A Fabry-Perot calibrator of the HARPS radial velocity spectrograph: performance report

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ABSTRACT

The radial velocity (RV) technique has pushed the planet detection limits down to super-earths. To reach the precision required to detect earth-like planets it is necessary to reach a precision around 1cm.s^{-1}. Part of the error budget is due to noise in the wavelength calibration of the spectrograph. The Observatory of Geneva has designed, built and tested in collaboration with ESO a calibrator system based on a Fabry-Perot interferometer to explore its potential to improve the wavelength calibration of RV spectrographs. We have obtained exciting results with the calibrator system demonstrated 10 cm s^{-1} stability over one night. By further improving the injection system we are aiming at a 1 m s^{-1} repeatability over the long term.

Keywords: extra-solar planets, radial velocity measurement, high resolution spectrograph

1. INTRODUCTION

The radial velocity (RV) technique is so far the most powerful extra-solar planets discovery tool. With the current precision achieved by RV of 69 cm.s^{-1}, it has pushed the planet detection limits down to super-earths (see p. ex. [1] and [2]). However, to detect earth-like planets it is necessary to reach a precision around 1cm.s^{-1}. This implies lifting some instrumental limitations, among them the wavelength calibration. While some groups are working hard developing sophisticated laser system for this calibration (see [4], [5], [6] and [7]), the Observatory of Geneva has designed, built and tested in collaboration with ESO a calibrator system based on a Fabry-Perot interferometer to explore its potential to improve the wavelength calibration of RV spectrographs. Unlike the Th-Ar lamps used today [3], this device allows the production of optimally and regularly spaced calibration lines covering all orders of the spectrograph. The stability of this system has already shown to be on par or better than the Th-Ar lamps.

2. SYSTEM REQUIREMENTS

The calibration system has been manufactured according to the technical requirements given in the table below. Conceptually it consists of a Fabry-Pérot (FP) etalon illuminated in white light in order to produce a spectrum with the following characteristics:

1. The calibration source must cover the full wavelength range of the HARPS spectrograph (λ:380-690nm).
2. The line position and shape stability of all lines is better than 10^{-11} over the instrument life-time.
3. The lines are not resolved by the spectrograph, since otherwise information is lost, respectively we do not take full advantage of the spectral resolution of the instrument. The resolution of the spectrograph is 115000, limited by the illuminating fiber size.
4. The line to line interval is perfectly stable (at the level of 10^{-11}) and ideally constant in $\Delta\lambda/\lambda$.
5. The line to line interval must be minimum 2 and maximum 4 FWHMs of the spectrograph IP.
6. The relative intensity of any neighboring lines must be stable at 10% over time.
7. The dynamic range of line intensities over the spectrum must be smaller than a factor 2.

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These performances are not easily achieved with a simple system. The expected performances expressed in technical and verifiable terms are given in the table below. The Fabry-Perot was manufactured and tested with respect to these values.

Parameter	Requirement	Units
Temperature variations	< 0.01	K (P2V)
Pressure variations	< 0.002	mbar day^{-1}
Spectral coverage	383 - 690	nm
Transmission at peak	30	%
Finesse of the FP etalon	6	
Separation s between peaks	2 < s < 5	FWHM
Line-intensity dynamics over *one order*	Factor 2	P-V
Photon precision per frame	< 5	cm s^{-1}
RV stability during a night	< 10	cm s^{-1} (rms)
equivalent relative λ-stability	< 3 10^{-10}	

3. DESIGN

3.1 General concept

The actual system as finally produced consists of:

- A 150W white Xe-arc light source, and a balancing filter to obtain an homogeneous intensity distribution from blue to red (after transmittance by the fiber, the FP and the spectrograph).
- A 600 µm optical fiber coupling the light source with the FP assembly
- The FP etalon, including collimating and focusing lens system
- A 300 µm optical fiber connecting the FP assembly with the spectrograph calibration unit /spectrograph feed)
- An injection stage with micrometric adjustment in all spatial directions to inject the calibrator light into the spectrograph via the telescope bonette.
- A vacuum tank in which the FP assembly is mounted and kept evacuated
- A temperature controller to stabilize the FP temperature

3.2 The Fabry-Pérot assembly

Figure 1 shows the two etalons produced, the first with pure Zerodur spacers, the second with specially-designed 'compensated' spacers (composite materials) to obtain theoretical absolute zero expansion and ambient temperature. This latter etalon was used for the tests.

Figure 2 shows a cross section through the FP assembly while Figure 3 shows a picture of the assembled Fabry-Pérot 'glasswork'. The system is completely optically contacted within a Zerodur support structure. The lenses are mounted inside the structure as well. The FP etalon is fed with filtered Xe light via the 600 µm fiber and a collimator. After the etalon a triplet focuses the light into a 300 µm fiber before going to the spectrograph's calibration unit.

