ELT -HIRES the High Resolution Spectrograph for the ELT: Fabry-Pérots for use as calibration sources

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ABSTRACT

High resolution spectroscopy enables the detection of atmospheres of exoplanets. To reach the required radial velocity precision of about 1 m/s, calibration with even more precise sources is mandatory. HIRES will employ several calibration sources, the most important ones are an Laser Frequency Comb (LFC) and Fabry-Pérots (FP). The LFC needs to be filtered with a set of FP. One possible solution is to illuminate this set of FP with a broadband light source and use them as calibrators, when they are not used for filtering the LFC.
It has been demonstrated that passively-stabilized FP can perform better than 10 cm/s per night. We give an overview of the currently used FP in different surveys and compare their individual features. For the FP which may be used in HIRES we discuss different configuration. We show that the Finesse and FSR of the FP needs to be optimized with regard to the resolution of the spectrograph and we outline how we aim to fulfill the requirements of HIRES.

Keywords: HIRES, Calibration, Spectroscopy

1. INTRODUCTION

1.1 Science drivers

One of the main driver in astrophysics for high resolution spectroscopy is the search for extrasolar planets. As a consequence more and more spectrographs designed for m/s wavelength precision become available. The radial velocity (RV)-method requires to observe the target at different epochs in order to extract a significant RV-signal. The RV-methods requires that the precision of a single spectrum in RV-domain has to be very high, up to 1 m/s. The accuracy of the calibration has to be stable over all epochs, or if this is not possible, it has to be known with a high precision. The detection of atmospheres on these planets require even higher single-spectrum precision and accuracy.

While the accuracy of the calibration can be tied to a frequency anchor like the GPS-signal or an atomic reference, the precision is more troublesome. Two fundamental challenges for frequency calibration of a single spectrum at this level are (1) provision of sufficient information to reach sub-m/s precision, i.e., a large number of lines, which can be determined with sufficient precision; and (2) uniform distribution of spectroscopic information across the astronomically useful frequency range without contamination of adjacent detector regions.

Spectra of hollow-cathode lamps (HCL) are typically heavily contaminated with gas emission lines often deteriorating the performance of the metal lines which are much narrower and stable but also very week. They can be

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used below 600 nm like with HARPS(-N) to avoid this. Cooler, redder stars, or to investigate the dependence of radial velocity shifts observations in spectral regions above 600 nm are needed. There strong gas emission lines pollute the detector significantly and pose serious problems to the strategy of simultaneous calibration using two fibers in parallel. As a solution, several projects added Fabry-Pérot (FP) etalons to their toolbox of calibration sources, e.g., HARPS,[1] CARMENES,[2] SPIROU,[3] and ESPRESSO[4] . As an example, the calibration strategy of CARMENES uses Uranium and Thorium HCL and FP spectra for both finding a daily pixel-to-wavelength calibration. The instrumental drift is tracked with FP using simultaneous calibration during nightly astronomical observations.

1.2 Calibration requirements

The science cases of HIRES include high precision and accuracy surveys. They require a wavelength calibration which can only be realised with a combination of laser frequency combs (LFC) and Fabry-Pérot etalons (FP).[5] The main requirements to the wavelength calibration flown down from the science cases are:

1. **Wavelength coverage**
   Over the bandwidth of HIRES (0.-1.8 μm) a calibration with known line positions of the respective wavelength standard should be possible. Equidistant lines with a separation of 2.4-5 (maximum) resolution elements are required to achieve the precision and accuracy aimed at. In order to achieve a good single spectral line precision the lines should remain unresolved.

2. **Precision and Accuracy**
   The precision on the level of the calibration unit should be 10 times better then the specifications for the spectrograph. Therefore, we aim at

   Accuracy better than 1 cm/s

   Precision better than 1 cm/s

   on the level of the calibration unit.

