Along the path towards extremely precise radial velocity measurements.

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ABSTRACT

In the last six years, thanks to the very high radial velocity precision of the HARPS spectrograph, it was possible to detect 21 out of the 30 super-Earth (extrasolar planets masses below 20 times the mass of the Earth) discovered up to date. The radial velocity precision of the instrument is estimated around 80 cm/sec on a single measurement.

The main instrumental limitations are the wavelength calibration and the stability of the light injection. We address both factors and present the results of recent tests on the HARPS spectrograph.

We have identified the laser frequency comb as the ideal wavelength calibrator, due to the width, density and flux of the lines, and to its intrinsic stability. The results from the recent tests that we performed on HARPS are encouraging.

The accurate guiding of the telescope is critical to maintain a stable light distribution at the injection stage, where the light is sent into the spectrograph entrance fiber. To pursue this goal we are testing a secondary guiding system which is able to apply the guiding corrections twenty times faster than the primary guiding system.

Keywords: Radial Velocity, Laser Frequency Comb, Guiding, HARPS, ESPRESSO, CODEX

1. INTRODUCTION

It is coming as a fortunate coincidence that several of the most compelling scientific questions of our times can be addressed by measuring the relative projected velocity (or Radial Velocity) of various astronomical objects with respect to our rest frame (we use the Solar system barycenter):

- do other planets like our own exist ?
- how did the Solar system form ?
- is the Universe expanding ?
- do the “Fundamental Constants” vary as the Universe evolves ?

These questions aim at finding our place in the Universe in which we live, and at trying to understand its nature and evolution. While there are surely various theoretical and experimental methods to approach each of the questions, all of them can be addressed by the same experimental technique: precise Radial Velocity (RV) measurements.

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This technique evolved greatly in recent times, especially thanks to its successes in detecting planets orbiting stars other than our Sun (exo-planets). The number of planets detected increases on a day to day basis; at the time of writing 460 exo-planets are detected, of which 430 (93%) with the RV method.

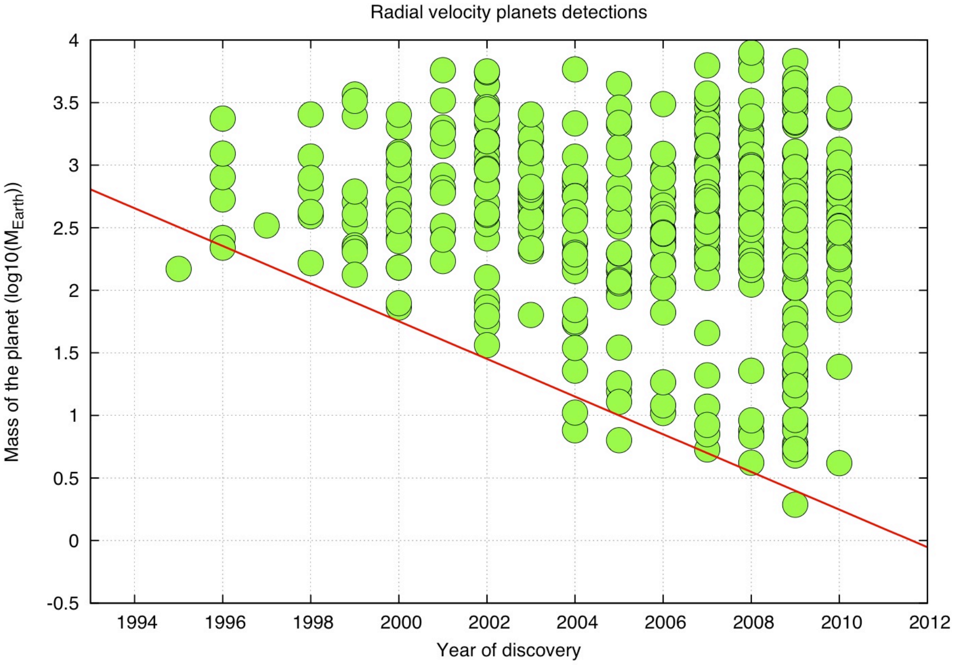

Figure 1: The mass of the discovered planets as a function of the year of discovery[1]. The red line is a Moore-like law.

