A new infrared Fabry Pérot-based RV-reference module for the SPIRou radial-velocity spectrograph

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ABSTRACT

Context. The field of exoplanets is moving towards the detection and characterization of habitable planets. These exo-Earths can be more easily found around low-mass stars by both the photometric transit and the radial-velocity techniques. In the latter case the gain is twofold: the signal induced by the planet of a given mass is higher because of the more favourable planet-star mass ratio and because the habitable zone lies closer to the star. However, late-type stars emit mainly in the infrared wavelength range, which calls for infrared instruments.

Aims. SPIRou is a stable radial-velocity (RV) infrared spectrograph addressing these ambitious scientific objectives. As with any other spectrograph, calibration and drift monitoring is fundamental to achieve high precision. The infrared (IR) domain suffers however from a lack of suitable reference spectral sources. Our goal was to build, test and finally operate a Fabry-Pérot-based RV reference module able to provide the needed spectral information over the full wavelength range of SPIRou.

Methods. We have adapted the existing HARPS Fabry-Pérot Calibrator for the operation in the infrared domain. After manufacturing and assembly, we have characterized the FP RV-module in laboratory before delivering it to the SPIRou integration site. In particular, we have measured finesse, transmittance, and spectral flux of the system.

Results. The measured finesse value of \( F = 12.8 \) corresponds perfectly to the theoretical value. The total transmittance at peak is of the order of 0.5%, mainly limited by fiber-connectors and interfaces. Nevertheless, the provided flux is in line with the requirements set by the SPIRou instrument. Although we could test the stability of the system, we estimated it by comparing the SPIRou Fabry-Pérot with the already operating HARPS system and demonstrated that a stability of better than 1 m s\(^{-1}\) during a night.

Conclusions. Once installed on SPIRou, we will test the full spectral characteristics and stability of the RV reference module. The goal will be to prove that the line position and shape stability of all lines is better than 0.3 m s\(^{-1}\) between two calibration sequences (typ. 24 hours), such that the RV-reference module can be used to monitor instrumental drifts. In principle, the system is intrinsically stable also over longer time scales such that it can also be used for calibration purposes.

Key words. extra-solar planets, radial-velocity measurements, high-resolution spectrograph, calibration, infrared

1. Introduction

SPIRou is a near-infrared (NIR) spectro-polarimeter/velocimeter soon offered as a new-generation instrument on the CFHT (Delfosse et al. 2013). Its main goals are a) the search and characterization of habitable exo-planets orbiting low-mass & very-low mass stars by using high-precision radial-velocity (RV) measurements and b) the study of the impact of magnetic fields in stars and planet formations by means of spectro-polarimetry. SPIRou is presently being integrated in Toulouse and will be transferred to the CFHT in Hawaii in 2017. Operations are planned to start end of 2017.

The radial-velocity method is employed to determine the Doppler shifts of absorption lines in the host star’s spectrum. M dwarfs give the opportunity to discover potential habitable planets due the larger radial-velocity signature induced by the planet on the lower-mass star (Quirrenbach et al. 2014). Also, the habitable zone (HZ) of an M star lies much closer in that than of a solar-type star, which again leads to a higher radial-velocity signal compared to the solar-type star case. However, since M-dwarfs emit most of their flux in the infrared wavelength domain (Reiners et al. 2010), a radial-velocity instrument has to operate at infrared wavelengths, to make best use of the stellar light. The wavelength range, resolution and the design of SPIRou, as well as its stability, have been optimized to search for habitable planets around M stars. The expected RV amplitude induced by a 2 Earth-mass planet in the HZ of an M5 dwarf, for instance, is of the order of 1.7 m s\(^{-1}\) (Barnes et al. 2011). In order to perform significant detection, a measurement precision, and thus instrumental precision, of the order or better than 1 m s\(^{-1}\) is required. It is well known that such a precision can only be achieved if both the spectral calibration and the instrumental drift are controlled to the same level. Both, calibration and drift monitoring make use of spectral references, which fix the necessary wavelength scale. The RV-observable corresponds to the measurement of the central wavelength of a spectral line, which has to be referred to a known laboratory standard. Unlike the visible case, for which multiple wavelength calibration sources exist, e.g. spectral lamps, iodine cells, and lately also laser frequency combs (LFC) and Fabry-Pérots, in the infrared wavelength domain we are lacking suitable references sources.

The precision limitations in the calibration of radial velocity measurements plays a key-role, especially when targeting the ambitious science cases listed above. For these kind of inves-
tigation, an ultra-stable, broadband, bright, flexible and reliable wavelength calibrator is required. To ensure optimal accuracy and precision, the spectrum of the ideal calibrator must have these several characteristics and these main criteria:

- Many narrow lines (not resolved)
- Cover full spectral range
- Known (or calibrated) line position
- Line stability
- No blending
- Homogeneous peak flux

In recent years, we have developed a Fabry-Pérot Calibration system with the aforementioned characteristics (Wildi et al. 2010) for the visible wavelength range. The first system, currently in use on the HARPS spectrograph, has proved suitable for instrumental drift measurement purposes. However, its performances and has completely replaced the ThAr spectral lamp for observing night, which allowed us to use them systematically for the simultaneous reference measurement (Pepe et al. 2004). Based on this second design, we have manufactured and tested a similar system for SPIRou. The only element which needed to be adapted is the étalon itself in terms of material and coatings.

In the next section we will describe the basic working principles of the Fabry-Pérot based RV-reference module for SPIRou. In section 3 we will describe the opto-mechanical design and the rationale that led us to the final parameter choice. Section 4 presents the laboratory measurement setup and the results obtained. In the final sections, we will also describe some of the particular aspects of RV precision, and we will provide an outlook on possible future developments.

### 2. Theory of the plano-plano Fabry-Pérot étalons

A plano-plano Fabry-Pérot (FP) consists of two flat parallel mirrors separated by an optical gap $d$. The inner surface of each mirror is coated with a partially reflecting coating, while the outer surface has an anti-reflection coating. The medium between the mirrors is transparent and has a refractive index of $n$.