3. **Flat Spectrum**
   The variations in the line intensities must respect the dynamic range of the detectors in the spectrograph. Strong intensity variations over several orders of magnitude cause problems during simultaneous observation with science light. We aim at:

   line intensity variations $< 10^2$

4. **Intensity**
   The intensity should be high enough to allow for the shortest exposure time ($\sim$ 1 s). For longer exposure times (up to $30 min$) the intensity may be dimmed using filters. The intensity of each line needs to be stable during a measurement, since variations may cause spurious RV-signals.

Comparing these requirements to those of CU in other spectrographs (SPIRou,[3] ESPRESSO,[4] HARPS,[6,7] CARMENES[8]) shows that the CU might become a heritage but also new solutions have to be found. The concept of how these solutions work together is explained in Huke et. al.[5]

One of the important differences between an LFC and an FP is their degree of coherence. A coherent light source, like the LFC, is producing a different noise than a less coherent light source. This does count for the light pollution inside the spectrograph and even more for the fiber modal noise.[9] As a consequence, for simultaneous calibration it is preferable to use a light source with a degree of temporal coherence comparable to the star light. Therefore, FP are mandatory for the simultaneous calibration in HIRES.

Here, we want to describe the solutions regarding the FP. In the following section we will give a short introduction to practical aspects of FP and a comparison between FP used in high-accuracy RV surveys. Different configuration of the FP for HIRES are possible and will be discussed in section 3. In section 4 we show, how we verify the precision and accuracy of FP using a Fourier-Transform-Spectrograph and an LFC.

2. ASTRONOMICAL FABRY-PEROT

Fabry-Pérots (FP) were invented by C. Fabry and A. Pérot in the beginning of the last century for astrophysical applications.[10] Their intention was to use an FP as a tuneable filter by changing the length of the FP. With this device they were able to record star-spectra with much higher resolution previously. The FP itself does not come with an absolute wavelength solution for its resonances and calibration was done using atomic standards (Cd-lines). The transmission of a symmetric FP, consisting of two plane mirror with identical coatings, can be calculated by the well-known FP-equation:

$$I_T = I_0 \frac{T^2}{(1-R)^2} \frac{1}{1+F\sin^2(\Psi/2)^2}. \tag{1}$$

with I_0 as the incident intensity; T, R: Transmission, Reflection coefficients for the mirrors; $F = 4R/(1-R)^2$: Finesse coefficient; Maxima occur at $\Psi = 2\pi n$, with n being an integer. The phase function is defined as

$$\Psi = 2\pi(2d\cos(\theta))/\lambda_0 + \epsilon. \tag{2}$$

with d as the optical distance between the two mirrors; θ the angle of incidence; λ_0:= wavelength of the incident light; and ϵ as factor for the correction of the phase changes. If the wavelength of the incident light is scanned over an FP mode, the reflected phase changes from $-\pi$ to π. The transmitted intensity is, for the most applications, not affected. If only light parallel and close to the optical axis of the FP is looked at the angle of incidence can be approximated to zero. For a symmetric FP two degrees of freedom are left:

- d the optical distance between the mirrors, defining the free spectral range between resonances

$$FSR = \delta\Psi = 4\pi d\delta\lambda/\lambda_0^2 \tag{3}$$

- R the reflectivity of the mirrors in the bandwidth where the FP will be used, typically expressed in terms of the finesse

$$\mathcal{F} = \frac{\pi}{2}\sqrt{F} = \frac{\pi\sqrt{R}}{1-R} \tag{4}$$

$\mathcal{F}$ is often called the effective number of round-trips a photon does in the FP. It controls the resolving power of an FP. Both together determine the width of the resonances $\mathcal{F} \approx FSR/\sigma$ with σ as the FWHM, see fig. 1.