The etalon's gap and the coating are designed to produce a contrast of 90% between the peak the intensity and the lowest intensity.

3.3 Environment control

The effective optical gap of the FP etalon depends on the refractive index of the filling gas. In order to avoid spectral shifts as the ambient pressure varies, the etalon has been installed in vacuum. The scientific requirement that the spectral line must not display shifts larger than 3 x 10^{-10} (equivalent to 1 cm s^{-1} in radial velocity) during one observing night (12 hours) calls for a pressure stability of 10^{-3} mbar for this time span. In operation, the system leakage converges towards the value of dp/dt = 0.002 mbar per day, which is about a factor of 2 higher than specified.

With the CTE of the spacers being about 2 x 10^{-8} K^{-1} the temperature must be kept within 0.015 K to achieve the required wavelength stability. A thermal control loop using a heater foil contacted to the vacuum-vessel cylinder and Silicon diode located close-by produces an accuracy of better than 0.01 K p2v. The thermal insulation and inertia of the glasswork further decreases any possible variations of the etalon where the temperature remains within 5 mK over the time scale of a night, and thus well within the specifications.

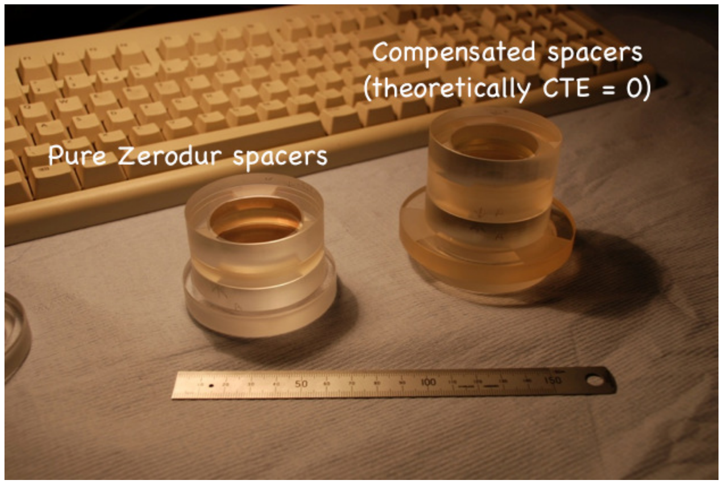

Figure 1: The two Fabry-Pérot etalons produced. L/h: Pure Zerodur-spacers etalon of low CTE. R/h: Compensated spacers for theoretical zero CTE (object of this test)

