A passive, cost effective solution for the high accuracy wavelength calibration of radial velocity spectrographs

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ABSTRACT

Today, the RV technique has pushed the planet detection limits down to super-earths but the reach the precision required to detect earth-like planets it is necessary to reach a precision around 1cm s^{-1}. While a significant part of the error budget is the incompressible photon noise, another part is the noise in the wavelength calibration of the spectrograph. In the past 3 years the Observatory of Geneva has designed, built and tested an commissioned 2 wavelength calibrator systems based on a Fabry-Perot (FP) interferometer with great success. The calibrator system demonstrated 10 cm s^{-1} stability over one night and 1 m s^{-1} over 60 days. By improving the system injecting the calibration light into the calibration fiber of the spectrograph we are aiming at 1 m s^{-1} repeatability over the long term. This technique is now being extended to cover the near infrared to the K band in the frame of the SPIROU project.

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

1. INTRODUCTION

The radial velocity (RV) technique is todayr 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. [5] and [6]). However, to detect earth-like planets it is necessary to reach a precision around 1cm.s^{-1}, i.e. a repeatability of 3 10^{-11}. 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 [3], [4] and [8]), the Observatory of Geneva is trying another route with a simple totally passive calibrator system based on a Fabry-Perot interferometer to explore its potential to improve the wavelength calibration of RV spectrographs. Unlike the Thorium-Argon lamps used today [7], this device allows the production of optimally and regularly spaced calibration lines with quasi constant amplitude covering all orders of the spectrograph.

2. THE SIMULTANEOUS CALIBRATION METHOD (REMINDER)

The HARPS spectrographs and their predecessors ELODIE and CORALIE use the so-called simultaneous calibration method to reach maximal radial velocity performance: The spectrograph has a doubled fiber input and produces 2 spectra on the detector: fiber A for the stellar spectrum (calibrated in wavelength by the calibrator) and fiber B for the reference spectrum which is measured during the calibration phase and also during the science exposure in order to track the spectrograph drifts. See [6]. The calibration spectrum is used on both fibers to define the "wavelength solution" of the spectrograph (no mixing). During the science exposure, the calibration is exposed on the reference channel B while the starlight is exposed on fiber A. Comparing the spectrum of fiber B between the time of the calibration and the time of the science exposure allows to determine accurately the instrumental drift and correct for it on the science channel.

To reach maximal accuracy, we must design a calibrator that has the following properties. The reference spectrum has to be highly stable; therefore the Fabry-Perot interferometer must be highly stable. It must cover the full wavelength range of the spectrograph; its lines are not resolved at the spectrograph resolution so that the spectrograph is insensitive to evolution of the lines profiles. There must be as many lines as possible in the spectral

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range to reduce the localization noise associated with each line. Of course, for stability, the environment has to be mechanically and thermally very stable and the index of refraction in the gap constant. The requirements applicable to the calibrator have been listed in detail in [8]

3. DESIGN

We are now building the third Fabry Perot based calibrator and we are taking advantage of the experience gathered on the two first ones.

3.1 Breakdown

- As a primary light source we are now using a Laser Driven Light Source. In fact a Xe lamp exited by a pulsed pump laser. It provides very high radiance broadband light closely corresponding to a 10’000K blackbody. Depending on the spectrograph transmission and the length of the fibers, it is complemented by a balancing filter to obtain a somewhat homogeneous intensity distribution from blue to red.
- A Fabry Perot (fixed gap) etalon,
- Reflective collimator and fiber injection lens.
- 600 µm diameter optical fiber for light injection into the FP system.
- 300 µm diameter optical fiber connecting the FP assembly with the spectrograph calibration light coupler box.
- A vacuum enclosure holding the FP assembly. An operating pressure below 10^{-3}mBar is required to insure 10^{-10} stability. (This is because the index of refraction of air will modify the free spectral range of the etalon).
- A temperature controller to stabilize the FP assembly temperature.