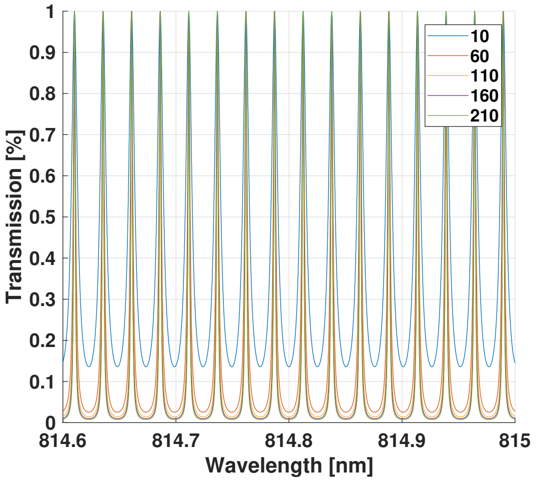

Figure 1. Spectrum of the normalized transmission of simulated FP with equal FSR but different Finesse $\mathcal{F}$. The linewidth increases with decreasing $\mathcal{F}$.

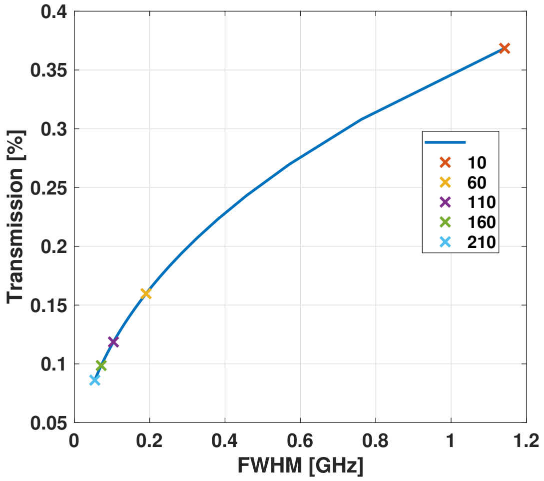

Figure 2. Transmission of simulated FP with equal FSR but different Finesse $\mathcal{F}$. The transmission is calculated using a normalized spectrum and constant R.

2.1 Practical Considerations

With these two parameters the FP can now be designed for astrophysical application. The FSR should be chosen so that the resonances can be clearly distinguished from each other in a spectrum taken with an astrophysical spectrograph. Depending on the Finesse the resonances should be sampled at minimum every 2.3 resolution elements (requirement in HIRES). As can be seen from fig. 1 for a low finesse $\mathcal{F}$ the minimum between two modes is significantly raised, so that a background is created. This may affect the fitting of the resonances in the data reduction pipeline. For a low finesse a higher FSR is needed. On the other hand, the FSR should not be too high, since each line contributes to the RV-precision of the whole spectrum and the local precision between the lines becomes bad. However, eq. 3 states that the FSR decreases with rising wavelength λ_0, so that the sampling decreases. Since the FSR is controlled by the distance d of the mirrors it also poses technical problems, if d is too small.

The finesse $\mathcal{F}$ is also restricted by two requirements. $\mathcal{F}$ should be not too high in order to transmit enough light that the FP can be used as a calibrator. In fig. 2 is shown the effective transmitted portion of the incident intensity. However, if the width of the lines become too broad, the RV-content of each line is getting small. Thus narrow lines are more useful, but this is limited by the resolution and sampling of the spectrograph. If the sampling, the pixel per resolution element of the spectrograph, is high enough and the lines are much narrower than the instrumental line shape (ILS), the lines are unresolved. Their true shape become less important and the ILS may be measured over the whole spectral range. This is advantageous for the fitting of the lines and increases the precision of the spectrum in RV-domain. A high sampling also means to either use large detectors or to measure over a small spectral bandwidth. Typically, the sampling is rather low (i.e. 2 pixel per resolution element) and the lines become undersampled. The narrow lines are not feasible any more and broader lines allow for a better fitting result.

