# The Exoplanet Hunter HARPS: performance and first results

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## ABSTRACT

HARPS is a new high resolution fibre-fed spectrograph dedicated to the extremely precise measurement of stellar radial velocities. After being used for about one year including the commissioning runs we report a very successful implementation of the measures taken to maximise stability, efficiency and spectral performance. Using the Simultaneous ThAr Reference Method a short term precision of 0.2 $ms^{-1}$ during one night and a long term precision of the order of 1 $ms^{-1}$ have been achieved. Equipped with a fully automated data reduction pipeline that produces solar system barycentric radial velocities in near real-time, HARPS promises to deliver data of unequalled quality. HARPS will primarily be used for the search for exoplanets and in the field of asteroseismology. First exciting scientific results confirm these expectations.

**Keywords:** spectroscopy, exoplanet, asteroseismology, radial velocity

## 1. INTRODUCTION

HARPS, the High Accuracy Radial velocity Planet Searcher saw its First Light at the 3.6m telescope of ESO's La Silla Observatory in February 2003, exactly 3 years after the project was formally launched as a cooperative effort between the HARPS Consortium and the European Southern Observatory ESO. The former consists of Physikalisches Institut der Universität Bern, Observatoire de Haute Provence (OHP) and Service d'Aéronomie du CNRS under the leadership of Observatoire de de Genève, on ESO's side substantial contributions came from La Silla Observatory and the Instrumentation Division at the Garching Headquarters. More details of the history can be found in Mayor.[1]

Following a very successful first commissioning run in February 2003 and two more runs in June and September (necessitated due to adverse weather), regular science operations started in October 2003 with the beginning of the ESO 6-month observing period 72. Already during this first period of operations HARPS was able to deliver an impressive amount of high quality science data.

Altogether HARPS observations were scheduled for 75 nights during this semester. They were allocated to 8 science programmes submitted by different groups of observers and include the guaranteed observing time given to the HARPS Consortium in exchange for designing and building the instrument, as is standard practice at ESO. In total approximately 7500 science exposures including a small number of calibrations were taken.

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Adding up the scientific exposure times (a total of 360 hours of "shutter open" time) and comparing them to the total night time available to HARPS results in an observing efficiency of 65 %. The observing time lost due to technical problems of the instrument was a mere 12.5 hours or 2.25 % – an impressive achievement for a brand new instrument within its first half year of operation!

The observations of this semester as well as those taken during the commissioning runs have already resulted in scientific results: New extrasolar planets have been discovered and the most extensive and precise series of asteroseismology data ever secured on a K star has been taken. See sections 7 and 3 below for details.

## 2. "SECRETS" OF SUCCESS - OR WHAT MAKES HARPS SO DIFFERENT FROM OTHER RADIAL VELOCITY SPECTROMETERS

From the beginning the specification for the instrument was to achieve a long-term stability of 1 $ms^{-1}$ which allows the detection of exoplanets with sub-saturnian mass. It was clear that all components of the system would have to be rigorously investigated for possible improvements. The system was supposed to reach the practical limits of technical feasibility and to test the physical limits of the radial velocity method.

### 2.1. ThAr Reference Method

The Simultaneous Thorium Reference Method was already employed for the detection of the first extrasolar planet,[2] although on a smaller telescope (1.93 m) and a spectrograph (ELODIE) not fully optimised for stability. Nevertheless it clearly demonstrated its superior performance already in this setup. The decision to further develop this method for the new planet hunter was therefore taken very early in the project history. The main reasons are stability of the reference source (ThAr calibration lamp), optical efficiency, and easy data reduction.

The role of a spectral reference in the precise measurement of radial velocity is two-fold: 1. To provide a precise wavelength calibration of the detector pixels, i.e. a precise relation between detector geometry and wavelength; 2. To track instrumental drifts – if any – and remove them from the measured stellar radial velocity. Up to now mainly two different techniques have been used successfully in the search for exoplanets with the radial velocity method:

