Astronomical Spectrograph Calibration at the Exo-Earth Detection Limit

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Following the development of the laser frequency comb which led to the 2005 Nobel Prize in Physics, we began investigating the possibility of using this novel technology for precise and accurate spectrograph calibration. A programme was begun, aimed at demonstrating the capabilities of laser frequency combs (LFC) when coupled to an astronomical spectrograph. In the last three years we have tested an LFC connected to HARPS at the 3.6-metre telescope in La Silla, the most precise spectrograph available. Here we show the very promising results obtained so far, and outline future activities, including the provision of an LFC system for routine operation with HARPS, to be offered to the community in the near future.

The most widely used wavelength reference in astronomical spectroscopy, the thorium–argon (Th-Ar) lamp, can achieve a precision on the determination of individual line positions of several tens of metres per second (m/s). The uncertainty in the wavelength of a spectral line can either be expressed as an absolute wavelength (such as in Å), as a fractional wavelength, e.g. 10^{-7}, or by scaling by the speed of light to express it in m/s. The limitation on Th-Ar wavelength precision is due not only to the measurement process (Palmer Engleman, 1983), but also to the production method (contamination) and aging of the lamps. Even when averaging over a wide spectrum with say, 10 000 lines, measurements are limited to an overall precision of 10^{-9} at best (the achievable precision is furthermore degraded by line blending, and non-uniform density of the Th lines across the spectrum).

This precision in the measurement of the positions of spectral lines is not sufficient for various compelling science cases:
- the measurement of the variation of the fundamental constants, which requires a precision at least as good as the precision with which the constants are determined; for the best known (the proton to electron mass ratio and the fine structure constant) this is ~ $3–4 \times 10^{-10}$ (Beringer et al., 2012);
- the amplitude of the recoil motion imprinted by the Earth on the Sun is ~ 9 cm/s. The radial velocity detection of an extrasolar planet with the mass of the Earth in a 1 AU orbit around its solar-type star therefore requires a measurement precision of about 3 cm/s, or 10^{-10};
- the direct measurement of the expansion rate of the Universe, which can constrain the cosmological parameters that define the metric of the theory of gravity, requires a measurement precision at the level of cm/s (10^{-10}) for over ten years (Liske et al., 2008).

The new class of giant telescopes with greatly increased light-collecting power will naturally ease the photon noise limitation to high precision spectroscopy by a factor of five to ten. A new calibration source is therefore needed, which enables these science cases and capitalises on the great opportunity that giant telescopes open up for high precision spectroscopy. The ideal calibration source would be at least ten times more precise than Th-Ar lamps allow and would have many unblended lines, with approximately the same intensity and equally spaced across the spectrum. The obvious choice is the laser frequency comb.

For the measurement of frequencies, LFCs represent the ultimate level of precision, as they are locked to the energy level of a well-known atomic transition via an atomic clock. They are the most precise time-keeping devices, and the unit of measurement of time in the International System (SI), the second, is defined by the caesium transition via a caesium atomic clock. LFCs have many applications, from metrology and precise time-keeping to laboratory atomic and molecular spectroscopy. Now the period is beginning when LFCs will "look at the sky".

The demonstrator programme

In 2006 ESO approached the group of Prof. Theodor Hänsch at the Max Planck Institute for Quantum Optics (MPQ), to study the possibility of using an LFC for the calibration of high-resolution astronomical spectrographs. Due to its unsurpassed stability, HARPS at the 3.6-metre telescope in La Silla provided the best candidate to validate the performance of this technique (Mayor et al., 2003). A fruitful collaboration was initiated between ESO, MPQ and Menlo GmbH, a spin-off company from MPQ which markets LFCs, with the goal of demonstrating the feasibility of operating an LFC to calibrate an astronomical spectrograph, thus opening up a new horizon for the current and next generation high-precision, high-resolution spectrographs.

The demonstrator programme started in 2007 (Araujo-Hauck et al., 2007) and concluded in 2011. In this period a prototype LFC dedicated to astronomy (or astro-comb) was developed and refined. The astro-comb was tested in the laboratory; in the infrared (IR) regime on a telescope for the first time (Steinmetz, 2008); to validate technical solutions; and in four campaigns in the visible, with HARPS at the 3.6-metre telescope in La Silla, to test the global performance (Lo Curto et al., 2010; Wilken et al., 2010; Wilken et al., 2012).