This technique is also crucial for the characterization of the exo-planets discovered via other methods (e.g. transits), as it delivers unique dynamical information about the bodies orbiting the star. Thanks to the substantial improvements in the technique it was possible to increase the precision of the measurements at such a rate that would be almost comparable to a Moore-like law for exo-planets detection. The RV method permits detection of a planet orbiting a star via the reflex motion of the star around the common centre of mass. The lighter and the farther is the planet from the host star the smaller is the effect. As a reference, Jupiter induces a reflex motion of about 12m/s on the sun over the course of its 12 years period, while the Earth contribute for only 9cm/s over the course of the year. It is clear that if we want to detect planets like our own, with the same mass and at the same distance from the star, we need a RV precision not worse than 3cm/s, or one part in 10^{10}.

The direct measurement of the expansion of the Universe requires also extreme RV precision[2]. In this case the RVs of the intergalactic clouds at high redshift on the line of sight of distant QSOs are measured at different times via their absorption lines. The goal is to measure an increase of this RV and therefore to obtain the direct measurement of the acceleration expansion of the Universe. Depending on the metric we can expect a change in the RV of these absorbers of up to 6cm/s in 10 years, defining again a requirement for the long term RV precision of our instruments of the order of the cm/s or few parts in 10^{11}.

Also the measurements of the variability of fundamental constants such as the fine structure constant α[3], or the electron to proton mass ratio μ[4], require high precision in the RV determination, in conjunction with a large photon collecting power.

Much progress has been made in the last decades, from the time of CORAVEL[5] (RV accuracy ~ 500m/s) to the time of HARPS[6] (RV accuracy[7] ~ 0.8m/s), an improvement of almost three orders of magnitude in 30 years. The scientific questions that we have highlighted will be pursued by the new generation of spectrographs optimized for high RV accuracy, such as ESPRESSO[8] at the VLT and CODEX[9] at the E-ELT. Today the HARPS spectrograph is at the forefront in the field of high precision RV measurements[10]. It is therefore natural to use it as a case study and as a bench test for probing new technologies and methods to overcome the current limitations to RV measurements. HARPS is the cross-dispersed, vacuum-stabilized, fiber-fed spectrograph installed at the 3.6m ESO telescope in Cerro La Silla, Chile[6]. It can perform calibration or, alternatively, sky measurement, simultaneously with the object acquisition.

2. RV ERROR SOURCES

In this section we summarize what we know to be the current contributions to the RV uncertainty. When more precise instrumentation will be available, it is likely that new sources of uncertainty will contribute to a level that today we are unable to measure. As usual we take HARPS as the reference for our considerations. The main contributors are:

- Photon noise
- Spectrograph's illumination
- Wavelength calibration

2.2 Photon noise

The fundamental limitation to RV measurements from photon noise has been described by Bouchy[11]:

$$\delta RV = \frac{c}{Q\cdot\sqrt{N_{e^-}}}$$

where c is the speed of light and Q is a factor which depends on the spectrum of the star and on the spectrograph's spectral resolution (how many lines, how sharp, how well resolved). Therefore a larger telescope collecting area, and a larger overall system efficiency, will not only allow to measure fainter objects, but will also make possible to achieve a higher precision in the RV determination for a given spectrograph stability. This is why ESPRESSO at the VLT and CODEX at the E-ELT will not only give us access to fainter objects, but they will also open the door to the realm of the cm s^{-1} RV precision.

2.3 Spectrograph's illumination

In a sense a fiber spectrograph projects the image of the entrance fiber on the detector as a function of wavelength. The variation of the illumination on the entrance fiber will reflect itself in a variation of the spot profile and position at the detector. Image scramblers are used to attempt to uniformize the light distribution at the entrance of the spectrograph, nevertheless some residual non-uniformity of the light distribution will be left over. Although the optical fibers have very good scrambling capabilities in the aziumthal direction, the unavoidable optical aberrations of the instrument optics, and imperfections in the fiber itself, might shift the center of the light distribution on the detector as a function of the input light distribution. The amount of this effect depends on the instrument (optics, aberrations, fibers) on which it is measured, and it is not possible to give numbers that are valid in general. However, using HARPS as a guideline, we have measured a RV offset of 3m/s when offsetting a solar type star by 0.5" from the fibre's center on a night with an atmospheric seeing of about 1". These numbers do not scale linearly, due to the profile of the input light beam and the nature of the optical aberrations in the instrument. We do know however that on average, the contribution of the guiding to the HARPS error budget, is of the order of 0.3m/s, while the centering accuracy[12,13] is of the order of 0.1".

