# The performance of the new Fabry-Perot calibration system of the radial velocity spectrograph HARPS

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## ABSTRACT

The Observatory of Geneva has designed, built and tested in collaboration with ESO a calibrator system based on a Fabry-Perot (FP) interferometer to explore its potential in the calibration of radial velocity (RV) spectrographs. 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. It is to address this problem that we have developed this new device. We have obtained exciting results with the calibrator system demonstrated 10 cm $s^{-1}$ stability over one night and 1 m $s^{-1}$ over 60 days. 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.$s^{-1}$, 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 [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 Thorium-Argon 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 and it now offered as an observing mode on ESO’s HARPS RV spectrograph

## 2. DESIGN

### 2.1 General aspects

The requirements applicable to the calibrator have been listed in detail in [8]. In short, what is important is that the Fabry-Perot interferometer is highly stable, that it covers the full wavelength range of the spectrograph, that its lines are not resolved at the spectrograph resolution and that there are as many of them as possible in the spectral range. Of course, for stability, the environment has to be thermally very stable and the index of refraction in the gap constant.

The calibration spectrum is used separately from the stellar spectrum to define the “wavelength solution” of the spectrograph (no mixing). 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

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is measured during the calibration phase and also during the science exposure in order to track the spectrograph drifts. See [2]

The technical specifications derived from the requirements can be found in the table below:

## 2.2 Breakdown

- Supercontinuum white light source, and balancing filter to obtain a somewhat homogeneous intensity distribution from blue to red (after transmittance by the fiber, the FP and the spectrograph).
- 600 µm optical fiber coupling the light source with the FP assembly
- FP etalon, including collimating and focusing lens system
- 300 µm optical fiber connecting the FP assembly with the spectrograph calibration light coupler box.
- Injection stage with micrometric adjustment in all spatial directions to inject the calibrator light into the spectrograph via the telescope bonette.
- vacuum tank holding the FP assembly.
- temperature controller to stabilize the FP temperature

## 2.3 The Fabry-Pérot assembly

| **Parameter** | **Requirement** | **Units** |
|---|---|---|
| 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 |
| Contrast | 10 | |
| Photon precision per frame | < 5 | cm $s^{-1}$ |
| RV stability during a night | < 10 | cm $s^{-1}$ (rms) |
| *equivalent relative $\lambda$-stability* | $< 3\ 10^{-10}$ | |

See captions in the Figure 1and Figure 2 below for a description of the assemblies

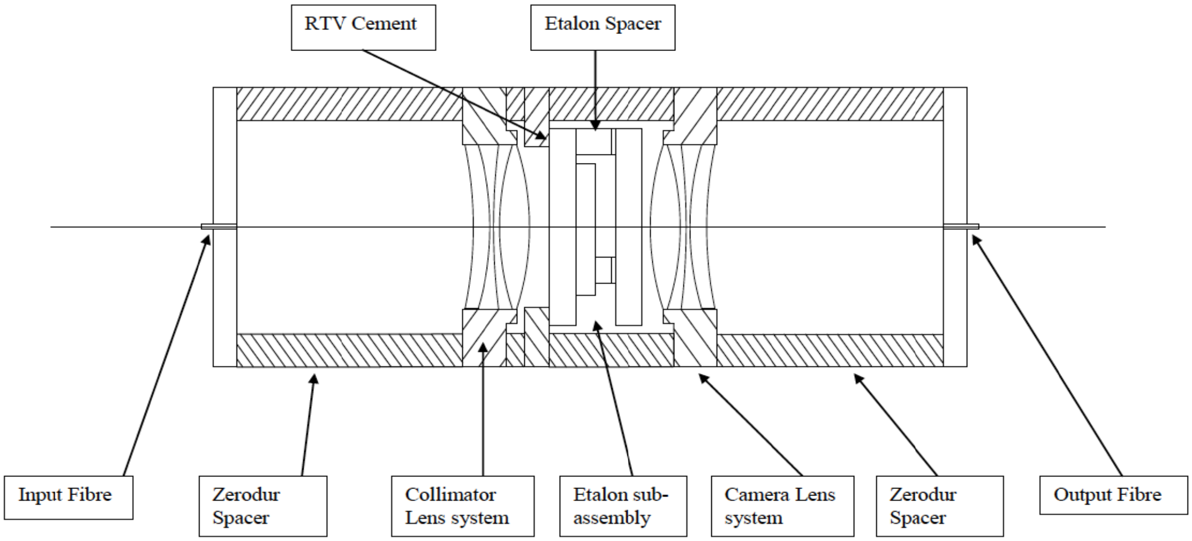

Figure 1: Section across the FP assembly. The FP etalon is fed with filtered Xe light via the 600 µm fiber and a collimator. After the etalon a triplet focuses the light into a 300 µm fiber before going to the spectrograph's calibration unit.