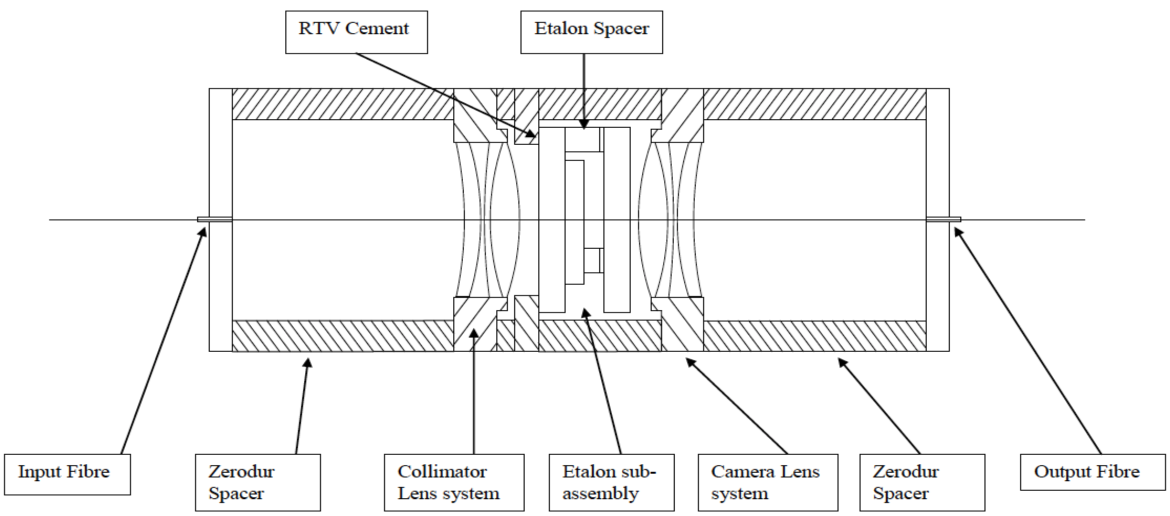

Figure 2: Section across the FP assembly

3.4 Illumination source

At first, a tungsten halogen lamp has been tested to illuminate the FP system. However, given its brightness temperature of only 3000 K, the blue flux provided by the lamp was up to 100 times lower at 380 nm than at 690 nm. In addition, most of the optics (FP Etalon, the 60m of fibers, spectrograph), have a lower blue efficiency too. This results in a large flux imbalance between the two extremes of the spectral range. In a 2nd step a 150W Xenon-arc lamp was used. Thanks to the higher brightness temperature of about 6000 K, both the absolute surface brightness (and thus the flux coupled into the etendue of the fiber), and the blue to red flux ratio increased considerably. Luckily, the Xe lamp does not feature sharp line in the spectral range of HARPS.

The Xe-arc lamp produces a flat spectrum across the visible range, but we still need to correct for the large losses in the blue. Furthermore, as will be seen below, the FP etalon itself has a poor efficiency below 420 nm, due to the soft mirror coatings. To equalize the flux, several a custom-made dielectric filters have been tested and the ‘2007’ series shown in Figure 4 was used. It has to be noted that after compensation we still observe about 8 times less blue photons than red ones.

Figure 3: L/h: FP etalon and glass work . R/h Vacuum vessel containing the FP etalon and glass work

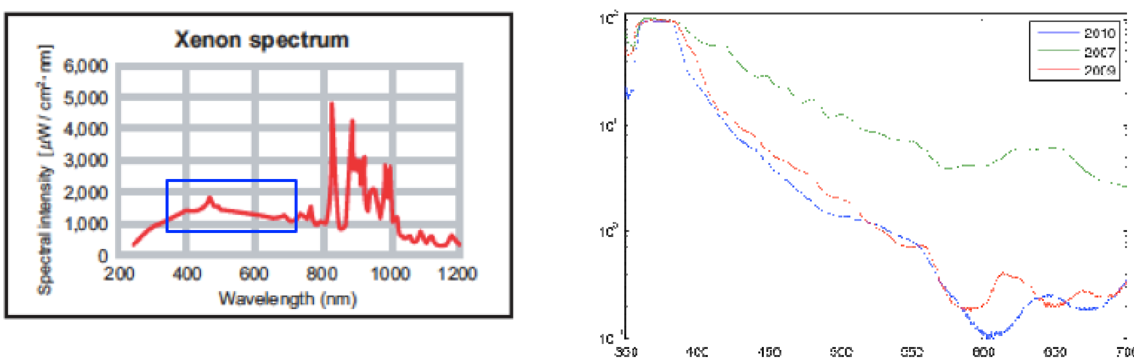

Figure 4: L/h: Spectrum of the Xe-arc lamp. R/h: Transmittance of various balancing filters. Filter 2007 was selected.

4. PERFORMANCE

For full scale tests, the FP calibration system has been installed on the HARPS spectrograph at the ESO 3.6 m telescope in La Silla. The vacuum tank is put inside a thermally isolated box which is itself located inside the thermally controlled spectrograph room.

4.1 Spectral performances

Figure 5 shows a small part of the transmission spectrum of the FP calibration system as recorded by HARPS. For comparison the other fiber was illuminated with the thorium lamp. Note the richness of the FP spectrum compared to that of the thorium.

The average transmission of the FP system has been measured by using a low-resolution laboratory spectrograph. The spectrograph recorded the white lamp spectrum alone and the same spectrum filtered by the FP system. The ratio of both spectra, which is basically the average transmission of the FP system including the fibers and the connectors, is shown in Figure 6 on the left side. Down to 450 nm the average transmittance is 10%. In order to determine the transmission at peak, however, this value has to be multiplied by the Finesse of the etalon. As we will see later, the finesse is 4.3; therefore the peak transmission must be of the order of 43% above 450 nm. In we consider that a significant fraction of the transmission losses are due to the two fiber connectors, we conclude that the peak-transmittance of the FP system is well above 50%. The much lower transmittance at short wavelength is, on one hand due to the fibers and the optical materials, which have generally lower transmission towards the blue, and on the other hand, is caused by the FP-etalon coating, which was not optimized for this wavelength region.