2.4 Wavelength calibration

The Palmer Th atlas published in 1983[14] is only accurate to 0.002cm^{-1}, i.e. ~ 30m $s^{-1}$for most of the lines. It is therefore not the appropriate tool to use when aiming for cm s^{-1} RV precision. Recently Lovis[15], using the HARPS spectrograph, has developed a new line list, adding new lines, removing blends, and improving the precision of the determination of the wavelengths of the lines already present in the Palmer atlas. Although this new atlas does not attempt to measure the absolute value of the lines wavelength, but rather the relative position of the lines, it increases the number of used lines to about 10000, and with it improves the precision of the wavelength solution of HARPS by a factor 3, from about 80cms^{-1} to about 25 cm s^{-1}. Spectrographs aiming at a RV precision 10 cm s^{-1} like ESPRESSO, or at 1 cm s^{-1} like CODEX have to rely to an alternative, more precise calibration system.

In this paper we report our progresses in trying to address these limitations to the RV precision of spectrographs. Namely we test a novel wavelength calibrator and a new guiding system on HARPS. We expect to reduce significantly the RV error originating from wavelength calibration (down to 1cm/s) and from light injection in the fiber (down to 10cm/s). In this way we could improve the RV precision of HARPS to 30cm/s on a single measurement, and demonstrate the feasibility of extremely precise guiding and wavelength calibration systems for the precise RV machines to come at the VLT and at the E-ELT.

3. TESTING THE LASER FREQUENCY COMB ON HARPS

We are using the HARPS spectrograph to test an alternative method for wavelength calibration, by way of a Laser Frequency Comb (LFC). The results of a previous test were recently published[12], here we give a preliminary report on the tests we performed in March 2010. The details of the setup of the LFC during the new, recent tests, will be discussed by another contribution to this conference[13]. Here it suffices to say that we are using a Yb doped fiber laser (1064nm), with a 250MHz fundamental repetition rate. This repetition rate is too high to be resolved by our spectrograph, therefore we need to filter out most of the pulses. This is achieved via two Fabry-Perot cavities in series with the comb generator. The repetition rate at the exit of the cavities can be adjusted, and we had configured it to 12GHz for most of the tests. The wavelength range of the spectrograph goes from 380nm to 690nm, for this reason the LFC output is frequency doubled before the light is sent to the spectrograph. At the end of this chain we have inserted, for only part of our tests, a non-linear Photon Crystal Fiber (PCF) for spectral broadening. Injection to the spectrograph happens via a 1mm multimode fiber, which passes through a scrambling unit before being coupled, via a de-magnifying lens, to the 300μm HARPS calibration fiber. When required, at the exit of the LFC optical bench, the light can be split in two for injection in both HARPS fibers (object and sky/reference).

Generally during the tests we acquire a sequence of spectra illuminating both HARPS fibers. We measure the line drift on both fibers with respect to a reference exposure and we subtract the drift on one fiber from the drift of the other. In this way instrumental drifts do not appear in the residual drift. Finally we compute the Root Mean Square (RMS) of the residual drift and, after comparing it with the estimated photon noise we use it as a figure of merit for the stability of the calibration source. We use a typical exposure time of 40s, which is the optimum for the Th-Ar exposures. It is also adequate for the LFC exposures provided the flux is properly adjusted. The duty cycle of our sequences is of approximately 70s (40s exposure + 30s readout time). We used the HARPS pipeline to reduce the data.

When the LFC was used without the PFC for broadening, the spectrum lied on order numbers 118, 117 and 115, with orders 118 and 115 filled only partially and order 116 falling in the gap of the CCD mosaic. The central wavelength of order # 117 is 523nm. With the final repetition rate configured to 12GHz, the average finesse was of 2.8. Due to the low value of the finesse and to the non-gaussian wings of the PSF there is some blending of the lines, at a level of few percent. Figure 2 well expresses the tremendous advantage of the LFC lines distribution over the Th-Ar lamp. The regularly dotted rows are from the LFC, the rows poorly populated and with lines of very different intensity are from the Th-Ar. Figure 2 was obtained after the broadening stage using the PCF, when the full spectrum of the LFC was spanning over 24 orders.