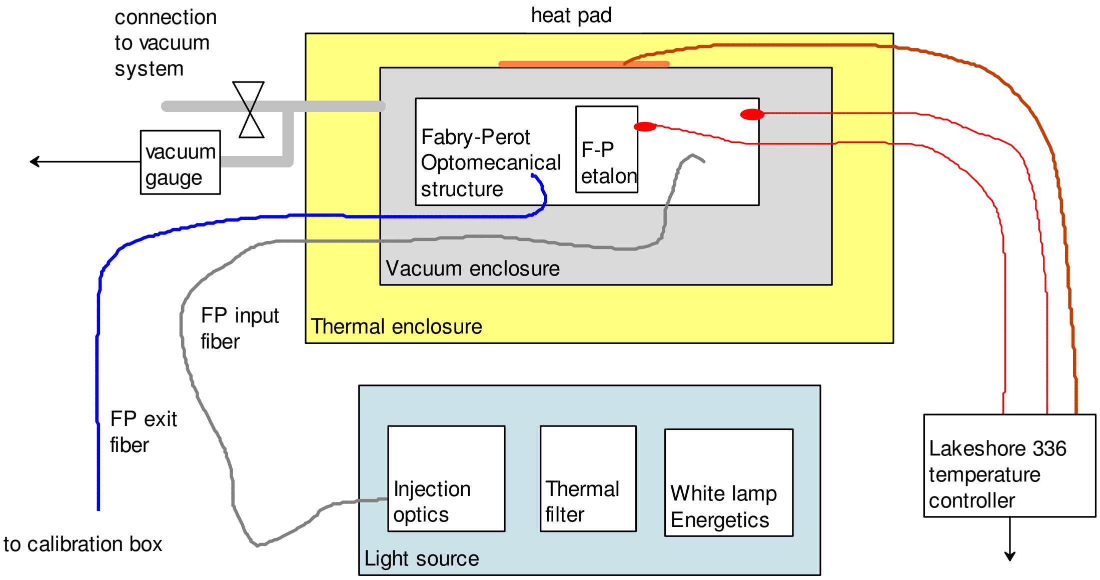

Figure 1: Functional diagram of the complete FP calibrator system.

While the original prototype calibrator opto-mechanical structure was a sophisticated assembly of Zerodur elements optically contacted to each other [9], this solution turned out to be too complicated, expensive and too difficult to maintain. A thermo-mechanical analysis showed that a more traditional aluminum structure, when in good thermal equilibrium would meet the performance, and it is now the baseline design.

Figure 2: The latest opto-mechanical structure of the FP calibrator. L/h CAD view. R/h the assembly in the integration lab, with the vacuum enclosure cover already mounted. This design allows the fibers to be mounted on FC connectors and changed easily if need. Moreover, the connector base can be aligned with screws and shims to give the best focusing and the best coupling.

To minimize the etalon free spectral range variation with respect to temperature, we have chosen to use an “air spaced” etalon, which in operation becomes vacuum spaced etalon. Provided we can maintain the pressure inside the vessel at a low enough level, it’s gap in only dependent on the dimensional stability of the spacer material. We are currently operating FP calibrators that are using etalons built with 2 different spacer designs:

- The 1st one is using a circular plain grade 0, aged Zerodur ring as spacer (HARPS-N, TNG, La Palma)
- The 2nd one is using a compound stack ring spacer made of a thick zerodur part and a thin BK7 part optically contacted together. The relative thicknesses of materials are computed to exactly match the expansion of a fused silica plate put on top of one of the base plates. (HARPS ESO, La Silla)