### 2.4 Environment control

To avoid spectral shifts as the ambient pressure varies, the etalon is put 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.

| **Parameter** | **Requirement** | **Units** |
|---|---|---|
| Temperature variations | < 0.01 | K (P2V) |
| Pressure variations | < 0.002 | mbar $day^{-1}$ |

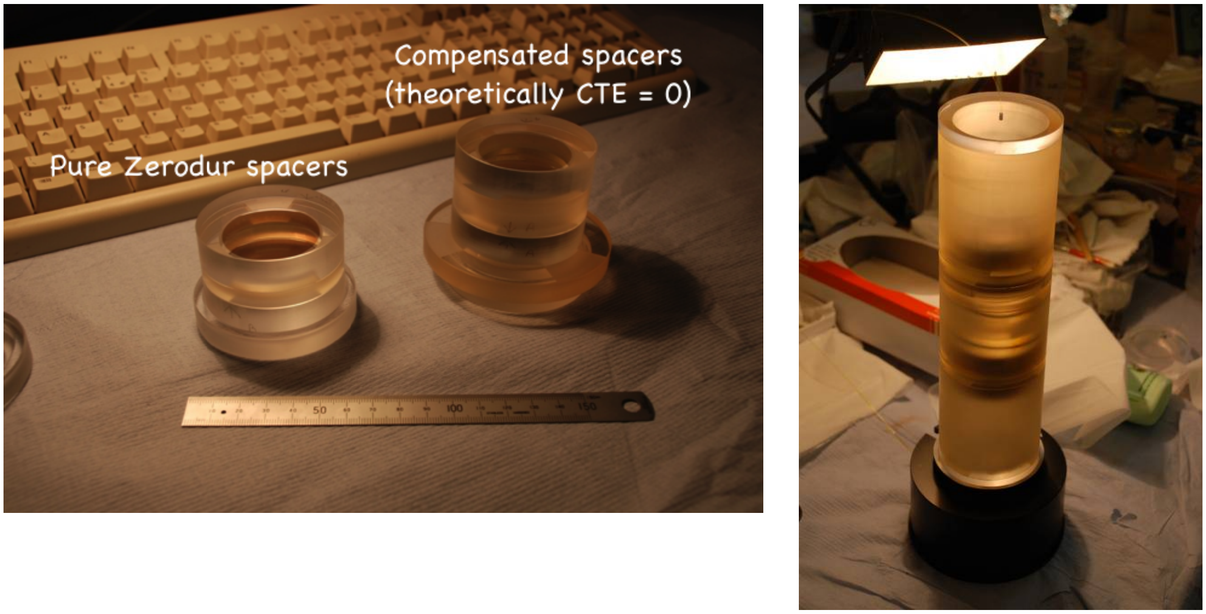

Figure 2: L/h The two Fabry-Pérot etalons produced. Pure Zerodur-spacers etalon of low CTE (spare) and etalon with compensated spacers for theoretical zero CTE (in service). R/h: assembled Fabry-Pérot ‘glasswork’. The system is completely optically contacted within a Zerodur support structure. The lenses are mounted inside the structure as well

### 2.5 Light source

In the original design, a tungsten filament lamp was used to illuminate the FP system. Unfortunately, the surface brightness and the color temperature of the tungsten lamp were both too low to allow an adequate SNR of the FP-system. Therefore, the tungsten lamp was replaced by a Xenon arc lamp. The Xe-lamp provides sufficient flux to obtain, a precision per frame of the order of 1-2 cm $s^{-1}$ after using a blue-balancing filter, On the other hand, we noticed, during testing, that the high flux level ‘heats up’ the FP etalon, and that a stabilization time of several hours up to several days is required for the FP system to remain within the 10 cm $s^{-1}$ stability limit. The consequence of this was that we would have to operate the lamp continuously. However, the lamp lifetime being limited to about 1000 hours, this would have implied complicated operation and maintenance scenarios.

We have therefore chosen to try another type of lamp, a super-continuum (SC) laser source. The total flux within the FP-system étendue was expected to be similar to the Xe-lamp, with a lifetime of the order of 20’000 hours, however. The spectra of the 2 sources is shown on Figure 3.