![Fig. 1: Concept of the plano-plano FP and sketch of the interfering light beams](image)

The FP is illuminated with a parallel light beam of divergence $\Phi$. The light is partially reflected and transmitted by both mirrors producing interference in both reflection and transmission as shown in Fig.1 (excerpt from Field guide to spectroscopy of Ball (2006)). The transmission function of the étalon, taking into account the losses due to unavoidable absorption and scattering, is given by:

$$T = \frac{I_{\text{trans}}}{I_{\text{inc}}} = \left(1 - \frac{A}{1 - R}\right)^2 \frac{1}{1 + \frac{4R}{(1-R^2)\sin^2\frac{\theta}{2}}}$$

(1)

where $R$ is the reflectivity the mirror, $A$ the absorption and scattering losses per reflection, and $\delta = 4\pi nd\cos\theta/\lambda$ the phase difference between successive beams. Defining the reflective finesse coefficient as $F_R = \frac{dR}{R}$ and assuming $A << 1 - R$, the equation (Eq. 1) is simplified to:

$$T(\lambda) = \frac{1}{1 + (2F_R/m)^2 \sin^2\frac{\delta(\lambda)}{2}}$$

(2)

This function reaches a transmission maximum every time the phase $\delta$ is an integral multiple of $\pi$, i.e.

$$2nd\cos\theta = m\lambda$$

(3)

The distance between two successive maxima, also called free spectral range (FSR), is defined by:

$$\text{FSR} = \frac{\lambda^2}{2nd\cos\theta}$$

(4)

Fig. 2 shows the theoretical transmission function of a Fabry-Pérot with finesse $F_R = 13$ at 1540 nm wavelength and FSR of $\sim 0.09$ nm. In this example we have chosen normal incidence ($\theta = 0$) and vacuum operation ($n = 1$). Transmission maxima are then reached for each wavelength $\lambda_n = 2d/m$ and the free spectral range simplifies to $\text{FSR} = \lambda^2/2d$.

![Fig. 2: Simulated curve for our Fabry Pérot passband.](image)
we can replace the reflective finesse \( F_R \) by an effective finesse \( F_e \) of the étalon, which can be expressed as:

\[
\frac{1}{F_e^2} = \frac{1}{F_R^2} + \frac{1}{F_D^2} + \frac{1}{F_F^2} + \frac{1}{F_P^2}
\]

(5)

where \( F_R \) is the reflectivity finesse, \( F_D \) is the defect finesse, \( F_F \) is the parallelism finesse, and \( F_P \) is the divergence finesse. \( F_D \) represents an approximation of the divergence finesse that is produced by the finite dimension of the illuminating entrance slit, which in turn produces a beam divergence of the quasi-parallel beam through the étalon. In the simulations we will present in the following sections, we shall replace the divergence finesse by an integration over the field positions of the slit, in order to compute a realistic transmission function of the étalon in the case of a large entrance slit.

Using the effective finesse and the definition of the resolving power \( RP \), we compute:

\[
RP := \frac{\lambda}{FWHM} = \frac{\lambda}{\lambda/(m F_e)} = m F_e
\]

(6)

3. IR Fabry Pérot for SPIRou

The Fabry Perot RV-reference module for SPIRou has the purpose of providing a large number of ultra-stable lines in the wavelength range of the spectrograph, that allow to measure the instrumental drift during the night (or, in other terms, on the time scale between two calibrations). From the general characteristics of an ideal calibration source described in the introduction we derive the requirements for the SPIRou RV-reference module:

- The calibration source must cover the full wavelength range of SPIRou, i.e. from 980 nm to 2350 nm.
- The lines must not be resolved by the SPIRou spectrograph, since otherwise information is lost, respectively we do not take full advantage of the spectral resolution of the instrument.
- The line separation must be minimum 2 and maximum 4 FWHMs of the spectrograph IP, in order to maximize the information content and avoid blends.
- The line position and shape stability of all lines is better than 0.3 m s\(^{-1}\) during a night and on the time scale in between two calibrations (typ. 24 hours).
- The lines are equidistant and the position of all lines defined by a limited number of system parameters.
- The relative intensity of any neighboring lines must be stable at 10\% over any time scale.
- The dynamic range of line intensities must be smaller than a factor 2 over one echelle order and a within a factor five over the full spectrum.

3.1. Spectral Characteristics

Assuming the aforementioned hypothesis, we are able to design the Fabry-Pérot’s spectral characteristics. First, we have to take into account the resolution of the spectrograph \( R_S \). In order to optimize the spectral content, we need to make the line spacing as small as possible but also ensure that on the blue side, where it is minimal, it remains larger than \( 3 \cdot FWHM \). This leads us to the first condition:

\[
FS R_B \geq 3 \cdot \frac{\lambda_B}{R_S}
\]

(7)

In the case of vacuum operation and perpendicular incidence, Eq. 3 simplifies to

\[
2 \cdot d = m \cdot \lambda.
\]

(8)

Combining this equation with the inequality in Eq.7, we obtain the condition for the étalon gap:

\[
FS R_B = \lambda_B/m = \frac{\lambda_B^2}{2 \cdot d} \geq 3 \cdot \frac{\lambda_B}{R_S}
\]

(9)

If we set the gap to exactly match the minimum FSR, we obtain the value

\[
d = \frac{\lambda_B \cdot R_S}{6}.
\]

(10)

On the other hand, the lines of the étalon, at constant finesse, are larger on the red side of the spectrum. There, we have to ensure that they remain narrower than the IP. Our choice was to under-resolve the FP lines by a factor of 2/3 and not less, such that unnecessary flux loss is avoided. This choice drives the second condition:

\[
FWHM \leq \frac{2}{3} \cdot \frac{\lambda_B}{R_S}
\]