An LFC consists of thousands of equally spaced frequencies over a bandwidth of several THz. It is based on the properties of femtosecond (fs) mode-locked lasers. The frequency difference between two neighbouring lines corresponds to

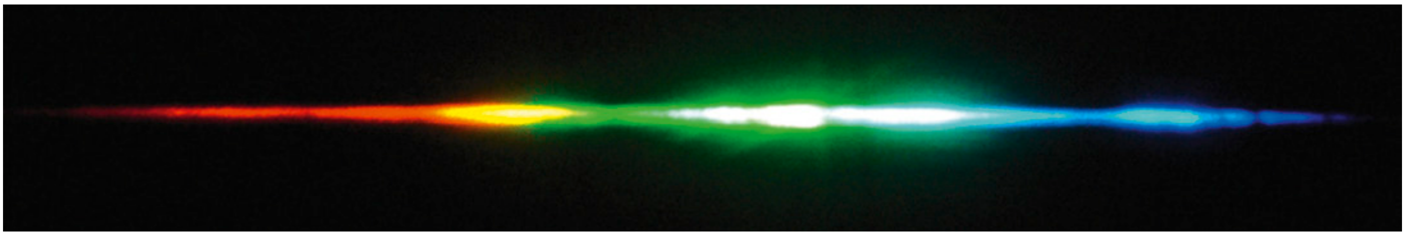

Figure 1. The spectrum of the LFC dispersed by a low-resolution grating and projected on a wall. The individual lines are not resolved and only the continuum is visible: its spectral structure is due to the spectral broadening stage and can be flattened out by a spatial light modulator (SLM).

the repetition frequency (f_{rep}) of the pulsed laser and is therefore constant across the comb spectrum. The entire LFC spectrum can be described by the simple equation $f = f_{off} + n \cdot f_{rep}$ where f_{rep} is the repetition frequency, i.e. the distance in frequency between two adjacent lines, and f_{off} is the "offset frequency" that can be interpreted as a "zero point"; n is a large integer which projects the radio frequencies f_{off} and f_{rep} into the visible domain. Since all frequencies used in the system are radio frequencies, they can be stabilised to an atomic clock using well-established electronic phase-locking techniques. In this way, each optical frequency obtains the accuracy and long-term stability of the atomic clock.

An LFC acts like a gear, transferring the precision of atomic clocks from the microwave regime to the optical. LFCs are the ideal calibrator for astronomical spectrographs if they can cover the spectral bandwidth of the spectrograph with a sufficiently flat spectrum and if their line spacing is adapted to the spectrograph's resolution. While there are several proposed frequency comb systems that will match the criteria for a spectrograph calibrator, our choice has been to use a fibre-laser-based LFC. Fibre lasers are technically mature and turn-key systems that are commercially available. When using Yb-fibre lasers, high-power amplifiers can be employed and the second harmonic of the central wavelength (1030 nm) is in the centre of the desired wavelength range for a spectrograph in the visible. However, the required fibre length limits the round-trip time in the oscillator, and thus the line spacing of the laser (its pulse repetition rate) is currently limited to roughly below 1 GHz.

Although an LFC based on fibre lasers is essentially an off-the-shelf product, its adaptation for use in an instrument like HARPS requires major developments. The basic turn-key LFC systems available on the market today deliver a comb of lines centred at 1025–1050 nm, with a repetition frequency of 250 MHz and generally cover only few nanometres in wavelength. Resolving spectral lines 250 MHz apart in the visible range requires a spectral resolution of more than six million, which is not practical for the typical use of an astronomical spectrograph. An LFC with such a line spacing would appear as a continuum source to instruments such as HARPS or UVES (see Figure 1).

New developments are needed to operate an LFC on an astronomical spectrograph in the visible with a spectral resolution of ~ 10^5:

1) increase the repetition frequency to ~ 18 GHz;
2) double the frequency of the spectrum to have it centred in the visible at ~ 520 nm;
3) broaden the spectrum to increase wavelength coverage.

These are the three steps where most of the efforts of the programme have been focussed.

Towards an LFC for astronomy

High finesse Fabry-Pérot cavities (FPCs) acting as periodic, high-resolution spectral filters can be used to increase the line spacing by transmitting only modes (lines) that are phase-shifted by an integer number of wavelengths and suppressing the intermediate ones. After this first step, the spectrum of the LFC undergoes two nonlinear processes: one for frequency doubling and one for spectral broadening. The challenge is to combine the frequency conversion and the high pulse repetition rate. A high repetition rate corresponds to low pulse energies that are detrimental to nonlinear conversion processes. The approach to overcome this dilemma employs two key components. First, a comb system based on an Yb-fibre laser enables the use of Yb-fibre high-power amplifiers to reduce the problem of low pulse energies. Second, when using specially designed photonic crystal fibres (PCFs), relatively low pulse energies are sufficient to obtain spectral broadening.