In addition, we have added a heat blocking filter, which cuts off out-of-band emissions.

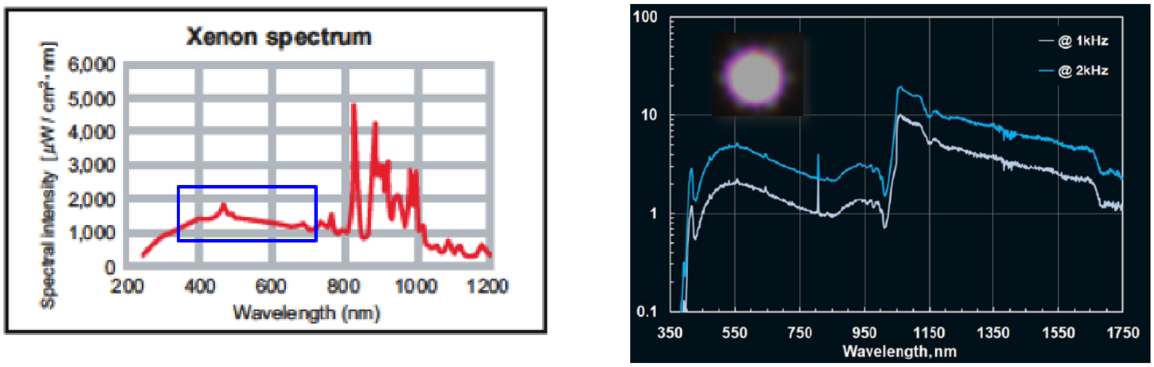

Figure 3: L/h: Spectrum of the Xe-arc lamp. R/h: Spectrum of the supercontinuum source in [mW/nm] at the output of the source fiber. SC sources are intrinsically fiber-coupled.

## 3. 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.

### 3.1 Spectral performances

Figure 4 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 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. As we will see later, the finesse is 4.3; therefore the peak transmission must be of the order of 43% a. 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 firstly to the fibers and the optical materials, which have generally lower transmission towards the blue, and on secondly to the FP-etalon coating, which was not optimized for this wavelength region.

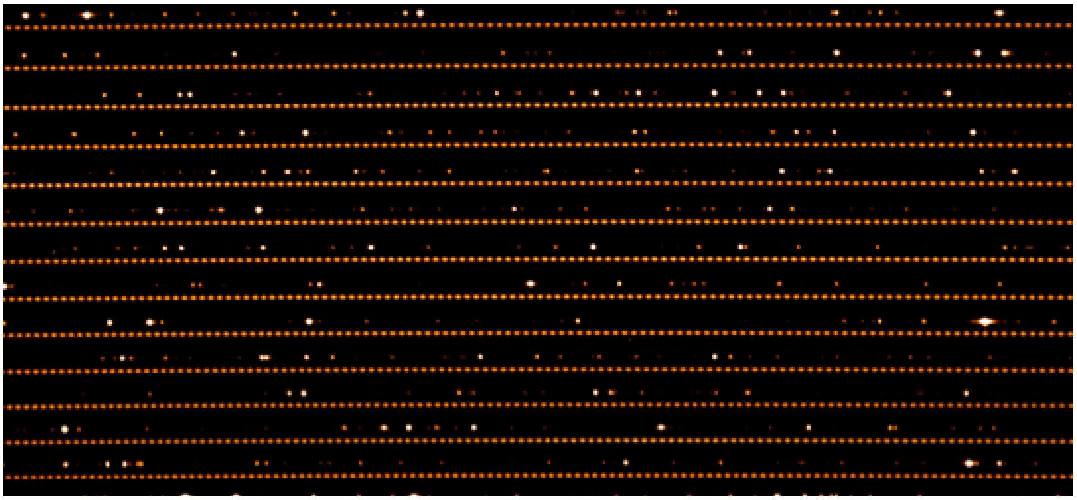

Figure 4: Top: Raw HARPS frame showing side by side the spectrum produced by the FP calibrator and the spectrum of the thorium lamp. Note the richness of the FP spectrum compared to that of the thorium.

The flux per extracted pixel at the peak of the echelle order is shown for a 40 s exposure with the FP system in the present configuration. A RV precision of about 4 cm $s^{-1}$ per frame is obtained on a single frame, 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.