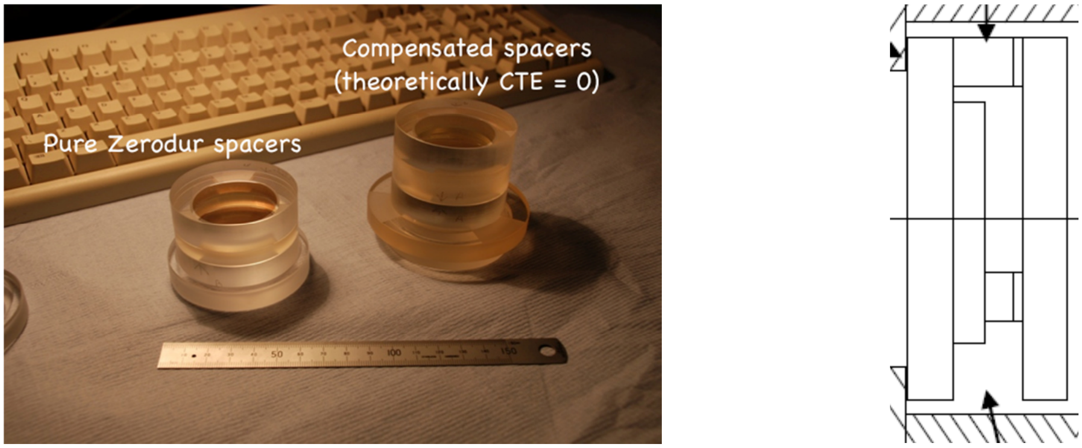

Figure 3: L/h The two Fabry-Pérot etalons produced. Pure Zerodur-spacers etalon of low CTE (spare) and etalon with compensated spacers for theoretical zero CTE (in service). Conceptual view of the thermally compensated etalon spacer. The vertical arrow at the top shows the compound spacer. The arrow at the bottom point to the additional fused silica plate. The thermal expansion of the spacer matches that of the silica plate.

The coatings of the etalons are designed to provide the right finesse across the range. Too high a finesse will reduce the absolute transmission but if it is too low the spectral lines start to be resolved by the spectrograph. For throughput reason, we are using dielectric coatings. They also allow us to design the proper reflectivity with stacks of modest complexity. We are currently in the process of designing a calibrator system for the SPIROU and we have a satisfactory design for a nominal 80% transmission coating. See figure below:

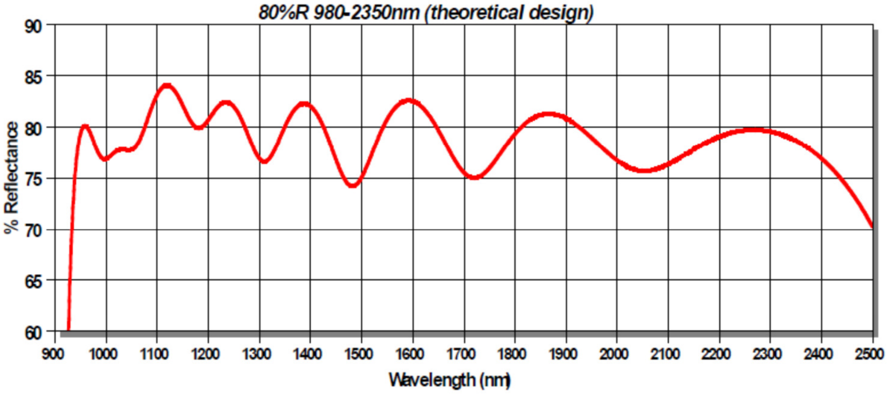

Figure 4: Baseline coating reflectivity for the SPIROU calibrator covering Y to Ks bands

3.2 Primary light source

The 1st FP calibration system has been installed on the HARPS spectrograph at the ESO 3.6 m telescope in La Silla in 2009. It was immediately clear that there was a photon flux problem with this system, particularly on the blue side. We improved it mostly by changing the light source, starting from a tungsten halogen filament lamp, through an Xe arc lamp and today a Supercontinuum light source from the Leukos company. The 2nd system uses a LDLS for its superior total flux and its larger etendue that fills the fibers better

One has to be careful when injecting the calibration light into the system: Due to the imperfect scrambling of the multimode fibers, variations in the injection from the calibrator into the fibers going to the spectrograph will induce a variation of the illumination pattern on the fiber (See [1 and [11]). It is highly desirable to have a source with a large etendue to overfill the fiber and be insensitive to alignment variations. However, this implies losing some flux, which has to be avoided to guarantee exposures the maximal SNR.