Another drawback from a high Finesse is the requirement it sets to the reflectivity of the mirrors. Typically, a high Finesse means to have a small bandwidth in which the FP can be used because the reflectivity varies strongly, depending on the design of the coating. While a simple metallic coating allows for a broad bandwidth it also comes with a high group delay dispersion (see next subsection) and the reflectivity can not be designed to the needs of the spectrograph. On the other hand, dielectric coatings are often, but not always, "soft" and deteriorate over time, especially in vacuum. As a consequence the resonances of the FP may move. Typically, the bandwidth reduces with rising finesse. Since using more calibration sources on a certain bandwidth is causing more trouble in the wavelength solution a larger bandwidth is preferred.

Schaefer et. al.[2] showed that the stability of the position of the resonances is strongly influenced by the optical path inside the FP d in eq. 3. As a consequence, most astro-FP are enclosed in a vacuum-pumped tank with a temperature stabilization. Only using this equipment, they were able to reach a spectral stability over night on the order of 10 cm/s. In table 1, we give an overview on FP used as calibrators for different spectrographs.

Table 1. Properties of FP used as calibrators for different spectrographs.

	CARMENES VIS	CRIRES+	HARPS	ESPRESSO	SPIROU
bandwidth $\lambda - \lambda$ [μm]	0.6 - 1.0	0.95 - 2.5	0.38 - 0.68	0.38 - 0.78	0.9 - 2.4
FSR [GHz]	15	30	20	20	12
Finesse	8-10	4	4	12	13
Resolved peaks	yes	yes	yes	yes	yes
Coating	soft	hard	soft	soft	hard
Spec. Stability [cm/s per night]	10	$75 \cdot 10^2$	10 - 20	10 - 20	10 - 20
Tank enclosure	yes	yes	yes	yes	yes
Vacuum [mbar]	0.00001	1	0.01 - 1	0.01 - 1	0.01 - 1
Op. Temperature [^{o}C]	13	10	20	20	20
T. precision [mK rms]	15		5	5	5

3. FP CONFIGURATION FOR HIRES

HIRES is a high resolution spectrograph with a large wavelength coverage. Its wavelength solution should be fixed at as many points as possible. A minimum FSR between these lines would be 2.4 resolution elements. Since the resolving power of the spectrograph is fixed to $R = 100.000$, the FSR in terms of frequencies has to decrease with increasing wavelength.

There are two types of calibration sources, which can be adapted to the needs of HIRES: The LFC and the FP. The LFC will have a repetition rate of $f_{rep} = 1$ GHz and FP for filtering to the optimum FSR are foreseen. Due to the large bandwidth a set of eight FP is needed for filtering, see fig. 3, complementing the eight cameras contained within HIRES. Each FP coating will overlap in the wings to prevent edge effects. This set of FP will be dither-locked to the LFC in their respective bandwidth. Obviously, the set of FP which may be used for calibration and the set of filter FP have the same requirements with regard to the spectral coverage and their FSR. Due to the high repetition rate of the LFC the finesse of the filter FP can also be rather low. Simulations show that the FP can be optimized for both needs, see table 2 and fig. 3. However, one disadvantage of the use of the filter-FP as calibrators is that they can not be used simultaneously with the LFC. As a consequence the cross-referencing between the sources becomes more difficult. However, the mutual use simplify the setup a lot and may be rewarded by a higher precision during simultaneous observation and calibration.

Table 2. Configuration of FP for optical filtering of the LFC. The FSR is optimized for each FP to come as close as possible to the value of 2.4 resolution elements/line for the blue end of the respective spectral bandwidth. The Finesse F remains a design parameter as it defines the width of the lines.