Another challenge comes at the FPC filtering stage and arises from the fact that the nonlinear processes (interactions between photons) in the PCF can amplify spectral lines that were intended to be suppressed. We saw this effect during our first test run in La Silla. The solution was to employ more FPC cavities, essentially one of them replicating the suppression of the unwanted modes, and with a higher finesse. Finally in our system we used three FPCs in series to guarantee a sufficient suppression of the intermediate lines. A series of four FPCs was also tested, but no improvements were noticed from the fourth cavity. The line spacing is increased to 18 GHz, which is well resolved by HARPS (the instrument has an intrinsic resolution of ~ 5 GHz).

After the last FPC a fibre amplifier is employed that can deliver up to 10 W to facilitate the subsequent nonlinear processes. The spectral bandwidth after these amplifiers suffers from re-absorption and gain narrowing. The initial 50 nm wide spectrum reduces to a 3 dB bandwidth of only 20 nm after the high-power amplifier. After re-amplification, the frequency of the light is doubled by a second harmonic generator (SHG), and finally injected into the PCF for spectral broadening. The broadening is a highly nonlinear process (four-wave mixing), and so the intensity distribution in the final spectrum can vary. For this reason, in the last test run, a spatial light modulator

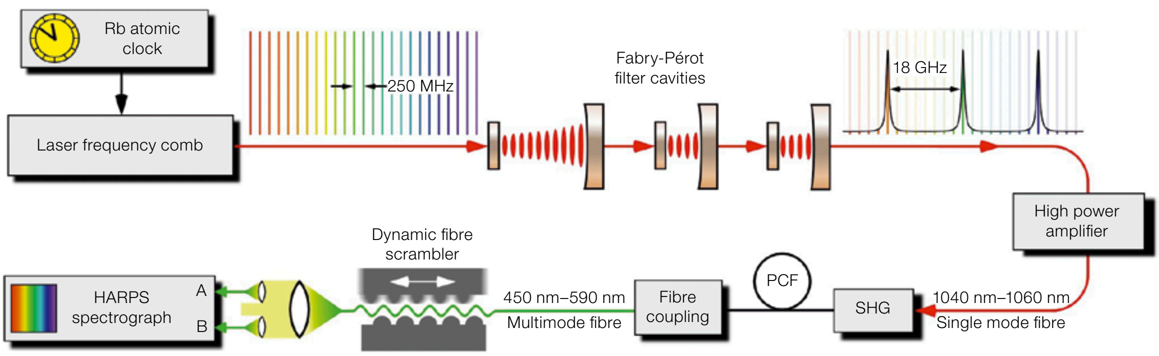

Figure 2. Representation of the HARPS-LFC setup as described in the text. The SLM after the PCF is missing in the figure because it was not always used during data acquisition (see text for details). From Wilken et al., 2012.

Figure 3. A comparison of a portion of one order of the LFC and the Th-Ar lamp as seen by HARPS.

(SLM) was sometimes inserted as a last stage of the LFC, yielding a flat spectrum envelope at the cost of an attenuation of 12 dB.

Light from the LFC is finally coupled to a multimode fibre that comprises a dynamic mode scrambler. Multimode fibres are mandatory, because starlight cannot yet be coupled efficiently to single mode fibres. The scrambler serves to reduce multi-pass interference effects and the sensitivity to the light injection by averaging over a large number of fibre modes. The light is then coupled, within the HARPS calibration unit, to the two HARPS calibration fibres, which simultaneously illuminate the telescope focal plane, injecting light into the "object" fibre and the "simultaneous reference" fibre. The system is sketched in Figure 2.

Characterising the LFC on HARPS

Some of the advantages of LFCs over Th-Ar lamps are immediately noticeable from Figure 3, where a portion of the order of the two sources is compared. The LFC has a very dense, non-blending line pattern (~ 350 lines per order), which is also very uniform in intensity. In contrast the Th-Ar lamp has fewer lines (~ 100 lines per order), some of which are saturated. The spectra in Figure 3 were obtained using both the object and the simultaneous reference fibres of HARPS, and by illuminating the spectrograph simultaneously with both sources.