(11)

Using the definition of the finesse \( F = FSR/FWHM \) and combining it with Eq.11, we obtain for the finesse:

\[
F \geq \frac{2 \cdot d \cdot 3 \cdot R_S}{m^2 \cdot 2 \cdot \lambda_B} = \frac{3 \cdot d \cdot R_S \lambda_B^2}{4 \cdot d^2 \lambda} = \frac{3 \cdot R_S \lambda_B}{4 \cdot d}
\]

(12)

Choosing the lowest possible finesse and by substituting the gap \( d \), we obtain for the finesse:

\[
F = \frac{3 \cdot R_S \cdot \lambda_B}{4D} = \frac{9 \lambda_B}{2\lambda_B}
\]

(13)

To summarize, the spectrograph’s spectral range and resolution, together with the general requirements for the RV-module described in the previous section, define the the Fabry Pérot parameters summarized in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPIRou start wavelength ( \lambda_B )</td>
<td></td>
<td>980 nm</td>
</tr>
<tr>
<td>SPIRou end wavelength ( \lambda_B )</td>
<td></td>
<td>2350 nm</td>
</tr>
<tr>
<td>SPIRou resolving power ( R_S )</td>
<td></td>
<td>75’000</td>
</tr>
<tr>
<td>Étalon finesse ( F )</td>
<td></td>
<td>10.8</td>
</tr>
<tr>
<td>Étalon gap ( d )</td>
<td></td>
<td>12.250 mm</td>
</tr>
</tbody>
</table>

Table 1: Spiriou’s main parameters and derived étalon parameters

To achieve a reflectivity-limited effective finesse of about \( F = 11 \), we have distributed the various finesse components of Eq. 5 as shown in Tab.2. As mentioned above, our starting choice has been to determine the effective finesse by the reflectivity finesse and to allocate to it a value of \( F_R = 13 \). The remainder of the budget is almost completely used up by the divergence finesse, such as to maximize the fiber diameter and minimize the physical size of the étalon. The remaining finesse values have been set much higher to keep \( F_e \) in budget.
Once the finesse values have been frozen, they define minimum requirements to the opto-mechanics of the étalon. The finite divergence forces us to make a trade-off between fiber size, the focal length of the collimator and clear aperture of the étalon. In principle, at fixed divergence value, the physical dimensions of the assembly are minimized when the smallest fiber is selected. However, this implies a loss of flux inversely proportional to the fiber size if an incoherent (extended) light source is used. In order to maximize the flux while still using an incoherent fiber, we decided to go for the source with the highest divergence, which is the high-temperature plasma bulb Light Source (LDLS) EQ-99 FC by Energetiq composed of a single field point (or, in other words, over each ray arising from the different points across the fiber tip), which will cross the étalon with slightly different incidence angles \( \theta \).

We have simulated the transmission function for different fiber diameters and as a function of the de-centering of the fiber from the optical axis, in order to understand how sensitive the finesse and the peak wavelength are as a function of these parameters. For the analysis, we need to consider that the fiber is spatially extended and the deviation of each ray from the parallel beam is:

\[
\theta = \arctan \left( \frac{x}{f} \right)
\]  

(14)

where \( x \) is the distance from the fiber center and \( f = 100 \text{ mm} \) is the focal length of the collimator (parabolic mirror). The angle \( \theta \) by which the beam crosses the étalon depends on the position of the fiber of entrance.

To obtain the total transmittance spectrum, we need to compute the integral over the surface of the fiber. For the simulations we assume circular fibers and uniform illumination, and we perform the integral in polar coordinates. The total transmittance can then be written as:

\[
T(\lambda) = \left( \int_0^R \rho d\rho \int_0^{2\pi} \frac{1}{1 + (2 \cdot F_{\text{eff}}/\pi)^2 \cdot \sin^2(\delta/2)} \, d\varphi \right) / A
\]

(15)

where \( R \) is the radius of the fiber and \( \delta = 4\pi n d \cos \theta / \lambda \), as defined earlier. The integral is divided by the surface \( A \) of the fiber tip in order to re-normalize the peak transmittance.

In case of a de-centering \( \Delta \) of the fiber with respect to the optical axis of the system, the angle of incidence \( \theta \) becomes:

\[
\theta = \arctan \left( \sqrt{(\rho \cos \varphi + \Delta)^2 + (\rho \sin \varphi)^2} / f \right)
\]

(16)

where, without loss of generality, we have assumed the fiber to be de-centered along the x-axis only.

It is easily understood that, if the fiber has infinitely small diameter, all the the rays will cross the Fabry-Perot with \( \theta = 0 \), such that we end up with the known Airy function. For the general case of finite fiber diameter, we perform a numerical integral to obtain the transmission as a function of \( D \) and \( \Delta \).

Fig.4 shows the transmittance as a function of fiber size for a system with focal length \( f = 100 \text{ mm} \). As expected, for small fibers the peak transmittance is close to 1 and the effective finesse is equal to the reflective finesse. For larger fibers, the transmission at the peak decreases and the width increases, which is equivalent to a reduction of the effective finesse. Simultaneously, the peak wavelength shift towards shorter wavelength, which reflects the fact that the number of rays having an incidence angle \( \theta > 0 \) has increased. Interestingly, the peaks remain symmetric, even for very large fibers, which is due to the fact that we have assumed uniform illumination and a circular fiber.

### 3.2. Sensitivity of finesse & RV-stability to alignment and fiber diameter

Up to now we have considered the transmission function of the étalon to be given by Eq. 2. Defects, non-parallelism and finite divergence have been taken into account by computing an effective finesse corrected for the various contributions. While this approach is satisfactory for the defects and non-parallelism of the mirrors, it is incomplete for the finite divergence. The finite divergence (or fiber diameter) not only introduces a loss of finesse but also a shift in wavelength of the transmitted peaks. Furthermore, a non-uniform light distribution across the fiber exit will produce a change in the shape of the transmitted peak. The resulting transmission function can be simply understood as the sum of the individual transmission functions from every single field point (or, in other words, over each ray arising from the different points across the fiber tip), which will cross the étalon with slightly different incidence angles \( \theta \).