No.	$\lambda - \lambda$	FSR	F	Res. Elem./Line
1	390 - 470 nm	22 GHz	153	2.60 - 3.14
2	450 - 565 nm	19 GHz	153	2.55 - 3.18
3	540 - 680 nm	16 GHz	153	2.52 - 3.18
4	660 - 840 nm	13 GHz	153	2.64 - 3.36
5	820 - 960 nm	11 GHz	153	2.73 - 3.20
6	940 - 1140 nm	9 GHz	153	2.51 - 3.04
7	1120 - 1410 nm	8 GHz	153	2.62 - 3.29
8	1400 - 1810 nm	6 GHz	153	2.80 - 3.62

Another difference is, that the FP for filtering should be free-space, i.e. not fiber-fed. If this set is going to be used as a calibration source with white light illumination, either the FP have to be actively stabilized or they must be put in a thermally stabilized vacuum tank with windows. Active stabilization can be achieved using the same locking technique as for the filtering (see below). In order not to pollute the spectrum with comb lines the dither locking can be done in a spectral bandwidth where the respective FP is not used. This is one of the reasons why they overlap at the edges. They also overlap on the different detectors used in HIRES to allow for a higher consistency between their spectral ranges.

3.1 Filter FP

FP filtering of the dense mode structure of a parent frequency comb requires careful design of the mirror coatings, stabilization mechanism, and the FP cavity itself.[11]

The transmission function of a FP cavity (eq. 1) includes a phase term ϵ which describes the dispersive properties of the mirror coatings. For coatings with high reflectivity (>98%), high finesse (>150) or broad bandwidth (>100nm), undesired oscillations in the mirror group delay (GD) and group delay dispersion (GDD) must be taken into account to prevent systematic misalignment between the regularly spaced comb modes and the FP FSR. The leading technical solution[12] is to employ cavities comprising complementary dielectric coatings, designed to provide zero GDD (and therefore flat GD) across the desired spectral bandwidth. The coating design process can also take into account the air dispersion introduced in the FP, providing high fidelity mode filtering without FSR misalignment.[13] An example of such a coating is shown in Fig.7 in appendix A.

Active stabilization of FP cavities is required to maintain high fidelity throughput of the filtered comb lines.

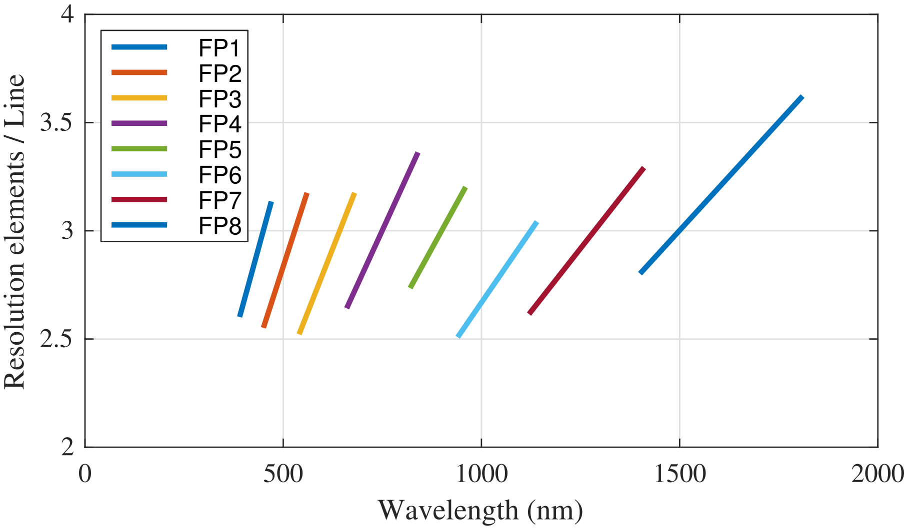

Figure 3. Resolution element per lines for all six FP used for comb-filtering. The FSR of each FP is chosen to start with one line every 2.4 resolution elements, a bit smaller as in table 2, where the FSR has to be a multiple integer of the initial comb FSR (1 GHz). The distance between subsequent FP modes increases in wavelength range.