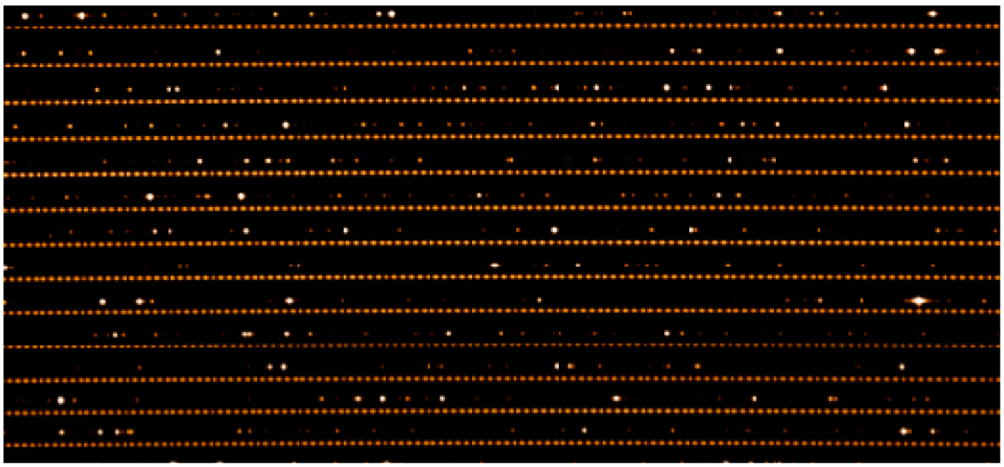

Figure 5: Top: Raw HARPS frame showing side by side the spectrum produced by the FP calibrator and the spectrum of the thorium lamp. Note the richness of the FP spectrum compared to that of the thorium.

The right side of Figure 6 shows the flux level at peak transmission across the FP spectrum as recorded by HARPS. The flux represented includes the lamp, the FP system and the spectrograph transmittances. For comparison, the same curve is shown when using a tungsten lamp. It can be seen that, for the tungsten lamp, the flux level in the 15 bluest orders is too low for them to be used for the wavelength calibration and drift computation, while only a few orders are lost in the case of the Xe-lamp. It must be noted that the curves of the Xe and the tungsten lamp have been normalized individually. The total flux ration between the Xe and the tungsten lamp is of the order of 16.

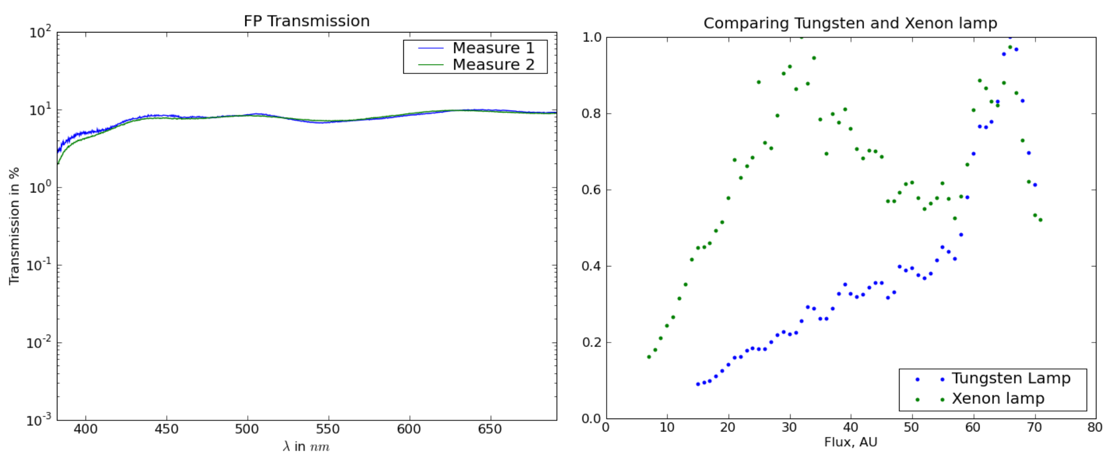

Figure 6: Left: Transmission spectrum of the Fabry-Pérot etalon alone averaged of a broad band (>> than a typical FSR of the etalon). Right: flux at the peak of a transmission line of the FP when illuminated by the Xe-lamp compared to the tungsten lamp. Measurements have been carried out with HARPS.

The finesse $F = \Delta\lambda/\delta\lambda$ (distance of two neighboring lines divided by the line width of a line) of the FP etalon has been first measured in laboratory by scanning the etalon's effective gap. The scanning was achieved by varying the pressure inside the vacuum vessel, introducing an effective optical path difference (OPD) sufficient to cover over a free spectral range. A commercial HeNe laser of $\lambda = 633$ nm was used for the line scanning measurement.

Figure 7 (L/h) shows the transmitted laser flux as a function of effective optical gap variation as computed assuming a linear relationship between pressure and refractive index of air. The red curve theoretically describes the transmittance function of the FP etalon with a single effective finesse F_E. The measured F_E , i.e. the ratio between the FWHM of a single peak and the distance between two peaks is $F_E = 4.1$. This value is lower than expected even if we take into account the natural line width of the HeNe laser.

