Future Wavelength Calibration Standards at ESO: the Laser Frequency Comb

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A new technique for precise wavelength calibration of high-resolution spectrographs using frequency combs has recently been proposed. After introducing the basic concepts and advantages of this technique, we describe the ongoing development between ESO and the Max-Planck Institute for Quantum Optics for a novel wavelength calibration system that aims, within three years, to construct a laboratory demonstrator.

The quest for improved wavelength calibration

With the advent of large (and extremely large) telescope collecting areas and superstable instruments, high-precision spectroscopy in astrophysics is becoming a very exciting reality. Several areas of forefront research have been developed in the last decade, such as the detection of planets around other stars, the measurement of possible variations in physical constants, the determination of element isotope ratios and the proposed direct measurement of the expansion of the Universe. All share the requirement of very high precision in the measurement of spectral line wavelengths.

High-precision wavelength measurements require a high-resolution spectrograph with special characteristics in terms of thermal and mechanical stability, detector linearity and reproducibility. The reader interested in more details can refer to the proceedings of the "High Precision Spectroscopy in Astrophysics" workshop (Santos et al. in press), held in September 2006 in Aveiro (Portugal). There is now a general consensus that an even higher precision is needed:

- for the detection of earth-mass planets in habitable zones around solar-type stars and/or the unambiguous characterisation of stellar systems with many orbiting planets (like our own Solar System), which will require a long-term precision of better than 10 cm/sec.
- to resolve the currently controversial issue of possible variation in the physical constants as derived from quasar spectra and to increase the precision in order to compete with space-based constraints from atomic clock experiments (e.g. from the planned ACES experiment by ESA), which requires an improvement of a factor between 10 and 100 over the present measurements.
- for measuring the change of the expansion rate of the Universe from Ly-α forest quasar absorption spectra, which requires a precision of a few cm/sec over a 30-year baseline (Grazian et al. 2007; Liske et al. 2007).

One (if not THE) crucial subsystem in any high-precision spectrograph is the wavelength calibration source (Lovis et al. 2006). The ideal calibration source should have a very high density of lines that are uniformly spaced and whose wavelength is known from first principles. All the lines should have similar intensity and should cover the whole spectral range of interest without blends. Crucially, they must be stable and reproducible to an exceedingly high accuracy for many years. All of this may appear excessive to some of our readers, but it is worth recalling that a precision of 1 cm/sec corresponds, on the focal plane of a typical high-resolution spectrograph, to a shift of a few tenths of nanometer, which compares to typical molecular sizes. Moreover, we aim to maintain this precision over a period of 10 years, or more!

The standard wavelength calibration sources used in most spectrographs are the hollow-cathode Thorium-Argon (Th-Ar) lamps. These lamps have been used for decades, because of their numerous advantages. However when pushing the performance, a number of limitations arise, the most noticeable being: line blending; long-term variability; and the high non-uniformity of the line distribution and intensity (see e.g. Lovis et al. 2006).

Prompted by the need to improve this calibration scheme, a group of researchers from different institutes has started to look into other alternatives, finding that a significant step towards the ideal calibration source might be achieved with the relatively new technology of laser frequency combs (Udem et al. 2002; Murphy et al. 2007).

The Laser Frequency Comb

A laser frequency comb 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 shorter the laser pulses, the broader the range of frequencies in the comb (see Figure 1).

The resulting modes of the frequency comb have their origin in the repetitive pulse train of the mode-locked laser. The mode spacing, which is constant in frequency space, is given by the pulse repetition frequency and resides in the radio frequency domain. The repetition frequency can readily be synchronised with a precise radio frequency reference such as an atomic clock. These clocks provide by far the most precise measurements of time and frequency currently available, the most reliably determined quantities in physics. Frequency combs therefore satisfy two requirements of the perfect calibration source which other methods do not: uniform line-spacing and long-term stability and reproducibility. The novelty of laser combs has been widely recognised, and the 2005 Nobel Prize in Physics was awarded to Profs. Ted Hänsch and John Hall, for their fundamental and pioneering work in the development of the optical frequency comb technique.