Table 2: Finesse budget and derived requirements

<table>
<thead>
<tr>
<th>Finesse</th>
<th>Budget</th>
<th>Formula</th>
<th>Req.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflectivity</td>
<td>13</td>
<td>( F_R = \pi \sqrt{R}/(1 - R) )</td>
<td>( R = 80% )</td>
</tr>
<tr>
<td>Divergence</td>
<td>28</td>
<td>( F_0 = 4 \cdot \lambda/\Phi \cdot \delta )</td>
<td>( \Phi = 2 \text{ mrad} )</td>
</tr>
<tr>
<td>Parallelism</td>
<td>40</td>
<td>( F_P = \lambda/(2 \cdot \Delta) )</td>
<td>( \Delta = 4.5 \text{ nm} )</td>
</tr>
<tr>
<td>Defect</td>
<td>40</td>
<td>( F_D = \lambda/\sqrt{2} \cdot \delta )</td>
<td>( \delta = 6.7 \text{ nm} )</td>
</tr>
<tr>
<td>Effective</td>
<td>10.88</td>
<td>Eq. 5</td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 3: Spectral power produced by the LDLS.](image)
Fig. 5 shows the results of the simulation as a function of the fiber de-centering, where we have fixed the fiber diameter to the chosen value of $D = 200 \mu m$. We observe also in this case a reduction of finesse and a blue-shift of the peaks with increasing de-centering. It is interesting to note, however, that, when combining a finite fiber size with de-centering, the peaks become asymmetric.

![Fig. 4: Simulated transmittance of a Fabry-Pérot for fiber diameters of 200, 500 and 900 \( \mu m \), assuming the fiber centered on the optical axis and a focal length of the collimator \( f = 100 \text{ mm} \)](image)

When de-centering, the value for the effective finesse approaches the nominal value of \( F_R = 13 \). It’s important to note that the effective finesse remains larger than \( F_{\text{eff}} = 11 \) for a fiber diameter up to \( \Delta \theta = 0.0035 \) (\( D = 350 \mu m \)), which perfectly justifies our choice for a 200 \( \mu m \). However, the plot as a function of de-centering also tells us that, if we want to ensure the required effective finesse, the fiber must be centered to better that \( \theta = 0.0015 \) (\( \Delta = 150 \mu m \)) for the optical axis of the system.

![Fig. 5: Simulated transmittance of a Fabry-Pérot for fiber de-centering value of 20, 250, 500 and 1000 \( \mu m \) assuming a fixed fiber diameter of \( D = 200 \mu m \) and a focal length of the collimator \( f = 100 \text{ mm} \)](image)

As mentioned before, the peak wavelength shifts toward the blue when increasing the fiber diameter or de-centering the fiber. When the Fabry-Pérot is used for absolute wavelength calibration, the position of the peaks must be known. Even more critical, when used as a RV-reference (to measure the instrumental drift between two calibration sequences), we have to make sure that the transmission peaks remain stable in wavelength. Their dependence on fiber diameter and centering will set the requirements on the focus and centering stability of our optical system. For this reason, we have expressed the wavelength shift in terms of ‘radial-velocity’ in the unit of [m/s]. The conversion from wavelength to speed is obtained by the relation:

$$\Delta v = \frac{\Delta \lambda}{c}$$

(17)

Fig. 7 presents the shift of the transmission peak as a function of, again, fiber diameter \( \Delta \theta = D/f \) and de-centering \( \theta = \Delta/f \). It can be seen that even a small change introduces shifts of several hundreds or even thousands of \( \text{m/s}^{-1} \). However, there is no reason, besides thermo-mechanical instabilities, for the fiber diameter or the de-centering to change with time. In order to better evaluate the calibration sensitivity to these parameters, we prefer therefore to presents the derivative of these curves (Fig 8). The curve having parabolic shape (as can be understood from the fact that \( \cos \theta \sim \theta^2 \) for small angles \( \theta \)), its derivative is nothing else than a slope. The left-hand plot simply shows us that, the larger the fiber, the more sensitive the system is to a de-focus, while, from the right-hand plot, the same conclusion can be drawn for the de-centering. Given the chosen fiber size (2 mrad), we derive that the radial velocity will change by \( 300 \text{m/s}^{-1} \) per mrad, or, in physical terms for our system, by \( 3 \text{m/s}^{-1} \) per micron in fiber size ‘change’. In terms of de-centering, the sensitivity will approach zero if the fiber is perfectly centered, while it will increase to \( 600 \text{m/s}^{-1} \) per mrad (6 m/s^-1 per micron) of additional de-centering for a fiber

The results for the finesse are summarized in Fig. 6. The plot shows the evolution of the finesse as a function of fiber diameter (left hand) and of the fiber de-centering (right hand). In order to be more general, we have expressed both, the fiber diameter and de-centering, in terms of angular values \( \Delta \theta = D/f \) and \( \theta = \Delta/f \), respectively. In the case of a small fiber diameter or small de-centering, the value for the effective finesse approaches the...
de-centered by 2 mrad (200 µm).

From this analysis we conclude that small fibers and excellent alignment are mandatory not only for optimum finesse and flux, but also to reach highest spectral stability. Below, we will use sensitivities derived to specify the thermo-mechanical requirements applicable the RV-reference module of SPIRou.

The analysis above shows that the RV-sensitivity of the étalon demands alignment precision to 10 µm (left) and to de-centering for a fixed fiber size of \( D = 200 \mu \)m. The blue area marks the limit area for which we are interested. The area is small because small changes introduces shift of several hundreds or more of \( m s^{-1} \) in both cases.