**The Simultaneous Thorium Reference Technique** The simultaneous thorium reference technique was already employed for the detection of the first extrasolar planet, although on a smaller telescope (ELODIE spectrograph on the 1.93 m telescope at OHP).[3] The idea is to use two fibres which feed the spectrograph simultaneously and form two well-separated spectra on the CCD detector. Both fibres are wavelength calibrated at the beginning of the night. During the scientific observation the first fibre is fed with the star light, and on this spectrum the stellar radial velocity is computed by referring to the wavelength solution determined in the beginning of the night. The second fibre is illuminated with the same spectral reference, the thorium lamp that was used to compute the wavelength. If an instrumental drift had occurred since the moment at which the wavelength calibration was performed, the (simultaneous) thorium spectrum on the second fibre would measure it. Although the predecessors of HARPS, ELODIE and later CORALIE on the Swiss-1.2 m Euler Telescope at La Silla, were not optimised for stability, this technique delivered excellent results down to a accuracy level of $3\,\mathrm{m\,s^{-1}}$. Stability of the reference source (ThAr calibration lamp), optical efficiency, and easy data reduction have proved to be the main strength of this technique.

**The iodine absorption cell** A description of this technique was given by Butler et al.[4] It consists of superimposing the stellar spectrum with the spectrum of an iodine absorption cell which provides a radial velocity reference on each scientific frame. This technique is also called "self-calibrating" since the iodine spectrum provides an absolute reference and no independent spectrograph drift measurement is needed. In theory this technique was supposed to be more precise compared to the Simultaneous Thorium Reference technique because the stellar and reference spectrum follow an identical optical path. In practice both techniques have proved in the past to provide similar fundamental accuracies.

A unique feature of HARPS is the fact that it is equipped with both calibration techniques mentioned above and a comparison of both in terms of fundamental accuracy limitations is being undertaken. The first year of operation shows however some clear advantages of the thorium technique. First, the whole visible spectral range can be used. On the contrary the iodine-cell technique covers only the 500 to 600 nm domain. Secondly, the iodine cell produces a mean absorption of the stellar light of about 50%. Finally, the data reduction is much faster, simpler and and more robust in the case of the thorium technique compared to the iodine technique. In summary, the observation efficiency is significantly higher when using the thorium technique. This aspect is particularly important for large programmes such as planet search surveys during which 40 to 80 stars are observed each night. Therefore only the thorium technique is used by our team for this purpose, providing excellent results.

## 2.2. Optical Concept of HARPS

HARPS is a fibre-fed, cross-dispersed echelle spectrograph. Two fibres, an object and a reference fibre, feed the spectrograph with the light from the telescope and the calibration lamps. The fibres are re-imaged by the spectrograph optics onto a mosaic of two 2k×4k CCDs, where two echelle spectra of 72 orders are formed for each fibre. The covered spectral domain ranges from 380 nm to 690 nm. The resolution of the spectrograph is given by the fibre diameter and attains a value of about $R = 115'000$. At this resolution each spectral element is still sampled by 3.5 CCD pixels. A summary of the main HARPS features is given in table 1. For a detailed description of the instrument we refer to Pepe et al[5,6].

**Table 1.** HARPS spectrograph characteristics

| | |
|---|---|
| Optical design | fibre-fed, cross-dispersed echelle spectrograph |
| Technique | simultaneous Thorium Reference |
| Number of fibres | 2 |
| Fibre diameter on sky | 1 arcsec |
| Collimated beam diameter | 208 mm |
| Spectral range covered | 380 nm to 690 nm |
| Spectral resolution | $RS$ =115'000 |
| Spectral format | 72 echelle orders<br>61.44 x 62.74 mm$^2$ |
| CCD chip | mosaic, 2 x EEV 2k×4k<br>pixel size = (15 $\mu$m)$^2$ |
| Sampling | 3.5 pixels/spectral element |
| Minimum inter-order separation | 30 pixels |

## 2.3. Unequalled stability

The real strength of HARPS compared to UVES and other high-resolution spectrographs is its extra-ordinary instrumental stability. Great efforts have been made to stabilise the instrumental profile (IP) and the physical position of the spectrum on the CCD. This goal is achieved by several design choices: a) The instrument is installed in the coudé room of the telescope building and does not move. b) It is fed by fibres which guarantee excellent input beam stability compared to slit spectrographs. This property is further improved by introducing a double image scrambler into the light path.[3] c) The instrument is operated in vacuum in order to avoid drifts of the spectrum on the CCD due to changes in atmospheric pressure. d) The temperature of the spectrograph is kept stable to better than 0.01 K over a year (cf. Fig. 1). e) Both spectral resolution and line sampling (3.5 px per FWHM) have been chosen as high as possible in order to minimise the impact of possible IP-variations on the radial velocity measurement.