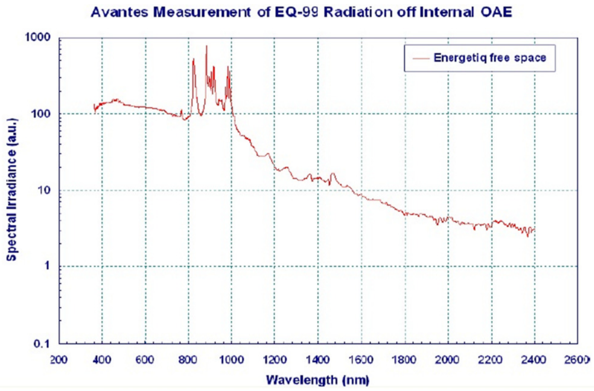

Figure 5: Spectrum of the Laser Driven Light Source used as the primary light source feeding the Fabry Perot. Appart from the residuals of the pump laser, the spectrum is close to a black body at 10'000 K.

4. PERFORMANCE

The 1st FP calibration system has been installed on the HARPS spectrograph at the ESO 3.6 m telescope in La Silla in 2009. The vacuum tank is put inside a thermally isolated box which is itself located inside the thermally controlled spectrograph room. The control error of the temperature loop is 1-2 mK rms, but we still have to characterize the measurement drift due to variations of the thermal environment of temperature controller.

4.1 Spectral performances

Figure 6 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 and how constant is the contrast.

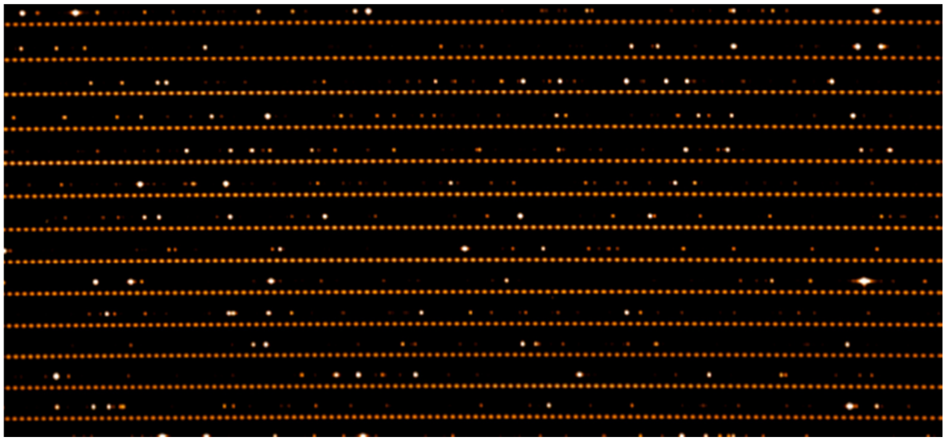

Figure 6: Top: Raw HARPS frame showing side by side the spectrum produced by the FP calibrator and the spectrum of the thorium lamp. Note the richness of the FP spectrum compared to that of the thorium.

The transmission of the FP system has been measured by using a low-resolution laboratory spectrograph. The average system transmission including the fibers and the connectors is about 10% down to 450 nm. In order to determine the transmission at peak, however, this value has to be multiplied by the Finesse of the etalon. The finesse in this case is 4.3; therefore the peak transmission must be of the order of 43% . When we consider the losses due to the two fiber connectors, we conclude that the peak-transmittance of the FP "glassworks" is well above 50%. Below 450nm the transmission falls off quite rapidly to 2-3% at 380nm. This is due in part to the FP-etalon coating, which was not optimized for this wavelength region. For future etalon in the same spectral domain, this is a parameter worth improving given that all other components have also more losses towards the blue (scattering in the fibers, material transmission).