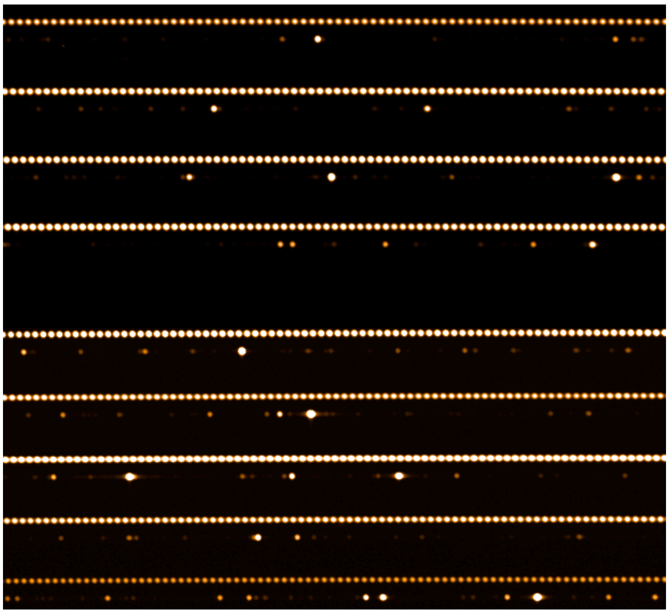

Figure 2: spectrum obtained with the LFC after broadening on one fiber and the Th-Ar lamp on the other fiber. The regularly dotted lines are the echelle orders illuminated by the LFC. Many comb orders are available. The large flux variation between Th-Ar lines and the paucity of Th-Ar lines with respect to LFC is evident.

3.2 The scrambling unit

The purpose of the scrambling is to reduce the interference among the modes due to the coherence of the light source. We used two independent scrambling stages, in a fashion that permitted to scramble separately the two injection fibers going to the spectrograph. Each scrambling stage consisted of a static twister bending the fiber in 5 points, a dynamic twister rotating with a frequency of the order of 5-10Hz and a small shaker, connected to the bent fiber in one point (bending radius ~ 10cm) and shaking it at a frequency of the order of 10-20Hz (quite difficult to quantify).

We have tested the contribution of the single components of the scrambling system, and we have marginal evidence that the shaker gives the main contribution. The shaker, which consisted of a cell phone vibrator motor, was operating at higher frequency with respect to the dynamic twister, and it was attached along a narrow loop (10cm radius) of the fiber. In any case we decided to keep all three scrambling components working during the rest of our tests.

During an acquisition sequence in which we were injecting light from the Th-Ar lamp and from the LFC, we stopped the shaker, the other components of the scrambling system being inactive. The result is dramatic and can be seen in Figure 3. The RMS of the residual drifts changed from 16cm/s to 1.1m/s, to be compared with the photon noise of 18cm/s. The need for a scrambling unit is evident from the results of this test.

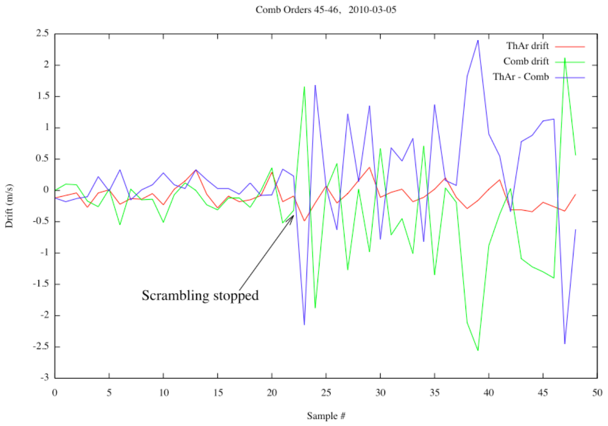

Figure 3: a series of acquisitions where the scrambling was stopped at acquisition # 22.

3.3 Repeatability

The stability of the LFC, or the repeatability of the line positions of its spectrum, is clearly one of the main figures of merit for this unit. We present in the following the results obtained from the LFC without using the PCF fiber to increase its wavelength range. The results on the broad-band LFC will be addressed in a dedicated section.

The repeatability of the drift measurement with the LFC over a series of 60 spectra is compatible with the photon noise: 13cm/s.

Source	Average (cm/s)	RMS (cm/s)	Phot. Noise (cm/s)
ThAr	5	21	8
LFC	-10	20	10
ThAr-LFC	14	13	13

Table 1: sequence of 60 measurements. The RMS of the residual drifts (ThAr – LFC) is consistent with the photon noise.

After subtracting the Th-Ar drift from the LFC drift, to take into account possible instrumental drifts, it is clear that we are limited by the photon noise.

We have obtained an even better result when using comb spectra on both fibers, after tuning the intensity to minimize photon noise without saturating. The LFC beam was spliced in two just before injection in the two HARPS calibration fibers.

