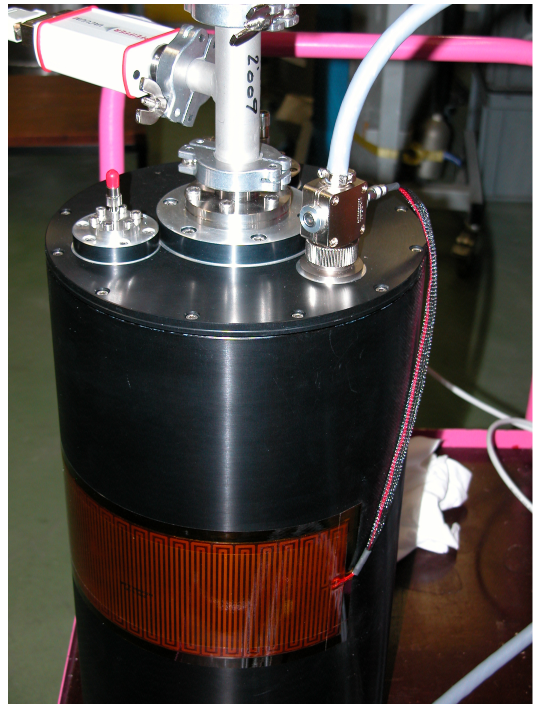

Fig 3: The FPCS in operation. The system in completely enclosed in the vacuum container. Light enters and exit the system via fiber optics feedthroughs. The heating pad seen on the bottom is part of the thermal control loop

5. LASER FREQUENCY COMB CALIBRATOR PRINCIPLE AND DESIGN

Laser Frequency Comb have been described by Udem *et al.* [16] and its use as a high precision wavelength calibration for spectrographs was proposed by Murphy *et al.* [15]; LFCs will provide a series of narrow modes which are uniformly spaced according to the laser's pulse repetition rate and whose separations are known a priori with high precision. From the calibration point of view LFCs turns to be almost the perfect calibration source.

The LFC developed at MPQ, for use in the visible range, is based on a mode locked Yb-doped fiber laser with a repetition rate of f_r = 250 MHz and a central wavelength of 1030 nm. At this frequency the comb modes cannot be resolved by HARPS, and it is one of the major technical challenges in the development of a suitable calibration source for high resolution spectroscopy. Two Fabry-Perot Cavities (FPC) with free spectral ranges of $m_1 f_r$ and m_2 ($m_1 f_r$) in series to suppress the unwanted LFC modes [15] and to increase the mode separation. The modes transmitted by the FPCs are then given by $f_N = n\, m_1\, m_2\, f_r + f_0 = N\, fr + f_0$ [16], with integer filter ratios m_1, m_2. Like for f_r, the common LFC offset f_0 is controlled by a Rb atomic clock with an accuracy of 5×10^{-11} (i.e. 1.5 cm/s). The mode number n which resolves the remaining 250 MHz 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 [20]. The cavities were tilt locked to the reflection signal of a continuous wave laser [21], which was locked to the LFC and whose frequency was monitored with a wavemeter. This ensures that the same comb modes were always transmitted by the FPCs.

LFC was set up with mode spacing of 6, 12 and finally 18 GHz for calibration, 3.4 times the nominal HARPS spectral resolution, which was selected as it minimizes the overlap between the wings of adjacent modes, making easier the spectra the analysis. Fiber amplifiers provide enough power for frequency doubling in a periodically-poled KTP crystal.

The calibration light is centered at about 514.9 nm with a FWHM of 2.1 nm. The output spectrum covers one echelle order with 362 modes, and its width is presently limited by the crystal's phase matching bandwidth.

A crucial component for the calibration repeatability turned out to be the interface between the LFC and the spectrograph. The light from the LFC (see Figure 4) is brought to the HARPS calibration unit using a 1 mm core multimode fiber (F1) where is imaged on one fiber (F2, multi mode, 300 µm core and 45 m long); the light from the Th-Ar calibration lamp is brought as well to the second F2 fiber. At the level of the telescope focal plane the light projected from each F2 fibers is collected by one of two fibers (F3, multi mode, 70 µm core and 38.5 m long), which bring the light to the spectrograph. The aperture in front of F3 has a diameter of 140 µm, and a microlens in front of the fiber converts the incoming beam to a convenient F/4 aperture. Finally, in the path to the spectrograph, an optical scrambler exchanges the F3 fiber near field and far field. Fibers F2 and F3 as well as the coupling optics are permanently installed at the telescope and could not be changed.