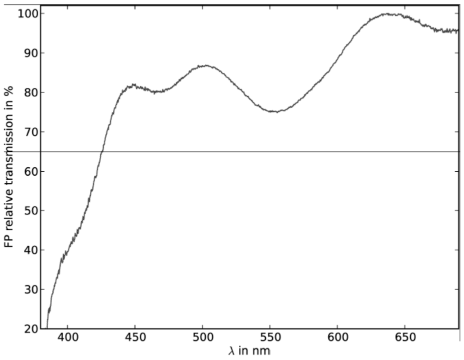

Figure 7: Relative transmission of the HARPS-N calibrator over the HARPS range.

Today, a RV precision of about 4 cm s^{-1} per frame is obtained on a single frame of 40s with the supercontinuum source, which is about twice a good as using the ThAr for the simultaneous drift measurement. However, this flux is about a factor of 10 lower than the one obtained with the Xe-lamp, which has an larger etendue which fills the calibration fiber better.

By optimizing the setup a value below 2 cm s^{-1} may be reached. In particular, the blue flux should be improved by increasing the source power and by using a blue-balancing filter. In the present situation, the orders below number 10 are not used for the drift computation.

5. ON-SKY TESTS AND OPERATIONS

In order to test the on sky performance we have observed, during the ‘Sousa’ mission in March 2011, two well-known targets. In order to compare the radial-velocity results, we have observed both targets in their standard modes. The first target, HD 85512, is a moderately bright stable star with one known planet. Usually, this target is observed in ‘simultaneous Thorium’ mode. The second star, HD 128621 or alpha Cen B, is very bright (Mv =1.3). Because of its brightness the frame reaches almost saturation in 15 s. The high flux level on the object fiber was observed to produce contamination of the simultaneous Th-Ar on fiber B, which in turn introduced errors of the order of 1 to 2 m s-1 on the drift measurement. Therefore this target is observed as ‘OBJA’, i.e.without simultaneous Th-Ar on fiber B.

The results in terms of radial velocity are shown in Figure 8 and Figure 9, respectively. It shall be noted that the long-term variation on HD 85512 are due to the low-mass planetary companion. Nevertheless, the some ‘high-frequency’ variations are observed on the measurements using the Th-Ar which are not seen on the FP measurements. For alpha Cen B it shall be noted that the long-term variations are due to the fact that this star is part of a triple system. The short-term variations, the scatter during the night, are however due to stellar pulsation while the night-to-night variations are due to stellar jitter.

The most important result is that in both cases neither a systematic offset nor a higher scatter is observed when using HARPS in the simultaneous Fabry-Perot system mode.