![Fig. 8: RV sensitivity to fiber-size change for a centered fiber](image)

![Fig. 8: RV sensitivity to fiber-size change for a centered fiber](image)

3.3.1. Alignment precision

The analysis above shows that the RV-sensitivity of the étalon to opto-mechanical mechanical misalignment increases with de-centering. A perfectly aligned system would not be sensitive to motions of the fiber, e.g. due to thermal or gravity effects, while even for slight misalignments our system could becomes unstable at a level beyond 30 cm s\(^{-1}\). Assuming that we can align the fiber by auto-collimation to better than 1/20th of its diameter, i.e. to 10 µm and using the results presented in Fig. 8, we obtain a sensitivity of 30 m s\(^{-1}\) per mrad (0.3 m s\(^{-1}\) per micron). In other words, the fiber position must be stable to one micron with respect to the focal plane of the collimator while the angular alignment of the étalon with the collimators must not change by more than 0.01 mrad.

3.3.2. Pressure stability

For an air-spaced étalon like SPIRou’s, any pressure change will induce a change in the optical gap and thus in the wavelength of the transmitted peaks. For these reasons we made the choice to operate the RV-reference module in vacuum (see Fig. 9). To establish whether the system must be pumped continuously or not, we have to compute the maximum pressure change allowed in a night of observation, i.e. the time following a wavelength calibration, which will invalidate the wavelength scale. Given the requirement for the spectral line stability of 30 cm s\(^{-1}\) during observing night (typ. 12 hours) and using Eq. 3 and Eq. 17, we compute that the refractive index \( \Delta n/n \), must not change by more than \( 10^{-3} \) in relative terms. Using the approximation for the air index \( n_{air} = 1 \), we compute that the pressure \( p \) inside the vacuum tank must not change by more than \( 7.4 \cdot 10^{-3} \) mbar per day.

3.3.3. Operating pressure

An aspect which is frequently forgotten, is that pressure does not only depends on air leaks but on volume of the air contained in the vacuum tank. The external ambient pressure changes due to meteorological effects will affect the volume of our vacuum tank, due to the pressure difference variations between outside and inside. Consequently, the index of the residual air inside the vacuum tank will vary and will degrade the calibration system. The sensitivity to atmospheric pressure changes depends on the air pressure (or density) inside the vacuum tank. We have therefore to understand at which (maximum) pressure we must operate the RV-reference module to avoid effects larger than 30 cm s\(^{-1}\).

![Fig. 8: RV sensitivity to fiber-size change for a centered fiber](image)

![Fig. 8: RV sensitivity to fiber-size change for a centered fiber](image)

 Bearing in mind Boyle’s law \( p \cdot V = const \), and defining \( V_0 \) as the initial volume and \( p_0 \) the initial pressure inside the vacuum tank, the refractive index \( n \) of the residual air can be written as:

\[
\frac{n - 1}{n_{Atm} - 1} = \frac{p_0}{p_{Atm}} \cdot \frac{V_0}{V} \cdot \frac{p_0}{p_{Atm}} \cdot (n_{Atm} - 1)
\]

(18)

where \((n_{Atm} - 1) \approx 2.7 \cdot 10^{-4}\) corresponds to the refractive index of standard air at atmospheric pressure \( p_{Atm} \), and \( p \) and \( V \) are the actual pressure and volume inside the vacuum tank.

The derivative of the refractive index \( n \) with respect to the change of the external pressure \( p_{out} \) can then be written as:

\[
\frac{dn}{dp_{out}} = \frac{dn}{dV} \cdot \frac{dV}{dp_{out}} = \beta \cdot \frac{p_0}{p_{Atm}} \cdot (n_{Atm} - 1)
\]

(19)

where \( \beta := -\frac{dV}{V dp_{out}} \) is the relative volume change of the vacuum tank as a function of changes in external pressure (at constant internal pressure).

By means of a finite element analysis of the vacuum tank (see the following chapters for the design description), we have computed \( \beta \sim 10^{-3} \) mbar\(^{-1}\). This value allows us to determine the maximum operation pressure to avoid radial-velocity...
changes of the RV-reference module larger than the specified 30 cm s$^{-1}$. If we consider that ambient pressure variations hardly exceed 10 mbar per night at 2500 m altitude (e.g. at the La Silla and Paranal Observatories), we derive an upper limit for the operation pressure of $p_0 < 30$ mbar. In practical terms, and given the maximum allowed pressure-rise rate determined in the previous section of $\frac{dp}{dt} = 7.4 \cdot 10^{-3}$ mbar per day, it is sufficient to evacuate the RV-reference module once every 10 years in the worst case.

3.3.4. Temperature stability

We have considered two effects induced by temperature variations. The first one is the thermal stability of the optical gap given essentially by CTE of the spacers. The spacer material being Corning ULE, the CTE is guaranteed to be lower than $2 \cdot 10^{-8}$ per Kelvin, which translates into a radial-velocity sensitivity of about 6.7 m s$^{-1}$ K$^{-1}$. Applying again the radial-velocity stability requirement we derive a requirement to the temperature stability of the RV-reference module of better than 0.05 K.

The second temperature effect may produce focal-length changes of the collimator, which would result in a ‘de-focus’ of the entrance fiber and an apparent increase of fiber diameter $d$. As we will see in Sec. 3.4, the Fabry Pérot assembly of our RV-reference module is made of aluminum (see also Fig.9). Considering the focal length of $f = 100$ mm and the coefficient of linear thermal expansion for aluminum as $CTE_{Al} = 2.3 \cdot 10^{-5}$ K$^{-1}$, we compute an absolute focal length change of $\frac{df}{dT} = 2.3 \mu m$ K$^{-1}$. The F-number of the fiber exit (or collimator) being $F/2.5$, we obtain an increase of apparent diameter $\frac{dd}{dT} \sim 1 \mu m$ K$^{-1}$. From the plot in Fig. 8 we can then derive that, for a fiber of 200 $\mu$m diameter, the radial velocity would change by $\Delta v \sim 3 m/s$ K$^{-1}$. In order to comply with the radial-velocity requirements, we have to keep the temperature of the system stable to 0.1 K.