The wavelength range of the LFC for HARPS now covers ~ 100 nm, and work is in progress to extend this to at least 200 nm. Owing to the high line density of the LFC spectra, we are now able to better characterise the detectors. For example, Figure 4 shows the effect of the stitching pattern of the CCD fabrication on the wavelength calibration. Every 512 pixels the wavelength solution encounters a discontinuity as the intra-pixel distance is slightly different along the stitching borders. The effect reaches over 60 m/s, well above the attainable stability of HARPS. Although the effect is clearly visible when using the LFC calibration, it goes unnoticed when Th-Ar calibration is used, due to the low number of lines present in the orders and their highly non-uniform distribution. This effect clearly underlines the need for a detailed characterisation of the detector when the highest radial velocity precision and accuracy are aimed for. Such in-depth characterisation can be performed with the use of the LFC, by modifying the parameters that define the spectrum, i.e. the offset frequency and the repetition frequency, effectively scanning the detector and probing all the pixels which lie within the spectral profile.

The characterisation of the stability of the LFC system when coupled to HARPS has been clearly the first priority during the tests. However with only one comb available we have to rely on its intrinsic stability as verified up to now on very many laser physics experiments. We are considering a test with two independent LFCs feeding light to HARPS in the future. Currently we are focussing instead on effects due to mode (mis)matching, coupling and injection. To characterise these, we inject light into both HARPS calibration fibres and illuminate both the object and the simultaneous reference orders (from here onward referred to as channels) in the CCD. We then monitor the relative drifts measured between the two channels, with the assumption that instrumental drifts are subtracted out when looking at the relative variations between them (an assumption which is the basis of the simultaneous reference method).

In Figure 5 the measured drift of all the spectra collected in the two test runs of November 2010 and January 2011 is shown. During the test run we stressed the system in many ways, well beyond what could be considered "standard operation": we completely disassembled the FPC chain and reassembled it again in January to test a fourth FPC; changed several PCFs; inserted and removed neutral density filters; misaligned the injection fibres; introduced polarimetric plates, integrating spheres, etc.... We also switched off the CCD cooling for few minutes. Despite this, each individual series of data shows a relative drift consistent with, or very close to, the estimated photon noise, and the relative drift between the two channels never exceeded 1 m/s, and the root mean square (RMS) of the relative drift was

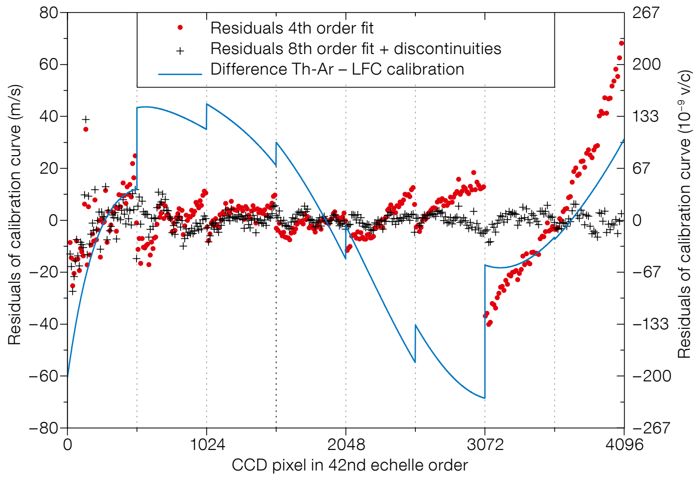

Figure 4. Evidence of the CCD stitching pattern as revealed by the LFC wavelength calibration. Due to the paucity of spectral lines, the Th-Ar calibration was unable to identify this effect. From Wilken et al., 2010.

~ 34 cm/s over the whole run. When the CCD cooling was stopped, and then restarted, we could measure a drift of 13 m/s on the individual channels, but the relative drift between channels was below 40 cm/s peak to valley, an indication that the method of simultaneous reference in HARPS is capable of reducing systematic effects by more than a factor of 30, at least when they originate from the detectors.

Two large deviations in the relative drift between the two channels are seen in the data (Figure 5). These correspond to the series of spectra acquired when an integrating sphere, with a diameter of 5 cm, was used to couple the LFC outgoing fibre to the HARPS calibration fibres. We do not yet understand the cause of this drift, but speculate it could be related to the strong intensity variation (close to two orders of magnitude) or to a different occupation of the modes after the transition through the integrating sphere. Possible alternative explanations point towards detector effects that could distort the instrument profile depending on light intensity, or data reduction effects, also related to a change of the instrument profile for very faint signals. Work is still being done to understand these measurements, but it must be stressed that this is well beyond what happens under standard operating conditions.