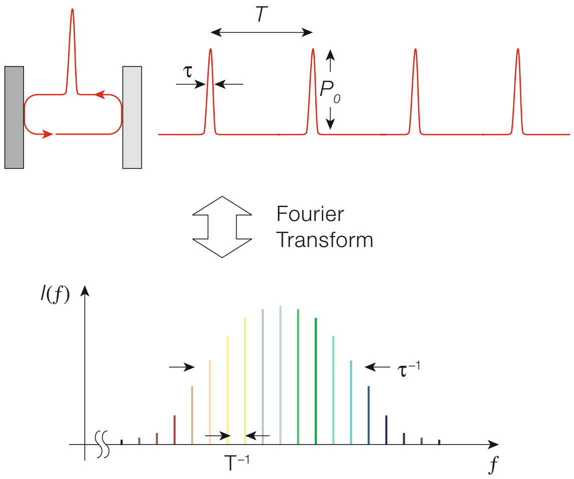

Figure 1: In the time domain, the pulses of a typical mode-locked laser (in red), characterised by its pulse repetition rate (T) and its pulse duration τ ~ fs, are shown (top). Shown below in the frequency domain, the pulse of the above mode-locked laser produces the frequency comb, with its parameters, the repetition frequency T^{-1} and spectral width τ^{-1}.

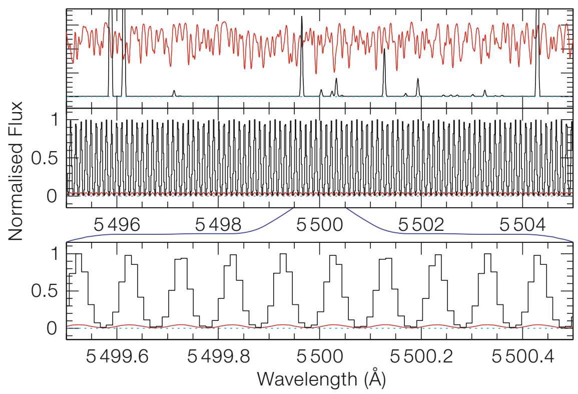

Figure 2: Th-Ar lamp (red) and the iodine cell spectra (black) as recorded at the focal plane of a high-resolution spectrograph (top), *versus* the simulated frequency comb spectra for the same spectral region (middle). In the lower frame is shown a zoom of the comb spectra for a 1 nm window, where the red solid line shows the error array, exaggerated by a factor of 25 (see Murphy et al. 2007).

The laser frequency comb has a number of advantages over other traditional wavelength calibration sources. It guarantees long-term stability over many years; the absolute wavelength of each line in the comb is known *a priori* (i.e. without the need for previous laboratory measurements); and it has a very high precision, only limited by the reference signal, which could be an atomic clock or a GPS receiver, depending on the required stability. Another interesting feature is the high density and equidistance of emission lines, over a wide wavelength range, both of which will allow tracing and modelling of the wavelength solution at the focal plane of the spectrograph with a very high accuracy, enabling higher S/N detection in spectra.

In Figure 2 we show the Th-Ar, the iodine cell and the simulated laser frequency comb spectra over the same spectral region for comparison. The advantage of the comb is evident.

Implementing a Laser Frequency Comb calibration system

ESO and the Max-Planck Institute for Quantum Optics (MPQ) have studied the technical feasibility of building a wavelength calibration system based on a laser frequency comb, which could be used in present and future generations of high-resolution spectrographs. The requirements and specification were based on a CODEX-like instrument (Pasquini et al. 2006). The conclusion of that study is that none of the presently available laser comb systems could provide all the characteristics required by this application, but the development of such a unit, although challenging, is feasible.

Two requirements have been identified as the most demanding (Araujo-Hauck et al. 2007): wavelength coverage; and frequency mode separation. The minimum spectral range of operation is in the visible band, from 400 to 680 nm with a possible extension from 350 to 1000 nm. Ideally, this would be obtained from a single comb by symmetric broadening of the frequency spectrum with some power constraint for the nonlinear conversions, like second or third harmonic generation, in order to reach the final spectral range.

Our simulations show that the optimum frequency mode separation for an R = 150000 spectrograph, is about 13 GHz. Commercial femtosecond lasers have typical frequencies as high as a few hundred MHz, which would appear as a continuum in our spectrographs. The feasibility of increasing the mode separation has not yet been demonstrated and is likely to be the most challenging part of this development, due to the high power required to carry out the nonlinear processes at high-pulse repetition rates. To date there is no laboratory demonstration of femtosecond laser sources with repetition rates larger than 10 GHz (Hoogland et al. 2005).