From the analysis above, we conclude that it is sufficient to control the temperature of the RV-reference module to a level of 0.05 K even when using aluminum for its structure. This kind of temperature stability is easily achieved with commercial components. Nevertheless, we have made a particular effort to design the opto-mechanical system in the most symmetric and stable way, and to thermally isolate the critical parts inside the vacuum from the vacuum tank. The operation in vacuum will further improve the thermal stability.

3.4. Design of the SPIRou RV-reference module

The RV-reference module designed for SPIRou (Fig.9) is derived from a concept that has been successfully developed for HARPS and the visible wavelength range (Wildi et al. 2010). The design was later made more modular and adapted for the infrared wavelength range by replacing lenses with mirrors. The new design was first successfully been applied to the HARPS-N and CORALIE modules and later essentially copied for SPIRou.

The system consists conceptually on a Fabry-Perot étalon filter illuminated in white light to produce a set of (in frequency) equally-spaced emission lines of uniform intensity across a wide wavelength range. For the illumination we use a laser-driven light source (LDLS by Energetix) that essentially produces a black-body emission of 10’000 K. While at visible wavelengths the surface brightness of such a source is considerably higher than a standard halogen source of about 3’000 K, the brightness difference at wavelength above 1 $\mu$m is much lower and almost negligible. For our system we nevertheless decided to use an LDLS with a 200 $\mu$m fiber output which perfectly matches the étendue of the étalon. The LDLS light is led to the RV-reference module through an octagonal fluoride fiber of 300 $\mu$m core diameter and 2 m in length, while the RV-reference module output fiber, which collects the light from the module and brings it to the spectrograph, is of 600 $\mu$m core diameter and 4 m length. A vacuum tank contains the fiber-fed Fabry Pérot opto-mechanical system (Fig.10). The pressure is initially pumped to $10^{-4}$ mbar or less, but eventually the valve is closed. More important than the actual pressure value is the pressure rise rate which must comply with the previously mentioned requirements. The temperature is controlled using heating resistor foils glued around the vacuum tank. Two precise silicon-diode temperature sensors (one on the vacuum tank for the control, the other close to the etalon for monitoring) and a Lakeshore 331 device close the temperature-control loop to better than 5 mK $rms$. The whole system is isolated and packed inside a box to avoid heat exchange with the laboratory environment.

The optical system is placed in the vacuum vessel and fixed to the top flange in only 3 points, using thermally insulating material to minimize thermal conduction from outside. The collimating and focusing optics are identical protected silver-coated parabolas with a focal length of 100 mm. Parabolic mirrors were selected because the low aberrations of this combination and guarantee that the line profile stays symmetric.

The light enters the vacuum tank through an octagonal silica fibers octagonal CERAMOPTEC (OPTRAN WF). Its diameter is 200 $\mu$m in accordance to the derived finesse requirements. The octagonal shape has been chosen in order to have a very uniform and thus stable illumination of the étalon (Chazelas et al. 2012), which is important to minimize possible illumination effects at the source level, as for instance PSF changes, variations of the illumination spot position or its angular distribution.
The F/2.5 beam of the fiber produces after the 100 mm focal length of the mirror a collimated beam of 40 mm diameter. The back-reflected beam is partially obstructed by the fiber and its spider, but we preferred to accept some light losses for the sake of symmetry. The beam crosses the étalon before being re-focused by a second on-axis parabola on the output fiber, both mounted in exactly the same way as the collimation part.

The output fiber inside the vacuum tank is circular and its diameter is 600 µm. A larger fiber has been chosen in order make alignment easier, collect all the light, and eventually increase the stability of the system. Being located after the étalon, the diameter of this fiber has no influence on the resulting finesse.

The Fabry Pérot étalon used in SPIRou is shown in Fig.11. Its physical diameter is of 60 mm while the clear aperture is 50 mm. The two mirrors are made of Suprasil. They have been polished and coated by the company Thin Films Physics, Switzerland. The surface flatness is of the order of λ/100. The coating reflectivity of \( R = 80\% + 2\% \) over the 980 − 2350 nm range was designed to match the reflectivity-finesse requirements (Fig.12). Both mirrors were AR-coated on the external face. Nevertheless, a wedge was introduced between the two faces of each mirror to avoid possible parasitic interference with the external faces. The two mirrors are separated by a set of three high-precision Corning ULE (Ultra Low Expansion material - CTE < 2 x 10⁻⁶ K⁻¹) spacers produced by sls-optics, UK. The étalon was finally assembled by dry optical contacting by ICOS, UK.

4. Laboratory test

4.1. Test goals

We have characterized the RV-reference module in laboratory with respect to its basic parameters. It turned out to be quite a demanding task to measure the high-resolution transmission function, given the high spectral resolution of the étalon itself. In order to well sample the line profile we would have needed a spectrograph or spectrometer of resolving power \( R > 500'000 \) that only an FTS can deliver. We decided to restrict ourselves to a tunable laser wavelength for this measurement. Once the spectral performances demonstrated at one wavelength, and knowing the étalon gap and the broad-band reflectivity, the performances can be determined also at other wavelength. Nevertheless, we have determined the broad-band transmittance and the flux delivered by the system separately. Also, we have measured the pressure and temperature stability in order to verify that the system complies with the technical requirements.

4.2. Measurements & Results

4.2.1. Finesse

Fig.13 shows the setup used for characterizing our étalon. We used a temperature controlled DFB laser diode at 1540 nm as a tunable laser. The center wavelength has a temperature coefficient of 0.095 nm K⁻¹. We are using this characteristic to scan the transmittance of the Fabry-Pérot as a function of wavelength. The source’s spectral width (FWHM = 2 MHz) is narrow enough to probe the line profile of our étalon (FWHM = 1 GHz). The flux is measured at the output of the system by an indium-gallium-arsenide (InGaAs) photodiode.