When looking at sequences of data during which we did not intervene to modify the system (orange and violet vertical stripes in Figure 5), the stability was seen to be superb. As in almost all series, the RMS of the relative drift between the two channels is consistent with the photon noise of ~ 7 cm/s. In order to decrease the contribution of the photon noise, we added an increasing number of exposures and computed the Allan (or two-sample) deviation (Figure 6). This estimator is capable of distinguishing statistical noise processes from systematics, e.g., drifts. In Figure 6 we see that the orange and violet points, corresponding to two quiet LFC series, follow well the curve of the estimated (not fitted) photon noise, up to a level of ~ 2.5 cm/s, where the data flatten. At this point systematics limit the stability of the system. Short-term (~ 2 hours) repeatability of the LFC+ HARPS system is at the level of 2.5 cm/s. Although we cannot say the same for the long-term stability due to the various drifts exemplified in Figure 5, we stress once more that these instabilities in the long term were most likely generated from our interventions in the system. In Figure 6 we display a similar measurement for Th-Ar calibration, and the limitation of Th-Ar lamps with respect to the LFC is clearly visible.

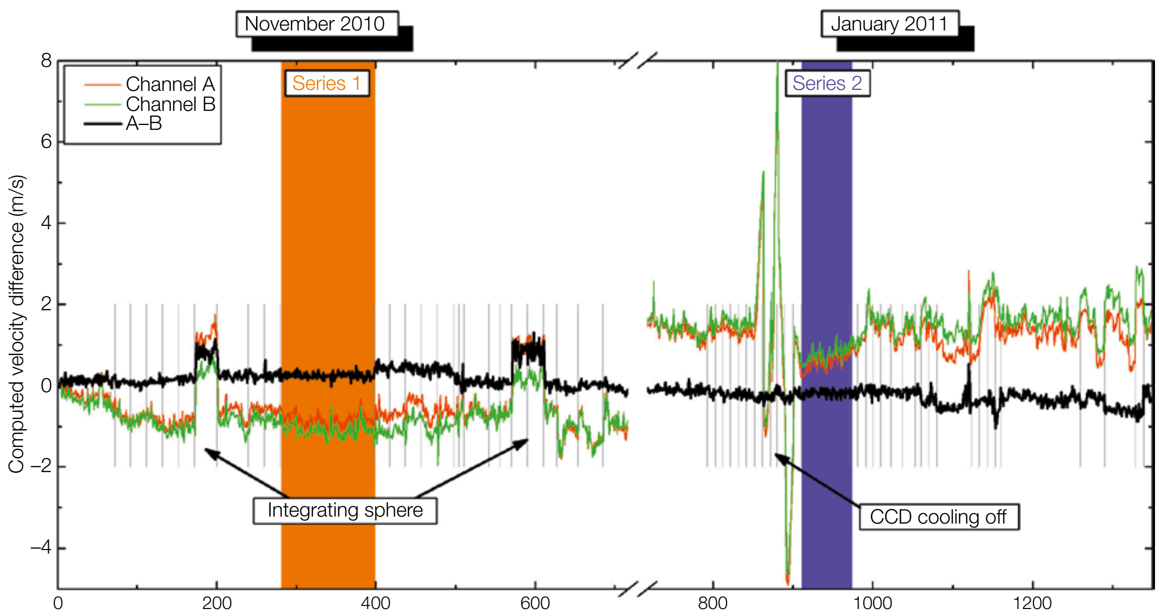

Figure 5. Drift of the two spectrograph channels for all the LFC data collected between November 2010 and January 2011 (almost 1300 spectra) is shown. The drift of the individual channels is measured with respect to an arbitrarily chosen spectrum. The relative drift between them is shown in black. The orange and violet vertical stripes indicate two long series (> 200 spectra in total) during which time the system was left unperturbed. From Wilken et al., 2012.

During our test runs in La Silla we monitored the radial velocity variation of the solar-type star HD 75289, known to host a Jupiter-mass planet with a period of 3.5 days. Using the LFC for wavelength calibration and simultaneous reference, we could reconstruct the orbit of the exoplanet. The measurements calibrated with the LFC nicely agree with previous data and the deviations from the fit could be due to stellar activity or pulsations. To our knowledge this is the first time that the orbit of an exoplanet has been reconstructed using LFC calibrations.