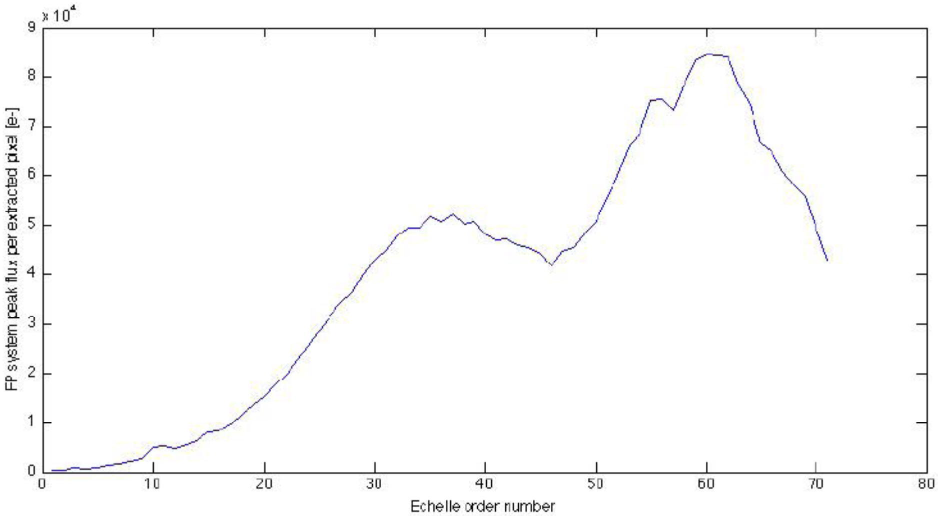

Figure 5: Peak flux per extracted pixel as a function of the order. The results were obtained using the SC laser source and an exposure time of 40 s..

The finesse $F = \Delta\lambda/\delta\lambda$ (distance of two neighboring lines divided by the line width of a line) and the free spectral range of the FP etalon have been first measured in laboratory by scanning the etalon's effective gap with air pressure and a laser. Then full spectral range was characterized with HARPS. These results have been presented in [8].

Once deconvolved by the instrumental profile of HARPS, the measurements show that the effective finesse of the FP is 4.3 instead of the design value of 6.

### 3.2 Short-term stability

We have tested the short-term stability by performing long series of Th- Ar and FP exposures (ThAr on fiber A, FP system on fiber A) and by computing the respective drifts independently. Figure 6 shows the drift from one exposure to the other as computed by the Th-Ar lamp and the FP system, as well as the difference of both to remove possible instrumental drifts.

For the Th-Ar alone we obtain a dispersion of about 0.19 m s-1 rms which should be compared to about 0.09 m s-1 pure photon-noise error. For the FP system we obtain 0.176 m s-1 rms dispersion, to be compared to 0.06 m s-1 photon noise. For the difference of both, we end up with a photon noise of 0.11 m s-1 and a measured dispersion of 0.14 m s-1. The dispersion of the difference is well below the square root of the quadratic sum of the individual drift measurements of 0.26 m s-1, demonstrating that both sources track a 'real' instrumental' drift. On the other hand, the difference between the photon noise and the measured dispersion leaves the room for a 0.08 m s-1 additional dispersion, which is not 'seen' by at least one of the fibers (or better sources). We suspect here a residual drift of the FP system or the ThAr sources (heating, instabilities, etc.) or very small instabilities of the light injection which do not affect both sources and fibers in the same way.

Currently, in HARPS, the thorium lamp is tuned to balance lifetime versus 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.

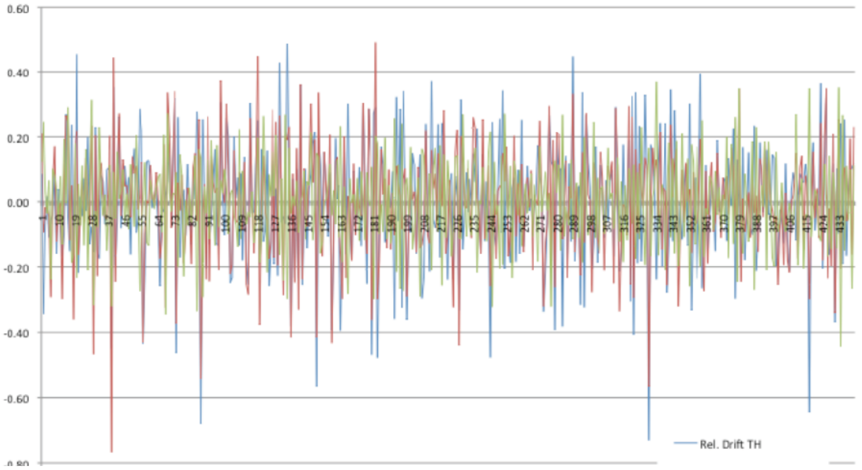

Figure 6: Drift measurement over 7 hours to test the short term performance of the FP system. Th-Ar drift in blue, FP drift in red and differential drift between Th-Ar and FP in green. X-axis in minutes of time, Y-axis in m/s.