Stabilization can be through the Pound-Drever-Hall method, in which the cavity is stabilized using a narrow-linewidth CW laser that is itself locked to a comb tooth. This method requires the FP cavity mirrors to have high reflectivity at the wavelength of the CW laser, with the additional requirement that the net GD for the filtering region and the CW wavelength are the same. A second method is to stabilize the cavity directly to the comb[14] using the dither locking technique, with nm-level cavity stabilities achievable over many hours without the need to reacquire lock. A caveat of this system is an ambiguity in which subset of comb modes have filtered by the cavity, which can be resolved using a Fourier transform spectrometer (FTS).[15]

The mechanical design of the LFC FP cavities emphasizes stability in the mirror separation (to achieve the precise FSR) and the angular alignment (to maximize the cavity finesse). While monolithic designs comprising HR coated low-thermal-expansion substrates are inherently stable, the material dispersion introduced in such cavities precludes their use across the entire spectral range of HIRES. Another highly-stable approach is to employ cage-mounted optomechanics housed within an environmental housing. The use of thin ($\leq$2mm) wedged mirror substrates enables high-speed locking with appropriate ring piezoelectric actuators without spurious back surface reflections. Such designs are mechanically stable when heated above room temperature, with all components lockable to prevent drift; active alignment can be implemented using piezo-controlled optomechanics, although with added complexity and increased cost.

4. REFERENCING FP WITH AN FTS

While the specified stability (line six in table 1) of most FP used as calibrators is on the order of 10-20 cm/s per night, the true drift may be higher. This is difficult to measure with an astronomical spectrograph. Therefore, we use a commercial FTS in double-sided symmetric mode. The IFS 125HR comes with a fixed arm which is 50 cm long. This limits the symmetric mode to +/- 50 cm. The resolution can be approximated to of $\delta f \approx 340$ MHz in terms of frequencies.

The wavelength-solution of our FTS is referenced to a frequency-stabilized HeNe-laser. Its light travels parallel to the science light and should not disturb the science light. The interference signal of the reference laser is captured with two photodiodes. The signal is used to calibrate the optical path length difference (OPD) between the arms of the FTS while changing the length of one arm. However, this reference strategy has two disadvantages:

- stray light of the reference laser hits the science detector and pollutes the interferogram / spectrum.
- the drift of the laser causes spectrum to spectrum drifts on the order of 10-20 m/s.

To eliminate the drift of the HeNe, we measure the light of an LFC (Taccor comb 1 GHz from Laser Quantum) in one part of the spectrum, from $\sigma\sigma \approx 9. - 12.000$ cm^{-1}. The other part of the spectrum $\sigma\sigma \approx 12.000 - 18.000$ cm^{-1} is used to measure the light of an FP (), see fig. 4. The two free degrees of freedom of the LFC, the repetition rate f_{rep} and the carrier envelope offset frequency f_{CEO} are stabilized with closed loops and measured simultaneously with a frequency counter (Scientific Instruments UCA6200). The closed loop controls and the frequency counter are tied to a GPS signal (antennae: Menlo Systems GPS-8). The achievable stability is on the order of 10^{-10} in 10s, the same as the GPS-antennae.