The proposed solution is shown in Figure 3. It consists of a High Repetition Rate (HRR) fs source, a non linear frequency conversion, and a mode filter cavity that will be the last step to achieve the desired mode spacing. The latter item presents a major development challenge, but has the significant advantage that the line spacing can be varied to lower and higher free spectral ranges in multiples of the fundamental comb line spacing.

On account of the common interest for ESO and MPQ, both organisations have agreed to start the research and development activities with the objective to build a laboratory prototype that meets the requirements of a wavelength calibration source. This research will focus on different key aspects of the desired system: identification of the high repetition rate light source, development of the non-linear conversion chain, and the filter mode cavity which will allow us to reach the desired frequency mode spacing. A Ph.D. thesis has been awarded on the subject at MPQ and a postdoctoral position devoted to support the project. The first set-up for the development of a filter mode cavity has been assembled on the MPQ optical bench, and is shown in Figure 4.

It is expected that within three years this research effort will result in a laboratory system that meets the performance requirements. A travelling unit to be tested, feeding a spectrograph operating at a telescope, could be available in a timeframe of approximately four years.

In conclusion, a programme to develop a frequency comb calibration system has been established in collaboration between ESO and the MPQ, with the aim to provide a wavelength calibration system of unique accuracy and long-term stability for astronomical spectroscopy. The success of this programme is crucial to maintain ESO community leadership in high-resolution spectroscopy and the associated scientific areas of research, such as exoplanet detection and cosmology from high-redshift absorption lines.

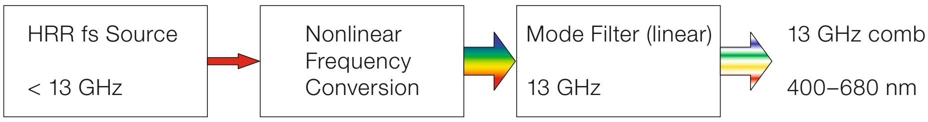

Figure 3 (above): Block diagram for the proposed laboratory demonstrator of the calibration system based on a frequency comb.

Figure 4 (below): Laboratory set-up at MPQ to test the filter cavity. The red line represents the laser path. On the left, the Fabry Perot filter cavity. On the right, the different optical components for analysis, control and diagnostics.

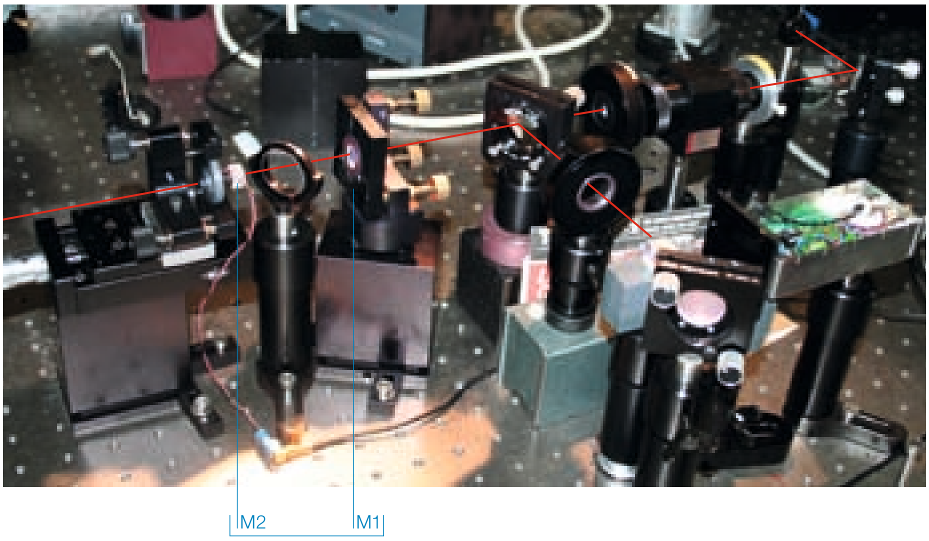

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Photo: H. H. Heyer, ESO

A recent view of the Instrument Integration Hall at ESO Headquarters in Garching. In the foreground are parts of the HAWK-I dewar.