Figure 7 (R/h) shows the computed 'finesse' as a function of wavelength (or spectral order). The computed finesse does not correspond to the FP finesse, since the lines are convolved with the instrumental profile (IP) which determines the spectral resolution of the HARPS spectrograph to about R = 115'000. The finesse so recorded is rather the ratio of the the distance between two neighboring lines and line's FWHM. If the line width was dominated by the spectrograph's resolution, we would expect a finesse of 3.1 at 400 nm (order nr. 8) and of 5.3 at 680 nm (order nr. 70). The lower value measured confirms, that the effective finesse of the FP etalon must be 4.3 instead of 6 (design value).

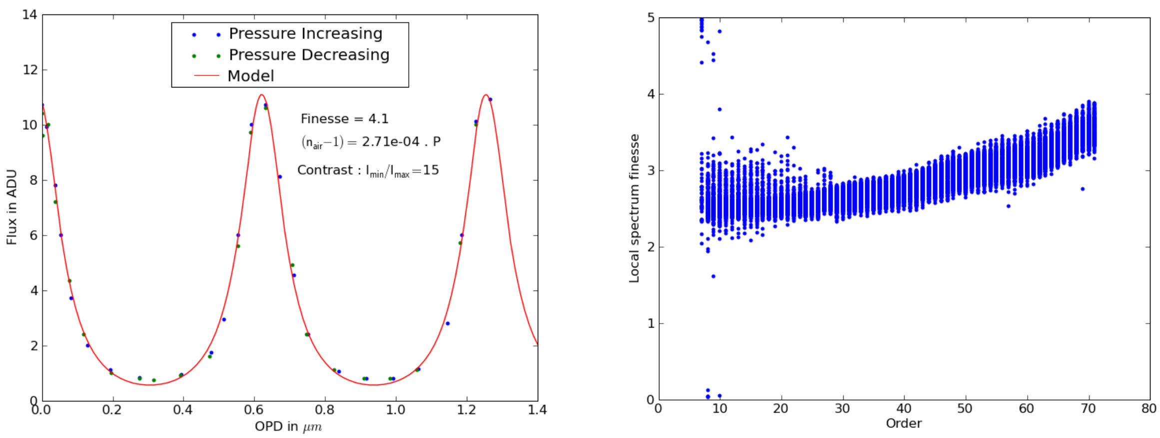

Figure 7: L/h: Direct measurement of the FP transmittance when varying the optical gap. R/h: Ratio of line separation to line width over the full wavelength range of the HARPS spectrograph. Order nr. 1 corresponds to 383 nm while order nr. 70 is located at about 680 nm. At short wavelengths some noise is introduced by the low flux

For the theoretical Fabry-Pérot the wavelength (or frequency) of a given transmitted peak (order) m is fully determined by a single parameter: the gap D. The corresponding formula is $\lambda_m = 2D/m$. Provided that we know the etalon's gap, we can, from this formula, directly determine the wavelength of a given line by knowing its order number. In practice, however, one does not know the absolute order number of the line, but only a relative numbering by assuming that the peaks must have continuously increasing and discrete order values. We have therefore inverted the problem by using the spectrographs calibration delivered by the thorium source and used it to assign a wavelength to each transmission peak. Using this wavelength and assuming a gap of $2D = 14.6$ mm we have been able to determine directly the order number of each transmittance peak appearing in the FP spectrum.

We did not expect the gap D to be exactly the theoretical values, nor to be constant as a function of wavelength due to the varying effective optical depth of the dielectric mirror coatings. Indeed, the computed order numbers were not all round integers. Nevertheless, their difference to the continuous integer number is always below 0.25. From this we can conclude that by rounding the order number obtained to the closest integer value we unambiguously identify the real order number. Using this fact, we have then used the so computed discrete order number and the wavelength assigned from the thorium calibration to determine the effective gap $D = D(\lambda)$ of the etalon. The result is shown in Figure 8. Note the mechanical gap of the etalon is of 7.300 mm and that in the figure the optical path difference $2D$ is actually shown.