Source	Average (cm/s)	RMS (cm/s)	Phot. Noise (cm/s)
LFC A	7.2	17.8	5.5
LFC B	1.4	20.0	8.0
A – B	5.7	8.5	9.5

Table 2: Residual drift from the LFC – LFC sequence. The RMS of the residual drift is within the photon noise.

Again, we are photon noise limited. We might expect, once we will be able to use the full 72 orders illuminated by the LFC, a repeatability at the level of 1cm/s, if the extrapolation via the factor 1/sqrt(72) holds. The available dynamic range, the spectral shape of the LFC spectrum and the decrease of the instrument efficiency towards the blue might deteriorate slightly this estimate.

From one side increasing the number of LFC lines in the detector decreases the photon noise, on the other side if the lines are too close to each other and blend, the precision in the lines position determination decreases. The optimum balance will have to be found from the tests performed once the LFC covering the full spectral range of HARPS will be available.

3.4 Wavelength calibration

The precision of the wavelength calibration is tested calibrating the same stellar spectrum with several calibration spectra. For this purpose we have used the non-broadened LFC, with a repetition rate of 12GHz; we also compare the LFC to the Th-Ar calibration.

After computing the Th-Ar wavelength solutions and comparing them with the LFC solutions, we noticed a large offset in the calibration, with average around 260m/s. We think this might be due to the FPC locking one comb line after the anchor frequency. The offset due to one comb line, at this wavelength, is of 130m/s which after frequency doubling becomes 260m/s. We add this value to the RV measurements performed by the LFC. We are interested in both the average value of the stellar RV, which is an indication of the absolute calibration accuracy, as well as to the RMS which expresses the precision of the calibration. The data obtained are presented in the table below.

	LFC RV mean	Th RV mean	LFC RV RMS	Th RV RMS
1 order	-7.73132km/s	-7.66583km/s	7.7cm/s	220cm/s
72 orders	-	-7.69770km/s	0.9/0.8cm/s *	24cm/s

Table 3: precision of the wavelength calibration. Comparison LFC – Th-Ar. * Note: the values for the 72 orders case for the LFC are extrapolated: a) using a 1/sqrt(72) scaling factor and b) using the same scaling factor measured on the Th.

The order number 117 was used for both the LFC and the Th-Ar when extracting the single order results. The photon noise on the LFC was measured to be 6cm/s, while on the Th was of 5cm/s. We notice the extreme precision of the comb with even only one order, which can be extrapolated to 1cm/s once the LFC will cover all the HARPS wavelength range. The difference between the Th and the LFC estimate of the RV is quite large. This could depend on the distribution of the stellar lines within the order. Indeed on this order, for this star, there are almost saturated absorption lines at both extremes of the order, where the Th wavelength solution is poorer.

It should be considered that the Th-Ar wavelength solution uses about 10000 spectral lines spread over the 72 HARPS orders, an average of 140 lines per order, while the LFC, with about 450 lines per order in the current configuration, triples this number. Using the LFC rather than the Th-Ar lamps there would also be a gain in the flux uniformity of the lines, which in turn, will allow optimum fine-tuning of the calibration acquisition to minimize the photon noise. But above all, each of the LFC lines is referenced to a Rb atomic clock, with an accuracy of the order of 10^{-11}. The extrapolation of the LFC performances to the full wavelength range would satisfy the requirements for a wavelength calibrator for ESPRESSO and CODEX.

3.5 The broad comb

When using the non-linear PCF to broaden the LFC spectrum we could achieve a spectral coverage of over 22 orders, equivalent to 110nm, and a photon noise of approximately 4cm/s. The number of spectral lines was of the order of 11000, more than the lines of Th-Ar in the full HARPS spectrum. The integrated flux through the LFC lines was already a factor 6 more than the flux contained in the Th-Ar lines. An example of a LFC spectrum with simultaneous Th-Ar spectrum is shown in figure 2. Although very good from the point of view of photon noise and spectral coverage, on the side of line stability the broadened spectrum of the LFC could not improve nor reproduce the results obtained with only one LFC order. The broadening stage seems to introduce instability in the line profile, or in the line position. Work is ongoing to address this problem. We plan, as soon as this effect is understood and the problem is solved, to perform a new LFC test on HARPS.

4. UPGRADE OF THE HARPS GUIDING SYSTEM

The goal of this upgrade is to improve substantially the guiding system of HARPS at the 3.6m telescope in La Silla, and to lower the contribution to the total RV error budget of the guiding system from the current ~ 30cm/s to below ~ 10cm/s. The current guiding accuracy is of 0.1", and we aim at reducing it to 0.01".