### 3.3 Long term stability

The long-term stability was tested in a similar way as the short-term stability. This time, however, the drift was computed with respect to a reference frame at the beginning of the two-month period. Frames were taken every 5 days. The idea was to monitor possible long-term drifts of the FPCS with respect to the ThAr2 lamp.

Figure 7 shows the results. Over the 2 months from March 24 to May 24, 2011, both Th-Ar and FP system drifted by about 4 m s$^{-1}$, reproducing most likely a real drift of the spectrograph. Relative to each other, the drift was smaller that 0.5 m s$^{-1}$ at the end of the period. This latter value shows clearly that the long-term drift of the FP system cannot be larger than typically 1 m s$^{-1}$ over 60 days, and must be thus below the specified 0.1 m s$^{-1}$ per night.

On the other hand we observe that the differential drift has attained values up to 2 m/s. It is not clear where this comes from. Again, we suspect small instabilities of the light injection which do not affect both sources and fibers in the same way, but we cannot exclude effects of any of the sources (FPCS or heating effects of the ThAr lamp). It should be note, however, that the differential drift is monitored with respect the same reference frame, and that therefore, we do not have to expect drift measurement errors of the same magnitude on a night-to-night basis, for which we have measured values of typically of 0.2 m s$^{-1}$ rms.

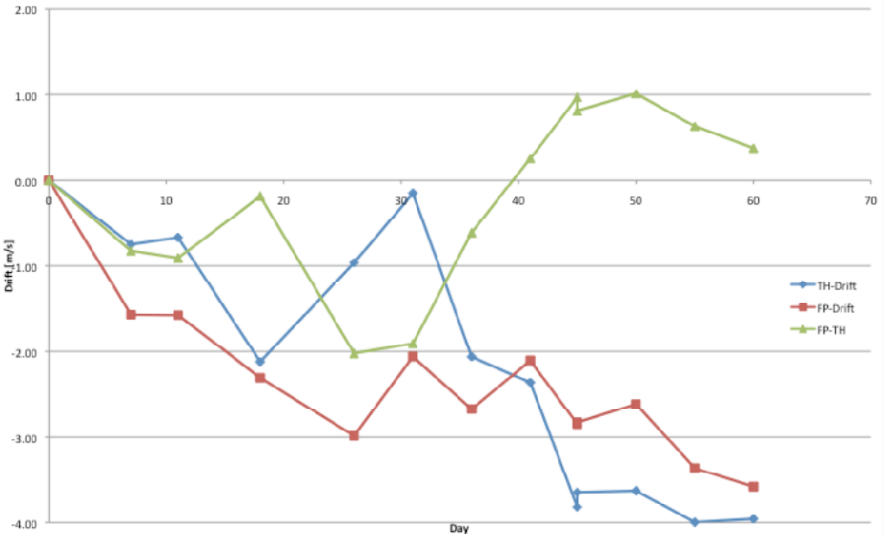

Figure 7: Drift measurements over 60 days to test the long-term performances of the FPCS. Horizontal ticks are tens of days. Vertical ticks are m/s

# 4. 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 (usually used 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.*

