Referenced Fabry-Pérot Etalon for the precise wavelength calibration of spectro-velocimeters

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Context and objectives

The Doppler measurement consists in determining the wavelength of an identified spectral line and comparing it with the theoretical value it would have when transferred into the solar system's rest frame. The Doppler equation links the measurement to the theoretical wavelength via the relative velocity vector, finally delivering the projection of this vector in the direction of the line of sight (radial velocity). In order to increase the precision, the average over several thousands of spectral lines is computed. It should be noted, however, that the radial-velocity measurement is affected by several potential error sources that have been discussed extensively[1,3,7,8]. The main error sources are: photon noise[3,9], instrumental errors[2,3,7], spectrograph illumination effects[10,11], spectral contamination[7,12], and stellar 'noise'[13-27], commonly referred to as stellar jitter. The term stellar jitter masks various stellar causes that produce radial-velocity effects at all time scales and of different magnitude. The discussion of all these effects lies again beyond the purpose of our review. Nevertheless, it shall be reminded that stellar jitter is probably the strongest limitations for Doppler velocimetry when aiming at sub-meter-per-second precision.

Present and future Doppler spectrographs will have to address the mentioned limitations. As a first step it will be necessary to increase the telescope size, since high spectral resolution measurements are photon-starved, even for relatively bright targets. The gain obtained with a large telescope is however easily lost if spectral resolution is low. In fact, for unresolved spectral lines, the measurement precision increases significantly with increasing the spectral resolution[9]. In the photon-noise limited regime the error $\varepsilon_{\mathrm{bary}}$ on the line-centre measurement can be estimated to

$$\varepsilon_{\mathrm{bary}} = \frac{\sqrt{\sigma^2}^{1.5}}{\sqrt{2 \cdot I_0 \cdot EW}} \cdot \sqrt{\left(1 - \frac{c}{2}\right)},$$

where σ is the measured width of the spectral line as seen through the spectrograph, $c = (I_{min} - I_0)/I_0$ is the measured line contrast and $EW = \sigma\, c$ the equivalent width. I_0 and I_{min} designate the photoelectron counts per resolution element in the continuum and the line minimum, respectively. It must be noted that the resolution element can be represented either by the detector pixel or the wavelength unit as long as all the parameters are expressed in the same units. It is commonly agreed nowadays that a spectral resolution of at least $R := \lambda/\Delta\lambda$ = 100,000 should be used in order to guarantee the best precision on slowly-rotating, quiet, solar-type stars. Spectral resolution and adequate line sampling not only allow us to achieve better signal-to-noise per spectral line, but also to reduce possible instrumental errors in both the radial-velocity measurement and the calibration process. To first order, instrumental errors scale with the size of the resolution element (expressed in wavelength units). Unfortunately, with increasing telescope size, spectral resolution is a considerable cost driver. For seeing-limited instruments the optical etendue E ($E = A \times \Omega$, i.e. the beam cross-section area times the solid angle) increases with the telescope size, and so does the instrument size if the spectral resolution is kept fixed[6]. In the era of 8-m class and extremely-large telescopes (ELTs), this aspect has become a technical and managerial challenge that is nevertheless successfully addressed by employing novel optical design concepts.

All the future projects for radial-velocity spectrographs aim at detecting rocky planets in the habitable zone (HZ)[29] of a solar-like and low-mass star (a distance to the star at which liquid water can persist on the surface of the planet). In order to attain this objective they must be photon-efficient and precise to the sub meter-per-second level. Photon efficiency is obtained with optimized designs and high spectral resolution. High precision requires also the control of all instrumental effects. It has therefore become state-of-the-art to design stable instruments[28]. Gravity invariance and illumination stability of the spectrograph are critical aspects that can only be obtained through a fibre feed[30,31]. Despite the intrinsic light scrambling properties of optical fibres[32-34] it was soon realised that the illumination produced by a circular optical fibre depends on how the star is fed into the fibre. In other words, motions of the stellar image at the fibre entrance would produce a change in the illumination of the spectrograph and mimic a radial velocity effect. A considerable effort was invested in improving image scrambling by employing double scramblers[32,4] and octagonal fibres[35,36]. Effective improvements have already been demonstrated on operational instruments[37,38].