Fig.14 shows the measured transmittance curve \( T(λ) \) of the RV-reference module. The finesse can be estimated by dividing the free-spectral range (distance between two neighboring peaks) by the FWHM of a single line. Alternatively, we have fitted the obtained curve by a theoretical transmission function (green curve in Fig.14) leaving the étalon gap (or the FSR) and the effective finesse \( F_E \) as free parameters. The so obtained values are \( F_E \sim 12.76 \) and \( FSR = Δλ = λ^2/2nD \sim 0.09 \) nm, both perfectly in line with the design values. The finesse is
Fig. 13: Principle of our test set-up. TCPS: temperature controller and laser diode power Supply; LD: laser diode; FP: Fabry-Pérot opto-mechanics, PD: photodiode

actually slightly higher than expected given the actual coating reflectivity of about 81-82% instead of the specified 80%. Finally, we would like to note the beautiful match of the fitted curve with the measured data demonstrating that we have well under control all the effects which could influence the line symmetry, such as the divergence finesse.

Fig. 14: Measured Fabry-Pérot transmittance as a function of wavelength (blue dots) and fitted theoretical curve (green line)

4.2.2. Transmittance and flux

We have measured the spectral power and transmittance of the system in the 950 – 1700 nm range directly with a laboratory Optical Spectrum Analyzer (OSA). Fig.15 shows the corresponding set up. Fig.16 shows instead the setup for the 1600 – 2400 nm spectral range. Here we employed a small optical bench with selectable band-pass filters to measure by means of a NIR photo diode the optical power and transmittance in four discrete bands.

Fig. 15: RV-reference module test setup for spectral flux and transmission measurement from 900 nm to 1700 nm. The setup includes an LDLS lamp, the Fabry-Pérot system, a test fiber of 600 μm, OSA (Optical Spectral Analyzer).

Fig. 16: RV-reference module test setup for spectral power and transmission measurement from 1700 nm to 2460 nm. A small optical bench is included to analyze the light: collimator, filter wheel, focusing mirror, NIR photodiode and voltmeter.

The power was estimated using the internal calibrations and conversion factors of the OSA and the photodiode. The measurements should therefore not be considered to be of great accuracy but to provide a coarse estimate of the spectral power density produced by the RV-reference module as a whole. Fig.17 shows the spectral flux produce by the RV-reference module as a function of wavelength. We originally observed a discrepancy of about a factor of 4.5 at 1625 nm where we have overlapping measurements on the two setups. We measured approximately the same factor when using an halogen lamp instead of the LDLS to light-feed the module Fig.18. This factor can be explained by the bad match of the fiber diameter used to feed the OSA (60 μm) with the RV-reference module output fiber. Not being able to correct for the coupling losses to the required precision, we have decided to scale the measurements obtained with the OSA to the more accurate measurements with the silicon diode. To obtain the correct spectral flux we have therefore multiplied the flux given for λ < 1600 nm on the Fig.17 and Fig.18 by the measured factor of 4.5. We should note that even then we obtain a lower limit for the actual flux, since we neglected transmission losses in the measuring system itself, i.e., mirror, diffuser, sensor coupling.

In interesting to note that the flux above 1000 nm produced by feeding the module with the two lamps (Fig.17 and Fig.18), the LDLS or the halogen lamp, is not significantly different, despite the very different temperature of the lamps, This actually as expected by the black-body emission law. We will therefore consider to use an halogen lamp in the final RV-reference module layout for cost considerations.
The transmittance of the RV-reference module by computing the ratio of the spectral power measured at the output of the test setup with the RV-reference module and without it. In the latter case we simply connected together the input and output fiber of the module. The corresponding measurements for flux and transmittance in the four bands are summarized in Table 3.

The last column indicates the transmission of the RV-reference module at the peak \( T_{FP} \) of the Fabry-Pérot line, and has been computed by multiplying the average (broadband) transmittance of the system by the finesse of the Fabry-Pérot.

### 4.2.3. Pressure and temperature stability

As explained in sections 3.3.3 and 3.3.4 the RV-reference module must be operated in vacuum well below 30 mbar and the pressure raise rate must be lower than \( 7.4 \times 10^{-3} \) mbar. After evacuating the vacuum tank and doing a leak test to ensure the absence of vacuum leak, we performed a pressure test as shown in Fig. 19. The residual outgassing rate is \( 7.2 \times 10^{-3} \) mbar per day, just within the specification. The experience on decreases as a function of time to a level much better than the required value.

![Fig. 19: Pressure (outgassing) as a function of time](image)

In a similar way we have tested the temperature stability. Fig. 20 shows the diagram of the set up for temperature monitoring.

![Fig. 20: Scheme of the temperature control](image)
proximity of the Fabry Pérot etalon. Fig. 21 shows the temperature of both sensors after turning on the temperature controller.

![Temperature graph](image)

Fig. 21: Temperature of the RV-reference module after switching on the control loop. The green curve shows the control sensor located on the vacuum tank, the blue curve represents the sensor located in proximity of the etalon.

The temperature of the vacuum tank stabilizes after less than one hour with a with a dispersion of $\sigma_T = 1.2$ mK, while the sensor close to the etalon reaches a stable temperature after about 40h with a slightly higher dispersion of $\sigma_T = 2.1$ mK. This can be explained by the fact that the test was made in a laboratory with no temperature control at all and thus night-to-day variations of several degrees. Even under these conditions the temperature stability of our RV-reference module is well within specification.