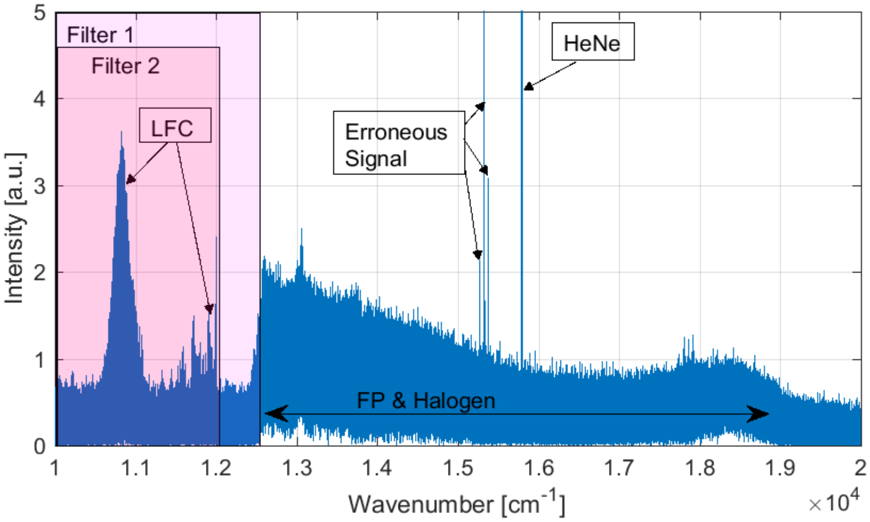

Figure 4. Spectrum taken with a commercial FTS (IFS 125HR, Bruker Optics). The LFC is filtered with two dichroics to reduce its intensity. The FP is illuminated with a Halogen-lamp. Due to the structure of the interferogram error signals appear. The signal of the reference-Laser (HeNe) is up to 100 times stronger than the rest of the spectrum.

Thus, the LFC can be used to calibrate the spectrum. However, the low resolution results in a spectrum where the lines of the LFC are unresolved. As a consequence, the instrumental line shape is sampled with only three points. Due to its structure (a sinc-function) it causes ringing, which results in a background in the LFC-part of the spectrum, see fig. 5. Due to this effect the fitting of the lines becomes difficult.

The high intensity of the LFC in comparison to the FP illuminated with a halogen lamp, renders the use of two filter stages necessary. Still, the LFC pollute the FP spectrum, see. fig. 6. Due to these effects we achieve at the moment only a precision of ~ 1 m/s.

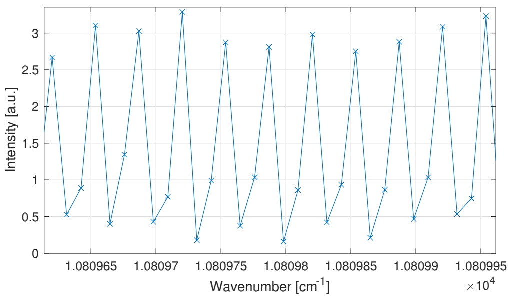

Figure 5. Part of the LFC spectrum. The lines are unresolved and only the instrumental line shape (ILS) broadens the spectral lines. Due to the background introduced by the ILS the lines are difficult to fit.

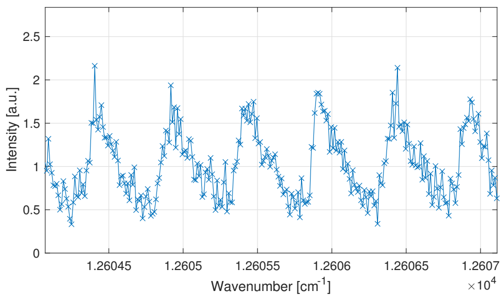

Figure 6. Part of the FP spectrum. The FP modes are well resolved and much broader than those of the LFC. Small lines from the LFC pollute the FP spectrum and they need to be removed.

5. SUMMARY

The requirements of HIRES to its calibration unit are challenging. As a consequence the calibration sources have to be designed deliberately. While the prime wavelength calibration needs to be done with a LFC, the simultaneous calibration during science operation will be realized using Fabry-Perots. Therefore, we show a comparison of the FP already in use for astrophysical applications. Based on this and the possible dual use of the FP for filtering the comb we developed a set of specification for the FP which may be used in HIRES. We show how we will verify the stability of FP using an FTS which is simultaneous calibrated with an LFC.