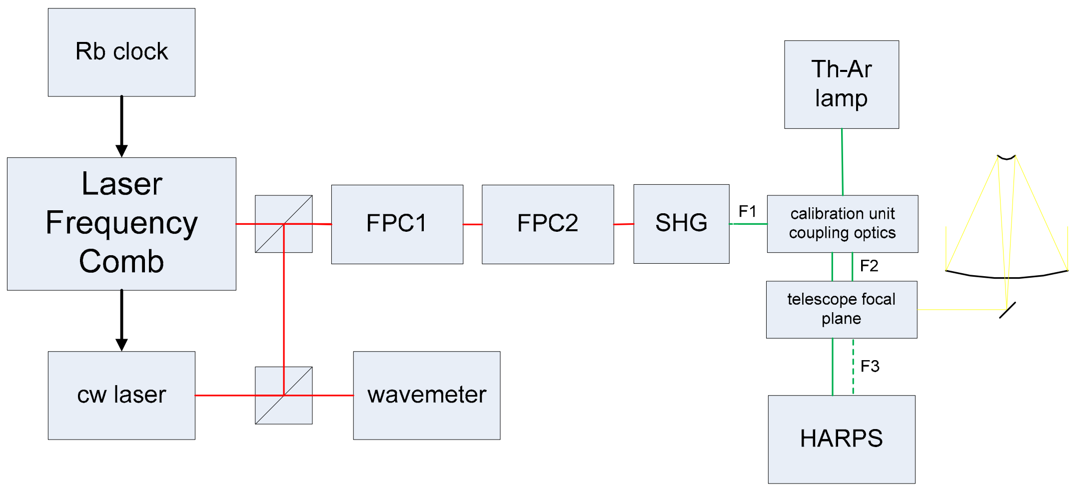

Fig. 4. The Laser Frequency Comb was filtered with two Fabry-Perot cavities (FPC1 and FPC2) to have a mode spacing of 18 GHz, and then frequency doubled (second harmonic generator, SHG) to a center wavelength of 514.9 nm. LFC light is injected in the calibration unit using fiber F1. From the calibration unit, two fibers (F2) brings, one the comb light and the second the Th-Ar. Using two F3 fibers, comb and Th-Ar signals are delivered to the HARPS spectrograph.

6. LASER FREQUENCY COMB TEST AND PERFORMANCE

The LFC setup, developed at MPQ, was delivered to La Silla observatory on January 2009, and assembled at the ESO 3.6 m telescope (see Figure 5). Technical time was allocated from January 6th to 14th to carry out the first tests of the LFC in HARPS [22]. Since the first moment the LFC operated very successfully and during the campaign the global system performances were adjusted and improved. LFC spectra with three mode separation ratios were obtained: 6, 12 and 18 GHz; however most of the data obtained used the larger mode spacing. The spectrograph feeding turned to be a critical point as the LFC light was injected in the HARPS calibration unit using a large diameter multimode fiber.

The tests carried out on HARPS were prepared to address the following aspects:

- Radial velocity measurement accuracy
- Sensitivity to spectral shifts
- Wavelength calibration

During all the tests, the LFC was always recorded simultaneously to the Th-Ar calibration lamp (see Figure 6), which allows monitoring the spectrograph drifts and the comb performances. By last it is important to remark that for all the further data analysis for performance evaluation we were using one of the 72 orders of the HARPS echellogram which was compared with the Th-Ar signal (spread in all orders) routinely in use in the spectrograph.