5. RV Performance

5.1. Photon Noise

By analogy with the HARPS-N Fabry-Pérot we know that the centroid of a single emission line featuring 100 000 $e^-$ per line can be determined with a photon-noise limited precision $\sigma$ of better than 2 m s$^{-1}$. SPIRou will be using an Hawaii 4RG detector with lower dynamical range than typical CCD detector. Let’s assume a conservative line flux of only 25 000 $e^-$ per exposure. Given the fact that the present étalon will produce about 14 280 lines in the spectral range of SPIRou, we will obtain a global precision of the drift measurement of

$$\sigma_{\text{tot}} = \sigma_{100000} \times \sqrt{\frac{100000/25000}{14280}} = 0.034 \text{ m s}^{-1}. \quad (20)$$

This value is significantly lower than the aimed precision of 0.3 m s$^{-1}$ for SPIRou, and therefore compliant with the requirements.

5.2. RV-stability

Radial-velocity stability measurement could however not be performed, since they would have required a spectral reference at least as stable as the RV-reference module is supposed to be. We have therefore decided to postpone these measurements to be done on SPIRou itself, where it will be possible to compare our module directly with a Uranium hollow-cathode lamp.

Nevertheless, we can refer to stability measurements of an identical system (besides the etalon coating, which are optimized for the visible) made with HARPS-N (Wildi et al. 2011). It could be demonstrated that the short-term RV-dispersion obtained using the Fabry-Pérot system was better than the one measured using the ThAr hollow-cathode lamp. Typical dispersion value are of the order of 0.1 to 0.2 m s$^{-1}$ on time scales from hours to a day. This is again perfectly in line to the specified RV-stability requirement. Given the almost identical design we have plausible reasons to expect similar performances on the SPIRou RV-reference module.

5.3. Modal Noise

Several studies have demonstrated that the finite number of modes in a wave guide such as a fibers may introduce noise in excess to pure photon noise. For instance, the modal noise limits the signal-to-noise-ratio (McCoy & Ramsey 2011) measured in the continuum of the measured spectrum. This modal noise increases with wavelength because of the fewer modes in the fiber and it may therefore represent a limit to the NIR radial-velocity precision budget. Let’s therefore analyse the situation for the SPIRou RV-reference module. The number of excited modes in a uniformly-illuminated fiber is inversely proportional to the wavelength and is given by the formula (McCoy & Ramsey 2011)

$$M = \frac{\pi \cdot d \cdot NA}{\lambda}, \quad (21)$$

where $d$ is the fiber core diameter, $\lambda$ is the light’s wavelength, and $NA$ is the fiber’s numerical aperture. In the wavelength domain of SPIRou and for the chosen fiber, we have $M = 9941$ at 980 nm and $M = 1741$ at 2350 nm. At first glance it appears that at short wavelengths there are enough modes for our Fabry-Pérot system, since we expect to obtain a signal-to-noise at continuum of the order of the square root of the number of modes, i.e. about 100. On the red end of the spectrum the mode-limited signal-to-noise ratio decreases to about 30, which is even below what we expect to be the limit to reach a precision of 1 m s$^{-1}$. However, we do not yet fully understand how the signal-to-noise in the flux impacts the photo-center measurement of a spectral line and thus its radial velocity, since this depends on many factor among which the optical design of the spectrograph. Nevertheless we think that this question deserves further tests and analysis going beyond the goal of this paper, though. We have therefore started and are currently conducting laboratory tests to understand the impact of modal noise in fibers in terms of radial-velocity measurement in general and on other systems, like e.g. our RV-reference module, in particular. We refer to Blind et al. (in prep.) for further details.

6. Conclusions

In this paper we have presented the design of a new infrared Fabry Pérot RV-reference module for SPIRou and we have described its key properties and spectral characteristics in detail. The primary objective was to build, test and finally operate a Fabry-Pérot-based RV reference module able to provide the needed spectral information over the full wavelength range of
SPIRou in order to measure instrumental drift to a precision of 30 cm s\(^{-1}\). It must be remarked that we have followed a quite strict top-down approach: 1) After establishing the requirements set by SPIRou we have 2) converted them into requirements for the RV-Reference module, 3) verified the assumption by analysis and simulations, 4) designed and manufactured the module according to the choices we had made, and 5) finally tested the key performances in laboratory. The obtained performances, at least this which could be verified in laboratory, demonstrated to be compliant with the requirements. Only the RV-stability requirements had to be postponed to a later stage when the SPIRou spectrograph will be ready for system tests. Nevertheless, we know by analogy with the HARPS-N RV-reference module, that we can expect an RV-stability well below 1 m s\(^{-1}\). In summary, we have been able to demonstrate that the SPIRou reference module can replace any cathode spectral lamp or absorption cell for drift measurements at relative moderate costs.

Our module also provides, over an extremely wide spectral range, equally-spaced spectral lines of uniform intensity, which could greatly help in measuring the detector geometry. Although the etalon does not have the intrinsic accuracy provided by an atomic transition and the mirror coatings may introduce slow variations of the phase (and thus causes group-delay dispersion, see Wildi et al. (2011)), it should be reminded that the line separation and position is perfectly smooth and continuous in wavelength. This information can be used to improve the wavelength solution, in particular to determine the higher-order terms of the polynomials used to describe the pixel-to-wavelength relationship, which are badly constraints by the sparse lines of hollow-cathode lamps only. In the absence of commercial and affordable laser-frequency comb covering the entire spectral range, we are currently investigating and implementing a combined use of hollow-cathode lamps and Fabry-Pérot calibration, the former providing the accuracy (or global wavelength ‘zero point’), the latter the detector geometry and the pixel-to-pixel and intra-pixel response. In fact, we are also considering the possibility of varying the line position of the Fabry-Pérot by changing the (low) pressure inside the vacuum tank, such to ‘scan’ and characterize the response of every detector pixel individually.

We can conclude that the presented RV-reference module for SPIRou is able to measure instrumental drifts at the required precision level and can replace the performance-limited hollow-cathode lamps and absorption cells with respect to this goal. Furthermore, we have identified possible developments and good potential to convert it into a calibration sources, which could turn the Fabry-Pérot based light source into a cost-effective alternative to laser-frequency combs, at least on the short and mid term.

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References

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