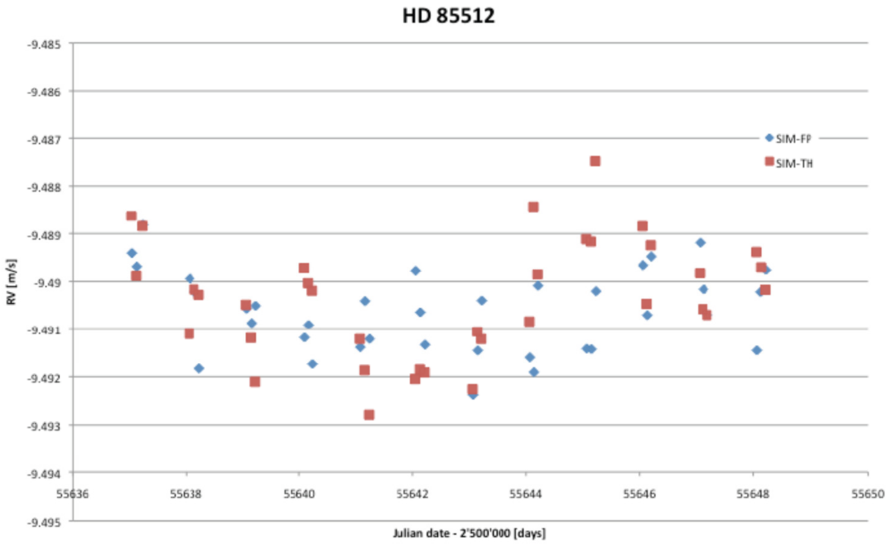

Figure 8: Observations of the star HD 85512 over a ten-days period with the simultaneous reference technique using the Th-Ar (red) and the FP system (blue). Radial-velocities are identical; although the dispersion seems to be even a little bit lower when using the FP system

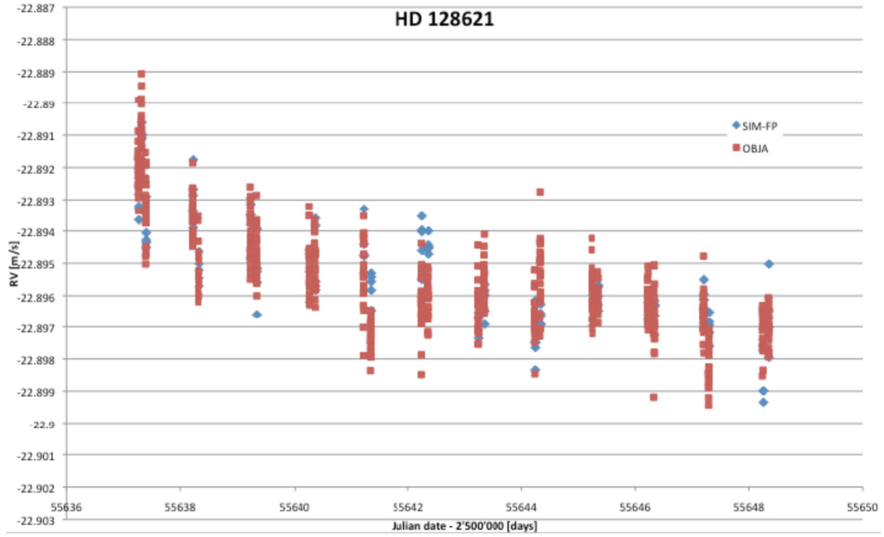

Figure 9: Observations of the star HD 128621 (alpha Cen B) over a ten-days period with the simultaneous reference technique using the FPCS (blue) and without any simultaneous reference at all. Radial-velocities are identical, indicating that the FPCS work well even on bright objects and that it does not introduce any systematic offset or error.

Unfortunately, because HARPS north was only commissioned fully at the end of spring 2012, we do not yet have fully educed data we could use to perform a trend analysis. Neither do we have conclusive data proving that the plain Zerodur spacer etalon is inferior or superior to the compound one we are using on HARPS @ La silla.

6. CONCLUSION

We have designed, built and tested a new Fabry-Perot Wavelength Calibrator and verified its performances in the frame of high-precision RV measurements with HARPS and HARPS-N. We are extending the concept towards the near InfraRed.

- Single frame photon precision better than the Th-Ar, down to 1-2 cm s^{-1}
- Nightly stability better than the specified 10 cm s^{-1}
- Clean and uniform spectrum with no contamination of the object fiber in the blue wavelength region.
- The system is easily extendable into the NIR spectral region where wide range calibration lamps do not exist. This is being done for SPIROU. The reference #12 gives more information on this project.
- The system is self-contained, requires almost no maintenance.
- The system has a moderate cost, has a short production time.
- The Geneva Observatory is happy to consider collaborations to design and to build wavelength calibrators for existing and future high resolution spectrographs.

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