Any kind of effect that introduces a distortion or a shift of the spectral line in the detector-pixel space will be interpreted, if not perfectly monitored, as a wavelength change and thus a Doppler shift[7]. Two methods of tracking the instrumental-profile changes have successfully been applied in the past: The first is to superimpose an absorption spectrum of a reference gas cell[1,3,39] on the stellar spectrum, such that the instrumental profile (IP) is continuously measured. The so-called self-calibration technique is particularly useful and effective in spectrographs with varying instrument profile, as in the case of slit spectrographs. The disadvantage of this technique is the restricted bandwidth of the gas-cell spectrum, the loss of efficiency due to absorption in the light path, and the necessity for a sophisticated de-convolution process in order to recover the stellar spectrum and thus the radial velocity. This latter step requires the introduction of many additional parameters for spectral modelling. In order to obtain a given precision higher signal-to-noise spectra must be acquired. The second method, the so-called simultaneous reference technique[4,5], is conceptually opposite. It assumes a stabilized IP that does not change between two wavelength-calibrations of the spectrograph, such that the determined relation between the detector pixel and the wavelength remains valid over these time scales (typically a night). A second channel carrying a spectral reference is continuously fed to the spectrograph to monitor and correct for potential instrumental drifts or IP changes. It must be guaranteed, however, that the changes suffered by the scientific and the reference channels are identical over timescales of one observing night. Therefore, the whole design of the instrument must be optimized for stability, requesting fibre feed and light scrambling, as well as pressure, mechanical, thermal and optical stability. The effort is compensated by an unrestricted spectral bandwidth and the acquisition of an 'uncontaminated' scientific spectrum.

Although, in the case of the self-calibration technique, the instrument profile is supposed to be recoverable by de-convolution, there seems to be general agreement on the fact that low-order instrument-profile changes must be avoided in any case and that a stable instrument will eventually deliver more precise measurements. There is also agreement on the need for better calibration sources. The laser-frequency comb[40-45], when available at full potential, will provide the aimed calibration accuracy and precision. In the meantime, alternative sources are being developed, as for example passive Fabry-Pérot cavities[46-48] for simultaneous reference, or actively stabilized Fabry-Pérot systems for wavelength calibration[49].

Tasks

The execution of the following sequence of tasks is proposed for the master thesis. It should be noted that tasks 3 to 5 can be discussed with Federica Cersullo, who has already executed part of it. It is important to understand the results, do the own program to reproduce the results, and modify whenever needed. The duration of execution of these tasks should be kept as sort as possible, however. Finally, it should be noted that the sequence below is given as a reference. It can and must be adapted in a interactive discussion with the director.

1. Study the literature related to the theory of Fabry-Pérot Etalon and wavelength referencing. (ALL)
2. Describe the transmittance function of a theoretical and a 'real' Fabry-Pérot etalon as a function of wavelength and considering the finite fiber diameter (angular units), surface quality, and coating reflection. (Pepe, Cersullo)
3. Understand the evolution of the Finesse as a function of fiber diameter (angular units) and departure from the perfect alignment on the optical axis (angular units). (Cersullo)
4. Compare real data obtained with HARPS and HARPS-N to the theoretical data and discuss differences. (Pepe)
5. Plot the effective (measured equivalent) Etalon Gap (spacing) as a function of wavelength using the wavelength calibration delivered by the thorium calibration. (Cersullo, Chazelas)
6. Propose a concept for referencing the existing Fabry-Pérot etalon to a gas cell. The development kit proposed by Thorlabs shall be integrated in the concept. Propose also an optical layout. (Wildi)
7. Order the essential components. (Wildi)
8. Characterize the ESPRESSO Fabry-Pérot étalon with the optical spectrum analyzer and compare the performances to the theoretical values. Discuss possible changes and improvement in view of a referencing or stabilization. (Cersullo, Pepe)
9. Prepare the laboratory set up, install and test components. (Wildi)
10. Measure the relative changes of the Fabry-Pérot spectrum to the reference spectrum and chacaterize the measurement precision and typical frequencies. (Wildi, Pepe)
11. Propose, if possible, a concept for active stabilization. (Wildi)

Master thesis manuscript

The master thesis manuscript must be concise but contain essential and complete information concerning the Master thesis work. It is not intended to review the whole domain of exoplanets, although an introduction will be appreciated. More important, however, is a description of the context and the objectives for this work. A possible table of contents could be:

1. Introduction (to the field)
2. Objectives and context (of the master thesis)
3. Theory of the Fabry-Pérot etalon
4. Laboratory characterization of the ESPRESSO etalon
5. Concept for precisely referencing a low-Finesse etalon
6. Laboratory setup and tests of the referencing system
7. Results and summary
8. Prospectives

A few personal suggestions for the manuscript:

- Sometimes less is more. It is more important to be precise than extensive.
- Plots are fundamental. In order to be useful, however, they have to be thought though in terms of ‘what do I want to show’. Make sure the plot axis are clear and the unit correct and meaningfull. Label and axis must be easily readable. The caption must contain (all but only) the description of what is seen on the plot. The discussion is made in the text.
- Start very soon with filling the manuscript with text, do not wait the master thesis to be finished to start writing. As soon as you have something to write, put it directly in your draft manuscript such that information won’t be lost.

We wish you all the best. François and Francesco

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