The internal stability of the instrument as well as the input illumination stability are of fundamental importance when aiming at the highest precision. It has been shown by Butler et al[7] that even using the "self-calibrating" iodine-cell technique guiding errors or spectrograph temperature drifts can lead to radial velocity

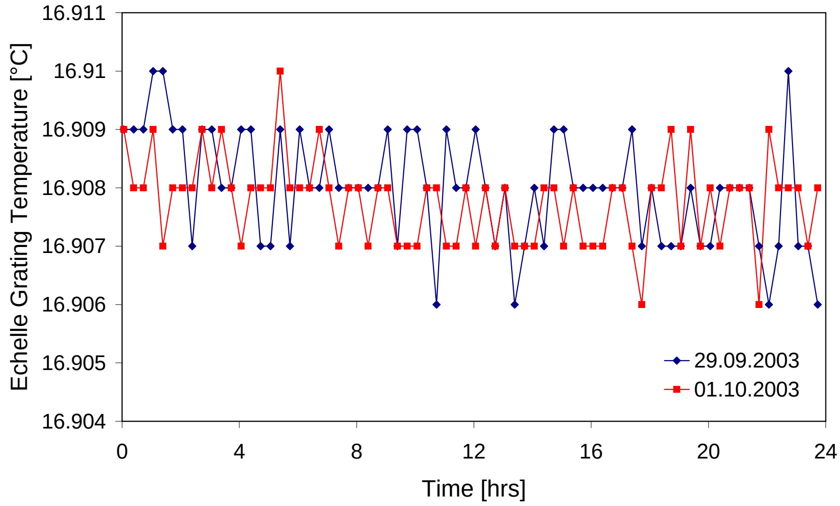


**Figure 1.** Temperature of the spectrograph echelle grating during 24 hours and at two different days. The stability during one day is of the order of 0.001 K *rms* while the yearly stability is better than 0.01 K

jumps and drifts of up to $10\,\mathrm{m\,s^{-1}}$. In the case of HARPS this kind of problems has been removed "at the source" by means of the solutions described above. In particular the guiding problems are considerably reduced by the scrambling properties of the fibres and by the optical scramblers built into both fibres. Thus, instrument drifts and IP variations are almost completely avoided. Possible residual drifts are finally removed by applying the simultaneous Thorium reference technique described above.

The extra-ordinary stability reflects itself directly in the stability of the radial velocity measurements. This is most impressively shown by the measurement series presented in Fig. 2. Both fibres have been exposed repetitively with the ThAr calibration light and the drift – expressed in $\mathrm{m\,s^{-1}}$ – was computed as a function of time. During several hours the total drift remains well below $1\,\mathrm{m\,s^{-1}}$ and the measurement is dominated by "noise". This noise is introduced by the CCD whose temperature varies by $\pm 0.02$ K and produces microscopic dilatation of the chip. In fact, both fibres show the same behaviour and when subtracting one fibre from the other this "noise" disappears and we obtain the dispersion values expected from the photon-noise level of the simultaneous ThAr reference. These measurements prove that the simultaneous ThAr reference technique is perfectly able to track instrumental drift at a level of $0.1\,\mathrm{m\,s^{-1}}$ rms.

### 2.4. Real-Time Data Reduction Pipeline

For efficient observations an extra-ordinary spectrograph alone is not sufficient. Nowadays, a high-performance data reduction must be part of the observing facility. The data reduction pipeline of HARPS offers a complete and final on-line treatment of the data: Dark and BIAS correction, removal of cosmics, order localisation, extraction, spectral flat-fielding, wavelength calibration, cross-correlation with a numerical mask, and fit of the stellar radial velocity including instrumental drift correction. All the reduced data products, i.e. the extracted and wavelength calibrated spectra as well as the precise stellar radial velocity (relative to the solar system barycentre) are delivered to the observer 25 seconds after the end of the exposure by a data reduction pipeline running under LINUX. They are also archived in the ESO Science Archive Facility. The observer leaves the observatory with a complete data set reduced to its final accuracy.

For large programmes this aspect is particularly important. Planet search surveys deliver several thousand frames per years, and long-lasting a-posteriori data reduction would be a clear handicap for the programme. On the contrary HARPS data can be directly used for orbital fitting and further scientific investigations. For an asteroseismology campaign the situation is even more critical. Such observations can deliver up to 1000 spectra per night which is a real challenge for any other data reduction process. The data reduction and archiving process can handle even this enormous stream of data.