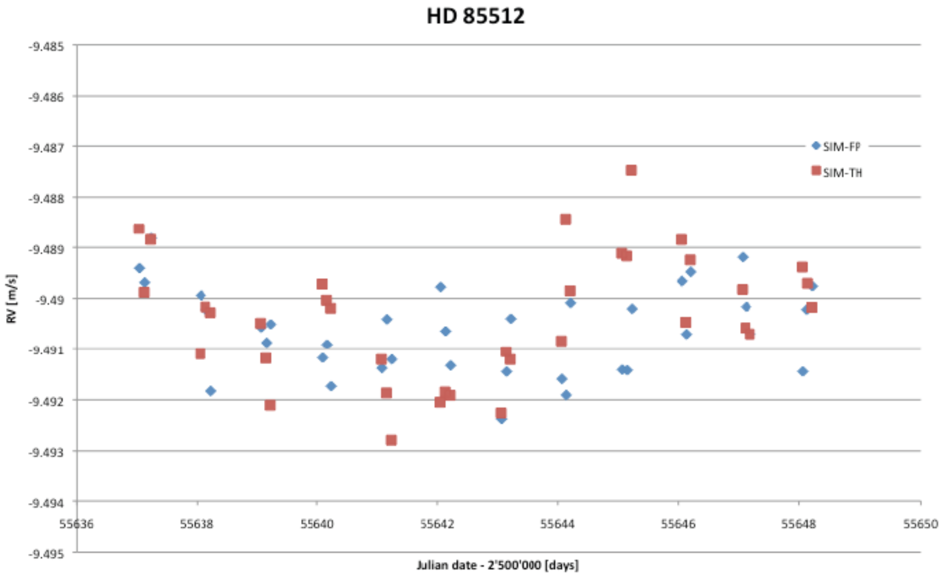

Figure 8: Observations of the star HD 85512 over a ten-days period with the simultaneous reference technique using the Th-Ar (red) and the FP system (blue). Radial-velocities are identical; although the dispersion seems to be even a little bit lower when using the FP system

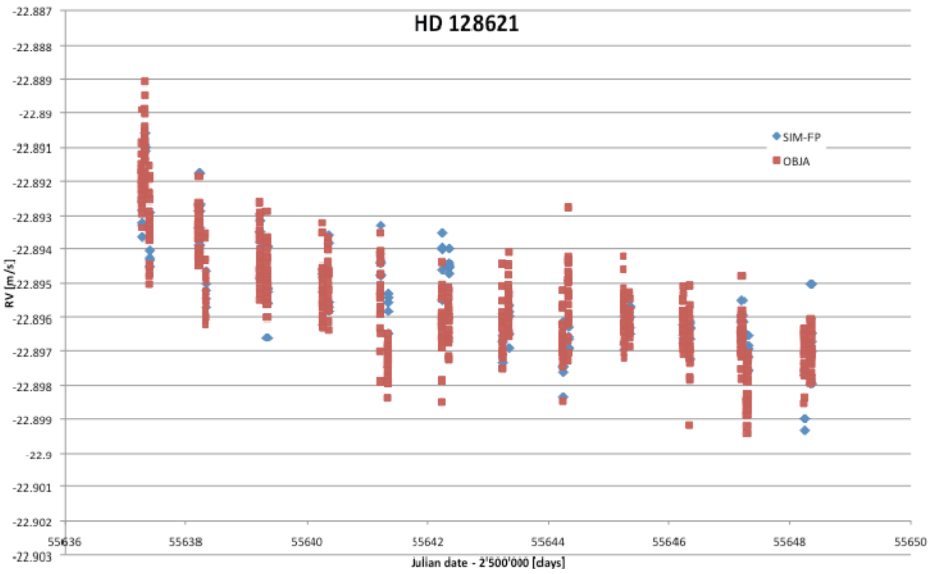

Figure 9: Observations of the star HD 128621 (alpha Cen B) over a ten-days period with the simultaneous reference technique using the FPCS (blue) and without any simultaneous reference at all. Radial-velocities are identical, indicating that the FPCS work well even on bright objects and that it does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

## 5. CONCLUSION

We have designed, built and tested a new Fabry-Perot Wavelength Calibration System and verified its performances in the frame of high-precision radial-velocity measurements with HARPS.

The system has reached the objective to provide an alternative to the simultaneous Th-Ar. In particular it provides:

- Photon precision on a single frame better than the Th-Ar, down to 1-2 cm $s^{-1}$
- nightly stability of better than the specified 10 cm $s^{-1}$
- a clean and uniform spectrum with no contamination of the object fiber in the blue wavelength region.

The FP system is now fully operational on HARPS. Ts use and the results of the pipeline are completely ‘transparent’ to the standard user

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 candidate for a calibrator in the infrared, where good wavelength calibration sources are missing. We are actually working on such a system for the SPIROU NIR spectrograph for the CFHT.

In future developments of FP systems we will try to improve the following parameters:

1) Use FP-etalon coatings with low absorption and thermally contact the etalon to a heat sink
2) Use even brighter sources and correct for better blue-red balance
3) Use source with even longer lifetime

Finally, we need mention that the wavelength stability of the system depends on the illumination of the calibration fibers. We have observed that different alignment of the source, the fibers or the lens, as well as vigneting inside the calibration light coupler box, can produce radial-velocity variation of several m s-1. The optical set-up of the coupler box was conceived together with HARPS and does not embed the latest knowledge we have We will seek to have the étendue of the calibration fiber overfilled by the étendue of the calibrating light, while coupling a maximum of light at the same time.

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