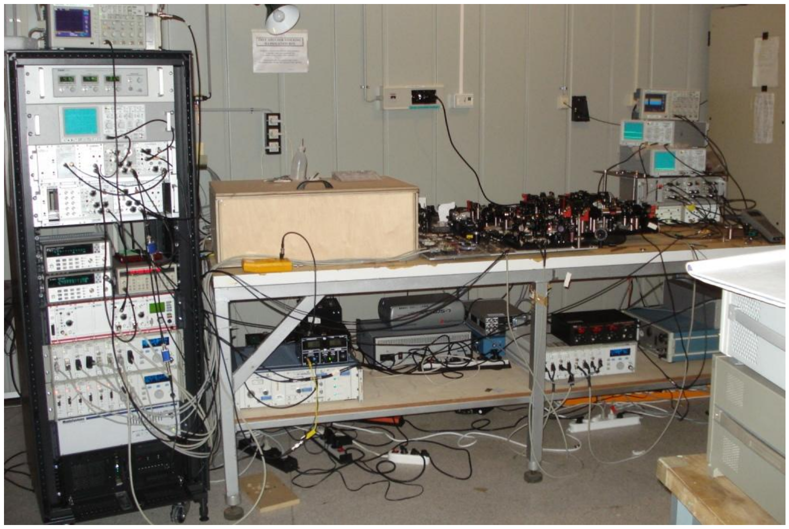

Fig. 5. LFC setup in January 2009 on HARPS. The Yb-doped fiber laser system is contained in the wooden box on the left hand side of the table, control and diagnosis electronics are in the rack and the breadboards with the Fabry-Perot cavities and amplifiers on the table. The LFC light is injected in the HARPS calibration box using an optical fiber .

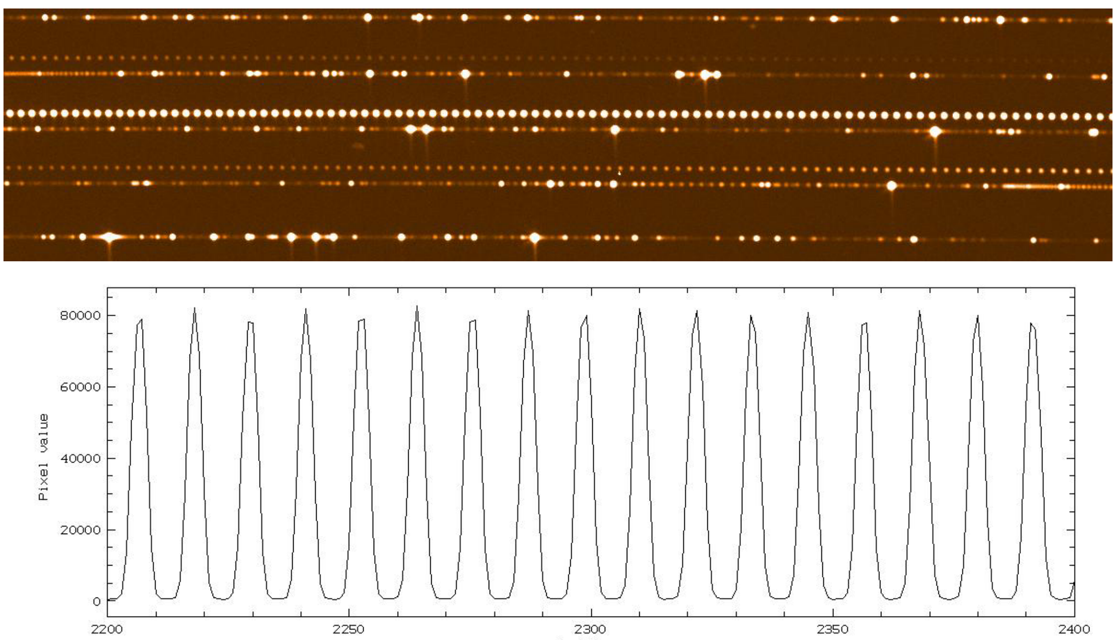

Fig. 6. Portion of the echelle spectra obtained during the test on HARPS. The spectrograph projects the signal from two fibers: one with the LFC signal, which is easy to identify in the image (row of equidistant dots) and whose cut profile is presented in the plot below, and the second with the Th-Ar spectra. The mode spacing for the LFC signal shown above was 18GHz. The graph on the bottom shows the LFC as sampled by HARPS

6.1 Radial Velocity stability

To perform the tests on radial velocity stability a number of high flux series were acquired. The exposures recorded LFC and Th-Ar signals simultaneously. The drift evaluation for the Th-Ar signal was computed using the 72 orders in the HARPS echellogram; however one order is used for the comb light. By comparing the series to the first image of each, it was clearly seen that the long term trend with a slow linear deviation, to which a semi periodic oscillation is superimposed. The fact that the oscillation is seen by the Th-Ar and the comb suggest to be a real shift of the instrument, which once it is subtracted the rms goes to 15.3 cm/s; considering that this is produced by the subtraction of data with comparable noise, and that the expected photon noise from the comb spectra is of 10 cm/sec, it indicates that we are dominated by photon noise.