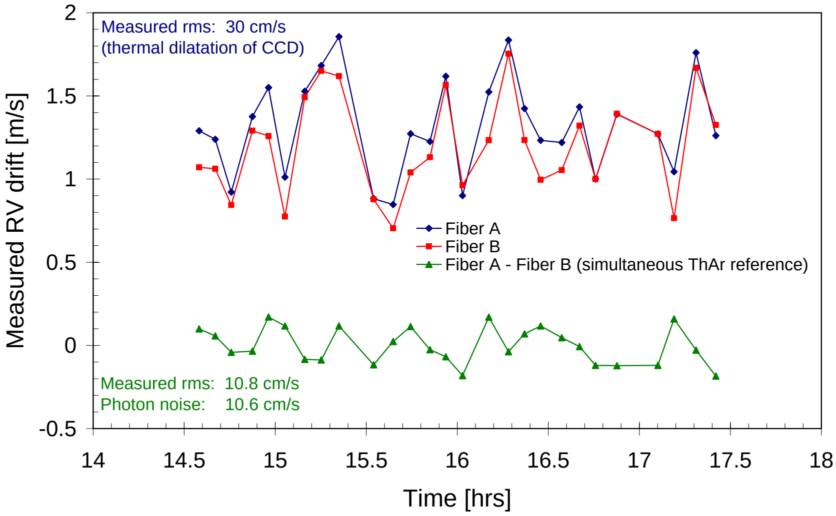


**Figure 2.** Tracking the instrumental drifts by means of the simultaneous ThAr reference. The two upper curves show the "position" of the ThAr spectrum on the CCD for both spectrograph fibres object and reference. Their position, expressed in $\mathrm{ms}^{-1}$, remains stable during several hours proving the excellent absolute stability of the instrument. During scientific observations fibre A is fed with the star while fibre B, illuminated by the thorium, measures the drift of the instrument since the last wavelength calibration. The drift value on fibre B is used to correct the stellar radial velocity measured on fibre A. The difference between both fibres shown on the lower curve indicates how precise the drift correction is: the position of both fibres follow each other perfectly at the photon noise level

## 3. SHORT-TERM STABILITY AND RADIAL VELOCITY PRECISION AT THEIR EXTREME

The short-term precision of HARPS has been characterised on the sky by intensive asteroseismology observations carried out during the instrument commissioning phase.[8] The observations proved that on short time-scales (one night) the precision is better than $0.2\,\mathrm{m\,s^{-1}}$ *rms* and mainly limited by photon noise and, in particular, by the intrinsic stability of the star itself. Besides tracking the instrument drifts the ThAr-lamp does also ensure the long-term precision of the instrument. Daily calibrations allow us to remove long-term trends, if any. It had been shown already with CORALIE that a precision of $3\,\mathrm{m\,s^{-1}}$ *rms* over more than 4 years can be attained. The first months of operation with HARPS indicate that even better long-term precision is within reach.

During the HARPS commissioning we monitored the star $\alpha$ Centauri B, a star a bit smaller than our Sun. During 7 hours we collected a total of 400 spectra with typical signal-to-noise ratios of 500 at 550 nm. The radial velocity measurement sequence plotted in Fig. 3a indicates a dispersion of 51 $\mathrm{cm\,s^{-1}}$ but the zoom shown in Fig. 3b shows that this dispersion is completely dominated by 4-minute stellar oscillations. In fact, the power spectrum of this sequence shown in Fig. 4 clearly exhibits a series of peaks around 4 mHz, corresponding to individual acoustic modes of the star, with amplitudes in the range 10-20 $\mathrm{cm\,s^{-1}}$. The positive interference of several oscillation modes may lead to amplitudes much larger than the amplitudes of single modes. From the power spectrum we estimate that the average contribution of modes reaches $0.44\,\mathrm{m\,s^{-1}}$. By quadratic subtraction of this value from the measured dispersion we obtain a noise level of $0.26\,\mathrm{m\,s^{-1}}$, which is in good agreement with the value extrapolated from the mean white noise level measured in the high frequency range between 6 and 8 mHz in the power spectrum. The photon noise on a single measurement is $0.17\,\mathrm{m\,s^{-1}}$, which leaves less than $0.2\,\mathrm{m\,s^{-1}}$ for all other possible error sources (ThAr noise, guiding errors, influence of the atmosphere, instrumental errors).