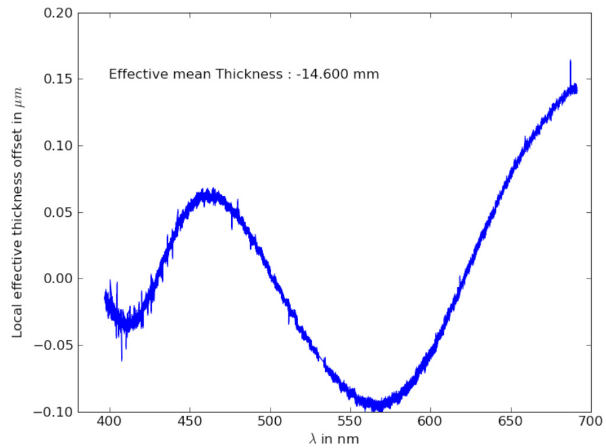

Figure 8: Effective etalon gap variation as a function of wavelength

It appears that the 'manufactured' mechanical gap of D = 7.3 mm is fully compliant with the measured optical path difference of $2D = 14.6$ mm within a quarter of wavelength, which confirms that the order numbering can be assigned unambiguously by assuming the theoretical gap value. If a wrong value D had been assumed, the $D(\lambda)$ would show a slope of at least one wavelength over the plotted spectral range.

Nevertheless, $D(\lambda)$ does vary significantly. The changes measured correspond to about 10^{-5} or, expressed in radial velocities, of about 3 km s^{-1}. We assume here that $D(\lambda)$ is constant in time and that thus the presented fact does not have any impact on ability of the FP system to track instrument drifts. However, we also conclude that the FP system cannot be used to perform *absolute* wavelength calibrations to better that 10^{-5}, unless the $D(\lambda)$ is calibrated externally (e.g. with a laser frequency comb or a thorium lamp).

Although $D(\lambda)$ seems well determined we have to note that short-scale patterns with amplitude of the order of 50 m s^{-1} have been recorded in $D(\lambda)$. At first glance the patterns seem to be linked to the FP system itself (the pattern is the same when comparing wavelengths present in two different orders), but we have not been able to assign it to intensity variations in the lamps light or transmittance variations in the balancing filter. The problem is under investigation.

We conclude here that the FP etalon behaves as expected in terms of spectral performances. The etalon gap has been manufactured (an measured) with an amazing accuracy. The effective gap $D(\lambda)$ varies with wavelength and although we do not see any *stability* issue here, this may be a limitation of the FP system alone to perform *accurate absolute* wavelength calibrations.

4.2 Photonic Doppler precision content

The ability to determine the position of a spectrum on the CCD (line position expressed in pixel) and associate it with a given wavelength depends on the width and the intensity of the line. In general one can say that the fundamentally attainable precision is proportional to the square root of the number of lines in the spectral domain and their intensity, and inversely proportional to their width. In HARPS, the formulae described in [8] are employed to measure the fundamental (photon-noise limited) precision content of a spectrum. Figure 9 shows the attainable precision using the FP system as a function of the square root of the relative flux measured on the detector. The flux was varied either by changing the variable neutral density-filter in front of the calibration lamp or by varying the exposure time. For comparison, also the results obtained with the hollow cathode thorium lamp are shown. In both cases it could be demonstrated that the relationship is perfectly linear as expected from pure photon noise, and that a precision of about 2 cm s^{-1} can be attained on a single spectrum.

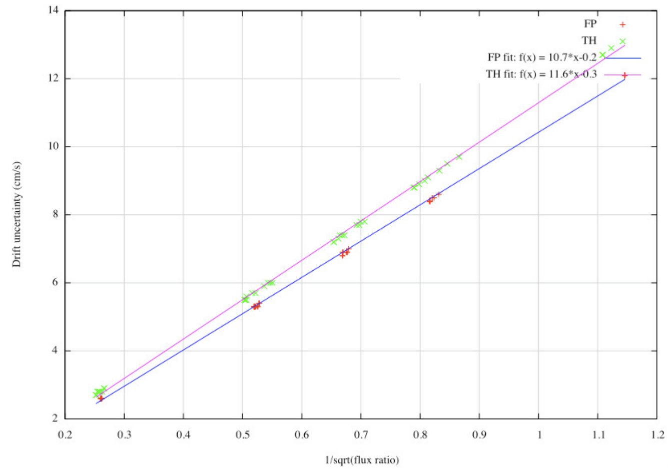

Figure 9: Fundamental (photon-noise limited) RV precision obtained on a single FP spectrum versus the inverse of the square root of the light flux. The results from the thorium lamp are shown for comparison. The FP curve is in blue and the thorium lamp is in purple. The FP curve is lower, therefore showing less RV noise.

Currently, in HARPS, the thorium lamp is tuned so as to balance lifetime and flux. In an exposure of 40 s, which is the (minimum) nominal exposure time for a wavelength-calibration, the precision level obtained is of the order of 7 cm s^{-1}. For the FP system, when used with the Xe-lamp and a '2007' balancing filter, a precision of typically 2 cm s^{-1} is obtained in a single exposure of 40 s.