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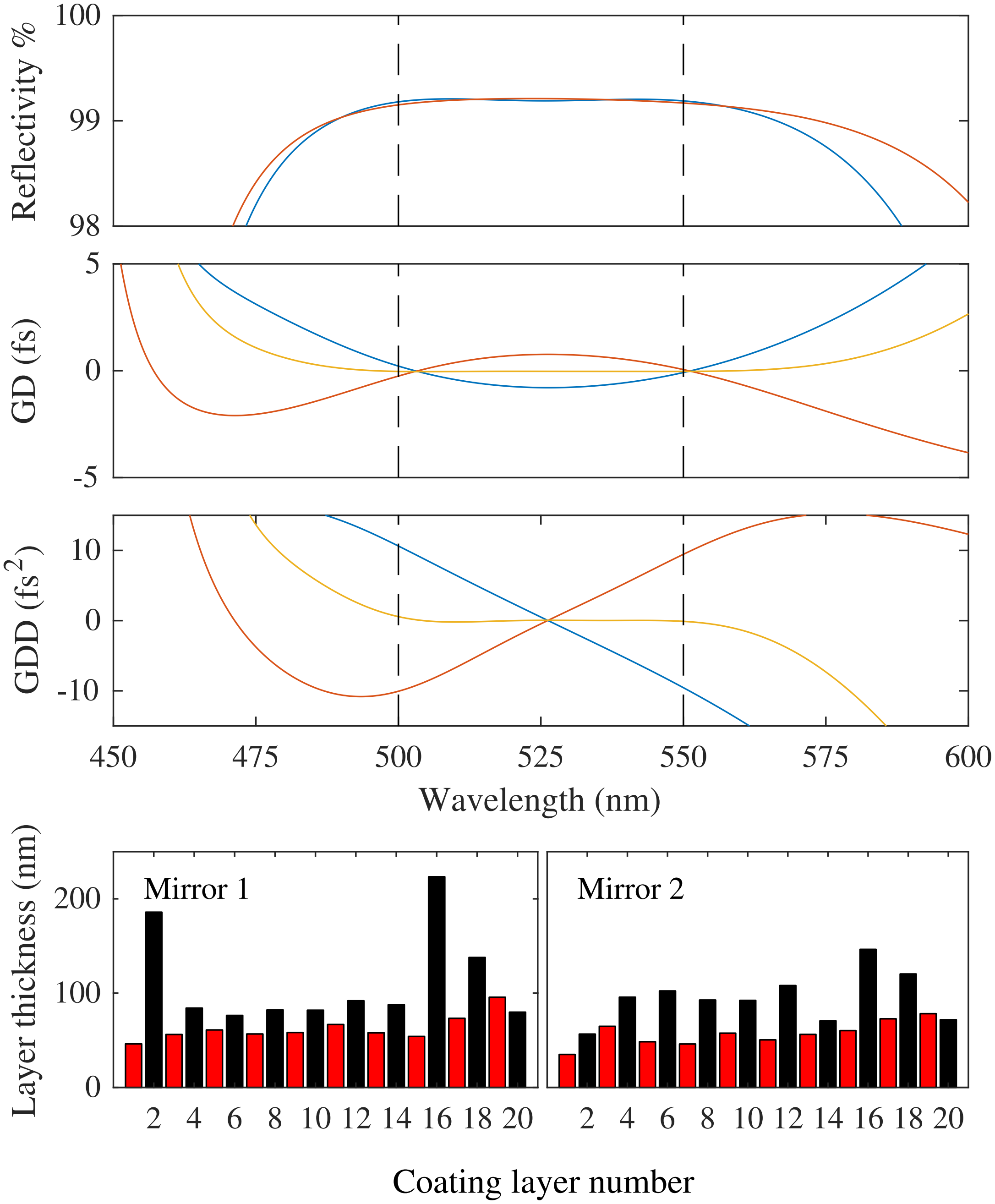

Figure 7. Example FP coating comprising a pair of complementary dispersion controlled mirrors. Upper panels: mirror reflectivity (top), optimized over 500-550 nm; Net GD, including air dispersion (middle); net GDD (bottom). Lower panels: Dielectric layer thicknesses for the two mirrors comprising the dispersion balanced FP. High-index layers are shown in red, with low-index layers in black.