Such a level of accuracy in the detection of solar-like oscillation modes has never been reached before. This result obtained with HARPS on a very short sequence (7 hours), clearly shows the unique potential of this instrument in the domain of asteroseismology. Long sequences (several nights are needed to reach a sufficient frequency resolution to characterise individual p-modes) of high sampling radial velocity measurements will permit to measure acoustic waves with amplitudes as small as few $\mathrm{cm\,s^{-1}}$.

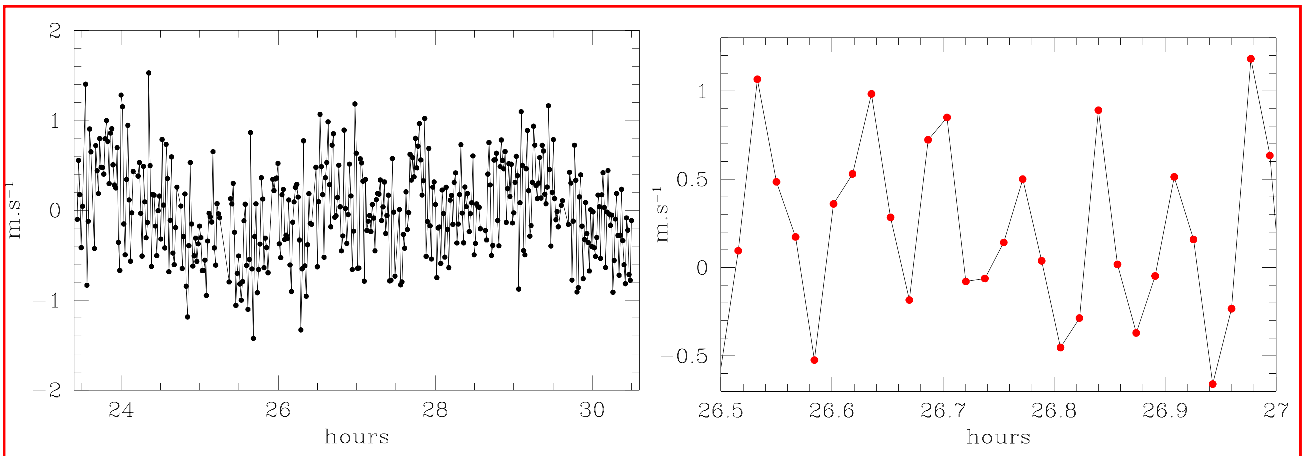


**Figure 3.** a) Series of 7 hours and 420 exposures on $\alpha$ Centauri B proving the extra-ordinary short-term precision of HARPS. b) Zoom into part a) to illustrate the presence of a periodic signal produced by the star's pulsation.

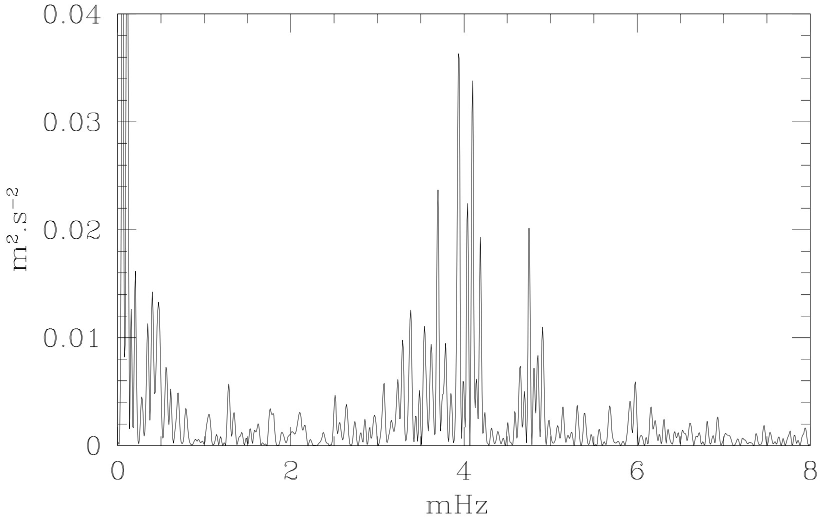


**Figure 4.** Power spectrum of $\alpha$ Cen B. The acoustic modes corresponding to the 4-minutes oscillation are clearly identified and emerge well above the noise.