During the four years of the programme the LFC system has improved much, not only in its performance, but also in robustness and operational stability. The laboratory test and the campaigns with HARPS have achieved successful results, which have consolidated the concept of the system. The achieved repeatability of 2.5 cm/s is sufficient to detect an Earth-like planet in a one-year orbit around a star like our Sun.

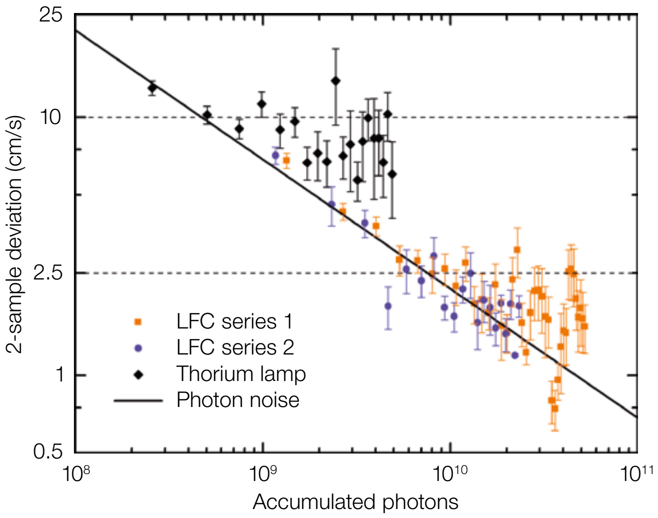

Figure 6. Two-sample variance of the LFC and the Th-Ar calibration. The black solid line is an estimation of the photon noise. The dashed horizontal lines at 10 cm/s and 2.5 cm/s indicate, for the Th-Ar and the LFC simultaneously, the level at which the data no longer follow the estimated noise and systematic effects become important. From Wilken et al., 2012.

Laser frequency comb for HARPS

After the successful completion of the demonstrator programme, beginning in February 2012, in partnership with the Instituto de Astrofisica de Canarias and the Universidade Federal do Rio Grande de Norte, we started a project aimed at the acquisition of a turn-key LFC system for HARPS. The system will be offered to the astronomical community after successful commissioning at the telescope. This project is not only directed towards improvement of HARPS, but also towards future instruments like ESPRESSO. The goals of this programme are to:

- gain experience in the use of the LFC, study its long-term behaviour and its reliability in operations, optimise the reduction tools to achieve the best performance with the LFC, with a view to its use on VLT and E-ELT instrumentation;
- bridge the gap between HARPS and ESPRESSO and acquire the potential of detecting a population of super-Earths in the habitable zone of solar-type stars;
- improve HARPS precision, which in turn will improve our capability for finding low-mass planets, further the understanding of stellar activity and refine the observation strategy for ESPRESSO planet searches.

The radial velocity (RV) precision of HARPS is estimated to be around 60 cm/s (Lovis et al. 2006). Knowledge of the instrument has permitted the instrumental causes that limit the RV precision to be identified: the light injection system and scrambling, the wavelength calibration system and, to a lesser extent, the temperature variations of the detector. After commissioning a new injection system in 2009, which improved the image stability at the fibre entrance, the Th-Ar wavelength calibration system is the strongest limiting factor to the long-term RV precision of HARPS. With the LFC, which has been shown to have a stability as good as a few cm/s with HARPS, the instrument is capable of reaching long-term RV precision below 30 cm/s, giving access to the detection of Earth-mass planets in close-in orbits, tracing out the path towards the detection of Earth twins. This RV precision is midway between the current HARPS performance and the 10 cm/s precision expected for ESPRESSO at the VLT, planned to start operations in about four years. The LFC calibration system will be one of the key components of ESPRESSO.

The step of moving from a laboratory prototype to a device to be operated at the telescope on an existing instrument will move us to the production phase, and will drive the development of an operational comb for the next high-precision radial velocity instruments for the VLT and the E-ELT. The experience collected with the HARPS LFC will be invaluable for ESPRESSO and beyond.

While delivering top RV precision data with HARPS, this project would permit an understanding of the long-term systematics (if any), early optimisation of comb operations and of the reduction software before ESPRESSO goes online and well in advance of the preliminary design of any high resolution spectrograph for the E-ELT.

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