The present guiding system corrects by offsetting the whole telescope and the correction frequency is limited by the telescope relaxation time, which is of the order of 2s. We intend to increase the correction frequency up to 10Hz in order to dump effectively perturbations with frequencies of fraction of Hz due to small mechanical jitter or wind buffeting of the telescope. We have modeled our guiding corrections and we have seen that with 10Hz guiding corrections we can achieve satisfactory dumping of perturbations up to 0.3Hz.

The new guiding system has recently been integrated at the telescope and it is in its testing phase. The system is constituted by a 32mm thick refracting glass, actually a cemented doublet of PSK3 concave and LLF1 convex glasses, minimizing chromatic aberrations, mounted on a mechanical table actuated by three voice coils, and free to oscillate around two axis, which are perpendicular between themselves and to the optical axis of the telescope (tip-tilt). A small rotation of the refracting glass moves the image of the star on the focal plane, allowing fast and precise centering on the fiber. The tip tilt table can oscillate with a frequency of up to 10Hz within the range of ± 7.5mrad on both axis.

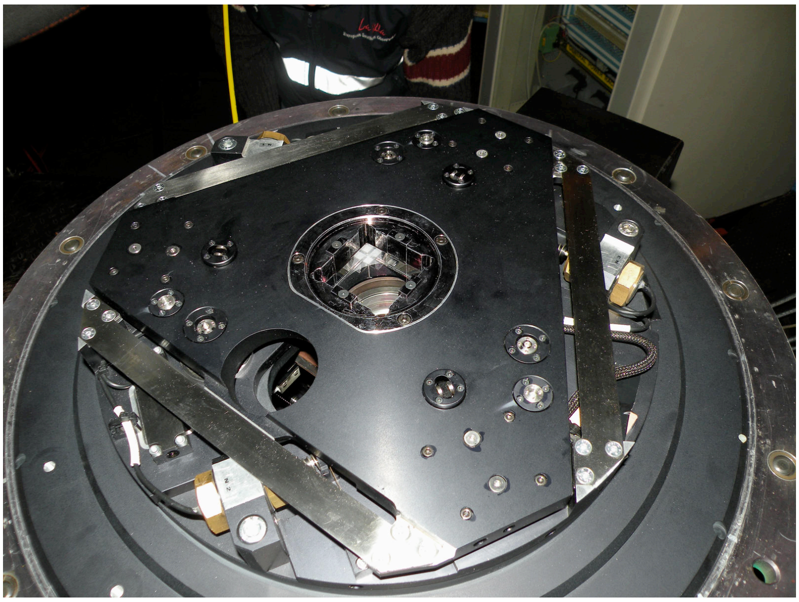

Figure 4: the tip-tilt table mounted on top of the HARPS adapter. The square tip-tilt glass is visible at the center, as well as the aperture for the return beam to the guide camera to the lower left.

Its stability and the repeatability of its movements are excellent and well within the specification of 10μm. The system is enabled by an air system with a pressure of 3bar, and once disabled it is extremely stable in its park position, therefore allowing to resort back to standard guiding in case of problems, as a backup solution. We have also verified the stability of the pivot point of the table as well as its operation at low elevation. Finally we could establish serial communication with the device within the software framework controlling also the 3.6m telescope. We have performed few standard HARPS observations using the tip-tilt table to guide and sending the corrections interactively from the control console.

The next step is the full automatization of this new guiding system and its performance verification at both slow and fast guiding speed. We expect to have the system fully characterized and running by the fall of 2010.

Similar systems (i.e. tip-tilt lens) will be also used for both ESPRESSO and CODEX and the outcome of this test will certainly be of interest to both future instruments.

5. CONCLUSIONS

We have described our work to improve the wavelength calibration by mean of a LFC on HARPS, and we have demonstrated the superiority of this technique with respect to the use of the Th-Ar lamps, at least restricted to the usable wavelength range of the LFC. Work is ongoing to broaden the available range to the full spectral coverage of HARPS. Extrapolation of the results obtained on only one LFC order to the full 72 HARPS orders confirms that the LFC satisfies the stringent requirements on the precision put forward by ESPRESSO and CODEX. We have also addressed the other main contributor to the RV uncertainty, i.e. the guiding errors. A new guiding system for HARPS has recently been delivered to La Silla, and the results of the first tests are very positive.

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