## 4. WHEN THE STARS LIMIT THE ACCURACY

After the amazing results obtained on $\alpha$ Centauri B we decided to monitor a small set of solar type stars. Fig. 5 shows short sequences of radial velocity measurements obtained on these objects. On *each* of these sequences the stellar oscillations are clearly visible. Stellar parameters and observed oscillation modes are listed in Table 2. As expected, these measurements clearly show that period and amplitude of the oscillation modes are directly related to the stellar properties. They demonstrate the full capability of HARPS for asteroseismology, not only on very bright stars.

These results show however also that the main limitation for HARPS will come from the stellar "noise" itself. The individual mode amplitudes of these stars are in the range 10-50 $\mathrm{cm\,s^{-1}}$ but their additive interference leads to modulation of the Doppler time series of up to 10 times their value. This is clearly a limitation for high precision exoplanet surveys at the level of 1 $\mathrm{m\,s^{-1}}$ and requires to define a precise strategy for target selection and observation. Short-period oscillations (4-8 min) of small amplitudes which occur in G and K dwarfs can

**Table 2.** Stellar parameters and oscillation modes properties

| Star | Spectral type type | Period | Peak-to-Peak modulation | RMS Dispersion |
|---|---|---|---|---|
| $\alpha$ Cen B | K1V | 4 min | $1.5\,\mathrm{m\,s^{-1}}$ | $0.5\,\mathrm{m\,s^{-1}}$ |
| HD20794 | G8V | 5 min | $2.5\,\mathrm{m\,s^{-1}}$ | $0.8\,\mathrm{m\,s^{-1}}$ |
| HD160691 | G5IV-V | 9 min | $5\,\mathrm{m\,s^{-1}}$ | $1.7\,\mathrm{m\,s^{-1}}$ |
| $\beta$ Hydri | G2IV | 16 min | $5\,\mathrm{m\,s^{-1}}$ | $1.7\,\mathrm{m\,s^{-1}}$ |

be easily averaged out with typical exposure times of 15 minutes. Sub-giants and giants, which can show larger amplitudes and longer periods, should however be carefully removed from the sample. This kind of precaution should permit to detect exoplanets at the level of 1 $\mathrm{m\,s^{-1}}$.

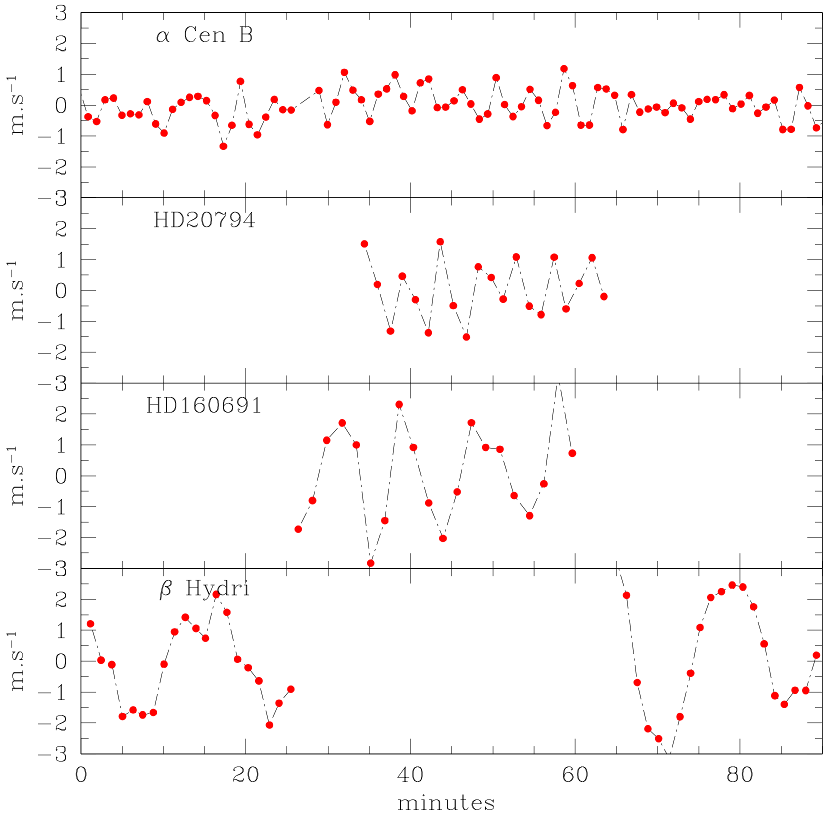


**Figure 5.** Summary plot of the radial velocity of stars for which we have made long observations series. All of them show clear indications of stellar pulsations

## 5. MEASURING RADIAL-VELOCITIES ON LONG TIME SCALES

In the previous section we have shown that on short time scales of typically one night the radial velocity measurement is no longer limited by the instrument precision but the star itself. HARPS is able to resolve small oscillations of the order of 1 $\mathrm{m\,s^{-1}}$. But apart from these oscillations the measured radial velocity of stable stars remains constant during the night at the level of the photon noise, proving that no variable systemic errors above 0.2 $\mathrm{m\,s^{-1}}$ are introduced by the instrument on this time scale.