4.3 RV-stability performances

In order to determine the stability of the FP system, we have carried out a time series of exposures during which we have illuminated fiber A of HARPS with the thorium lamp and fiber B with the FP light. and we computed the drift of both the thorium and the FP spectra with respect to the first exposure. The drift measurements of both sources are plotted in Figure 10. It is expressed as a change in stellar radial velocity (RV) producing a Doppler effect on the light. It's unit is expressed in m s^{-1}, which is equivalent to $\Delta\lambda/\lambda = \Delta\nu/\nu = 3\ 10^{-9}$. The dispersion is about 20 cm s^{-1} for both lamps and is mainly dominated by 'CCD 'breathing', i.e. CCD size change due to oscillations in the CCD thermal control loop. When subtracting the thorium drift from the FP drift, the dispersion decreases to about 15 cm s^{-1} (Figure 10). This dispersion value is actually very close to the value expected from photon-noise. Indeed, if we consider that, during the series, both sources showed about 7 cm s^{-1} precision in the single spectrum, the double difference of the differential drift is expected to be affected with a noise a factor of 2 higher.

Nevertheless, even the differential drift curve (Figure 10, R/h) shows a residual drift. This makes us suspect that some drift may occur on the FP spectrum or that of the thorium. The drift is, if real, very small, of the order of 10 to 20 cm s^{-1} over more than 6 hours of observation. The pressure leakage induced drift would be of the order of 10 cm s^{-1} in 12 hours, being about a factor 2 to 4 lower than the measured drift. In order to verify the scale factor of the RV sensitivity to pressure we have recorded a spectrum prior and after re-pumping the FP system. For a pressure change of 0.024 mbar we have measured a RV change of about 4.4 m s^{-1}. The sensitivity is thus of 16 cm s^{-1} for a change of 0.001 mbar, which is slightly higher than expected from theory.

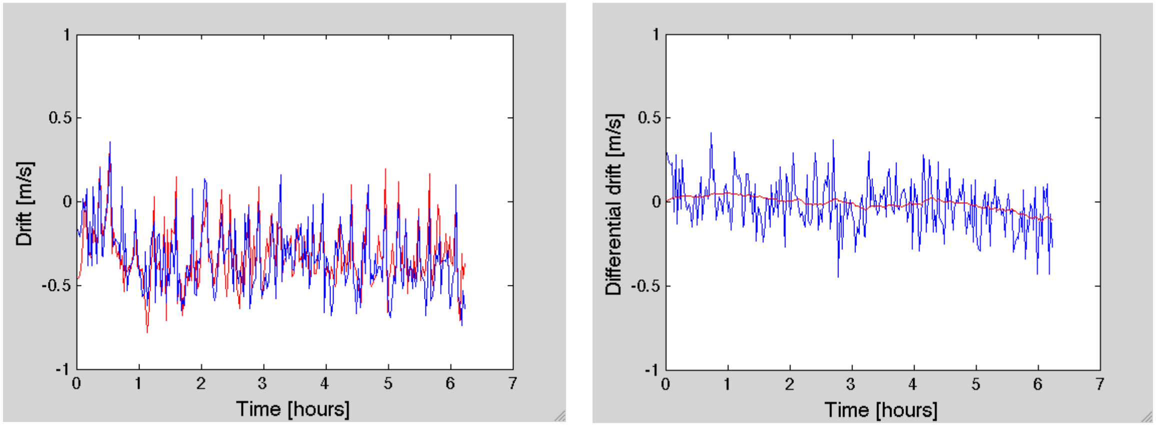

Figure 10: L/h: Drift of the thorium lamp (red) and the FP system (blue) as a function of time. R/h: Differential drift between the FP system and the thorium lamp as a function of time.

Drifts induced by temperature variations are expected to be of the order of 10 cm s^{-1} for a temperature change of 0.01 K. Being the temperature of the glasswork more stable than 0.005 K P-V over the time scale of a night, we may also exclude this cause.

At such a low level several effects may cause drifts. It should be remarked that for instance the stability of the thorium has not been proven at that level of precision. Nevertheless, we think that some residual drift indeed arises from the FP system rather the thorium lamp. Here we give a possible list of effects ordered by likeliness:

- Light-injection effects. Indeed, we have observed some high sensitivity of the measured RV with respect to the fiber alignment in the calibration unit. Given the fact that the optical components are under-dimensioned, a small misalignment of the fiber direction and position may cause vignetting in the system, which in turn changes the illumination of the spectrograph and thus the recorded radial velocity.
- Fiber-Fiber connectors. At several locations there are fiber connectors and interface pieces. Thermo-mechanical instabilities may produce illumination instabilities and thus RV instabilities.
- Aging of the Zerodur spacers. The length of Zerodur has been measured to change of the order of $\Delta l/l = 10^{-7}$ over a year in the first years after production of the material.
- Residual (non-monitored) pressure and temperature effects. For example, heating of the FP-etalon coating by the injected light and consequent thermal variations in the etalon. This would require the time constant of the phenomenon to be 10's of hours given that the light source was on for the duration of the run.