6.2 Sensibility to shifts

Shifts from 200 KHz to 60 MHz were artificially introduced and compared to one reference spectrum. For information it is important to remark at this point that a drift of 1.94 MHz corresponds to shift of 1 m/sec in radial velocity. For each group of observations at a given shift the average comb shift was computed as well as the average Th-Ar shift, which has been subtracted, as a zero point measurement. The results (induced shifts minus measured shifts) shown that the artificially induced shifts are measured back with quite a good accuracy, for instance the smallest introduced shift, which corresponds to 20 cm/s, was found within a few cm precision.

6.3 Wavelength Calibration

The wavelength calibration is another important aspect that was investigated; as in previous cases results are restricted to one single order on the HARPS detector. The analysis carried out shown that after a 5^{th} order polynomial fit, residuals for (λ_{fitted} - $\lambda_{predicted}$) brings a rms of 10 m/s and in addition show structure with 512 pixel periodicity, corresponding to the CCD fabrication masks, which are visible in detector flat fields. The interpretation is that these pixels are substantially (up to 5 %) smaller than 15 microns (pixel size in the detector), so when the residuals are computed for the next pixel, the difference between the expected and the measured λ is large (up to 40 m/sec), because the previous pixel was smaller. The difference then becomes smaller and smaller as we move far from the discontinuity, producing the ramps clearly seen in Figure 7. The high density of the comb will allow calibrating this effect, otherwise if one has bad luck, a stellar or QSO line may have up to 30 - 40 m/s wrong wavelength just because of this effect. Figure 7 shows the difference in wavelength calibration across the order 42.

7. CONCLUSION

At present it has not been possible characterize the performance of the Fabry-Perot based calibrator system. We are taking aggressive measures to make sure it is ready for the technical run that ESO has allocated for tit in September this year. We do have high hopes that this calibrator will allow a more stable calibration than the ThAr lamps used today.

The Laser Frequency Combs it turning to be a very promising route to obtain accurate and a higher stability wavelength reference [15] as it provides a series of perfectly equidistant (in frequency) emission lines covering a large wavelength domain and stabilized at 10^{-11} to 10^{-15} level. The Laser Frequency Comb based calibrator performance for HARPS calibration has already shown very promising result; even with signal in a single order of the spectrograph echellogram, radial velocity accuracies down to 15 cm/s have been achieved, just above the photon noise. Another run, with the LFC modified with spectral broadening and spectral equalization is scheduled for February 2010.

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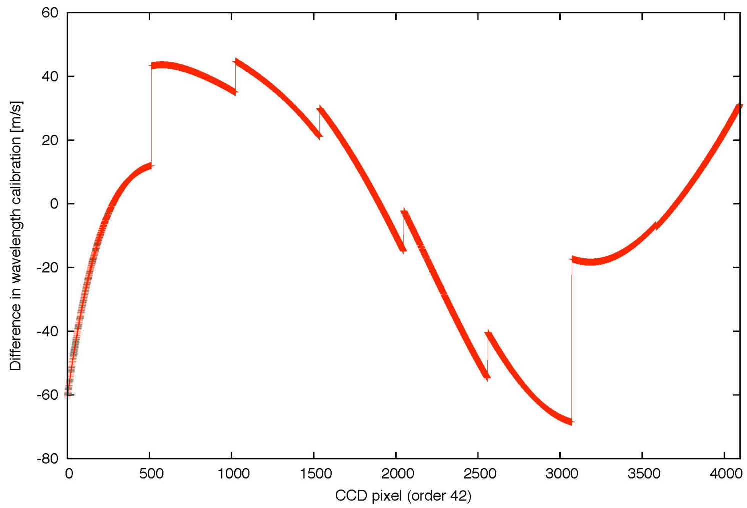

Fig. 7. Difference in wavelength calibration between standard Th-Ar and the LFC for echelle order 42.

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