Despite all these potential effects, the results are quite impressive and very close to the specified precision. The FP system can certainly be used to replace the thorium lamp for the drift measurement on fiber B of HARPS. However, we have to remark that the 'absolute' zero point (or calibration) of the spectrograph cannot be determined with an accuracy of better than several tens of m s^{-1}. The reason is two-fold:

Although the injection system is mechanically very stable it seems to introduce quite a remarkable RV offsets each time the calibration unit is re-aligned. Reference [9] addresses this problem and studies ways to reduce its importance.

The FP system does not provide an absolute wavelength reference, since the effective etalon gap is not known with sufficient precision (see also previous sections). The 'zero point' of the FP system would need to be calibrated by means of an external source, e.g. a laser or a spectral lamp.

4.4 Stellar RV measurement with simultaneous FP-drift measurement

Up to now, only very few exposures could be made 'on the sky' with the FP system. In that cases, fiber A was illuminated with the star and fiber B with the FP light. The FP was thus used in exactly the same way as the simultaneous thorium. Because of the lack of data, we shall neither present here any detailed discussion nor the data themselves. It shall only be mentioned that the ‘simultaneous FP’ behaved as expected and similarly to the ‘simultaneous thorium’. As mentioned above we think that the FP can easily replace the thorium in this task, having in addition the advantage to deliver more numerous very homogeneous and non-saturating spectral lines, thus avoiding contaminating the stellar spectrum with calibration light from the neighboring simultaneous reference (fiber B) as it is the case for the thorium. We are therefore aiming at officially commissioning this observation mode by autumn 2010.

5. CONCLUSION

We have designed, built and tested a new Fabry-Perot Wavelength Calibration System. The goal was to demonstrate its feasibility and verify the performances in the frame of high-precision radial-velocity measurements with HARPS. The FP system proved to be suitable for the simultaneous drift measurement which is a corner stone of HARPS-like spectrographs.

For HARPS, and in the frame of the search for extra-solar planets, we were looking for a system with extreme stability. Although accuracy was not the primary goal we have investigated to which extend the Fabry-Perot can deliver an absolute calibration. We have demonstrated that 10 cm s^{-1} stability is achievable during one night. By further improving the injection system we think that a 1 m s^{-1} repeatability over long term can be obtained which is extremely exciting for extra-solar planet search. Because of the ‘passive’ concept, however, the FP system has only limited absolute accuracy of the order of 3 km s^{-1}. To improve this performance, the FP will need to be cross-calibrated with an absolute wavelength-reference source. Here we see a huge potentiality when combining the FP system with a stabilized laser. Possibly, this solution represents a valid alternative to the broadband laser comb, with its high intrinsic complexity.

The FP calibration system is conceptually very simple, it is portable and adaptable to almost any wavelength range. During our work we have realized that the FP system is actually a perfect calibrator for the infrared (IR), where good wavelength calibration sources are missing. It allows covering a large wavelength range with dense and equally spaced spectral lines. Just by varying the etalon gap it can be adapted for any spectral resolution.

Many – if not most of the - E-ELT instruments will operate in the IR/NIR, and among them we will find several spectrographs. We are convinced that the FP calibration system may be a suitable calibration source for them. It combines simplicity, stability, flexibility and low costs

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REFERENCES

[1] 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, DOI:10.1038/nature04828

[2] 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

[3] C. Lovis and F. Pepe, “A new list of thorium and argon spectral lines in the visible”, A&A . 468, 1115, 2007

[4] 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, DOI:10.1038/nature06854
[5] 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
[6] 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, DOI: 10.1126/science.1161030
[7] 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, DOI: 10.1007/s00340-009-3374-6
[8] F. Bouchy, F. Pepe, D. Queloz, "Fundamental photon noise limit to radial velocity measurements", Astronomy and Astrophysics, v.374, p.733-739 (2001).
[9] B. Chazelas, F. Pepe, F. Wildi, F. Bouchy, "Study of optical fibers scrambling to improve radial velocity measurements", *Modern Technologies in Space- and Ground-based Telescopes and Instrumentation*, SPIE 7739-191 (2010), San Diego