The proof for long-term precision is more difficult to deliver. In principle one “only” has to find one or more stable stars within the whole sample of monitored stars. In practise, however, almost all stars show intrinsic radial velocity variations. For examples, if for a given star one measurement point is taken every day, the non-resolved p-mode pulsations mentioned above would appear as extra noise of the order of 1 $\mathrm{m\,s^{-1}}$ *rms* or more. Stellar jitter or flares related to the stellar activity can result in even larger radial velocity variations which may attain several tens or hundreds of metres per second over times scales of days or months. Finally, a star can be orbited by an undetected planet which could in turn be interpreted as noise or long-term drift.

To solve these problems a statistical study would be required, based on a sample of several hundred stars monitored for many years. This kind of data set is however not yet available for HARPS. We have therefore chosen a slightly different approach using data currently available: Among our planet search sample we have selected those stars with the lowest *rms*. For each star we have independently determined the mean value and subtracted it from the data points of the corresponding star. For all stars we have plotted the residuals on one single graph (Fig. 6). The total *rms* is of the order of 2 $\mathrm{m\,s^{-1}}$, “all included”, i.e. photon noise, instrumental errors, tracking errors, external error source and intrinsic stellar variability. For some measurements the photon noise attains a level of 2-4 $\mathrm{m\,s^{-1}}$. We have therefore also computed the dispersion by taking into account the photon noise error of each exposure and weighted the measurement point accordingly. The resulting *weighted rms* is only 1.6 $\mathrm{m\,s^{-1}}$. Even more impressive is however the fact that the mean value of the residuals remains constant during one year, from the “First Light” of HARPS in February 2003 until March 2004.

This result is especially remarkable considering the fact that the instrument suffered several critical interventions between “First Light” in February 2003 and start of operations in October 2003. Among these changes done is an exchange of the spectrograph fibres and of the calibration lamps. None of these produced any offset on the stellar data, proving definitively that the simultaneous thorium reference technique is not subject to instrumental profile (IP) changes: While the IP is kept perfectly stable during one night, the thorium calibrations at the beginning of the night remove completely the effect of possible night-to-night IP variations.

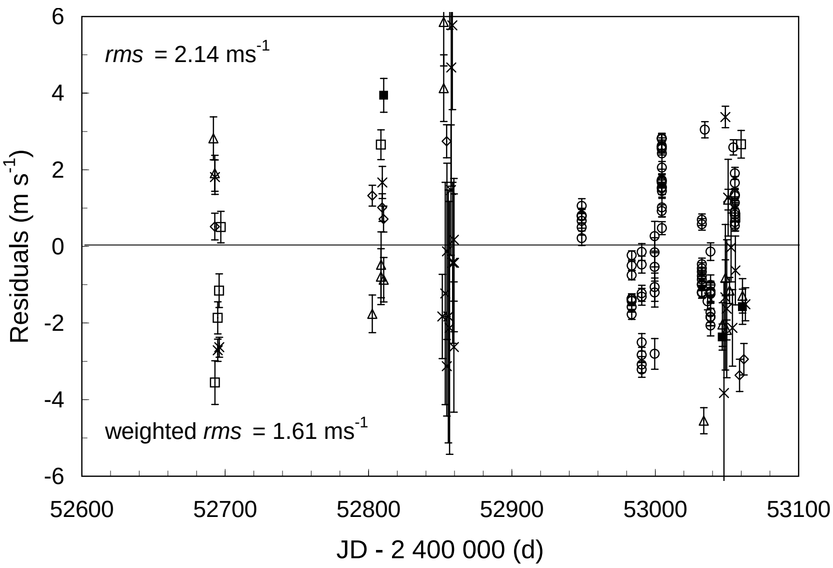


**Figure 6.** Plot of the residuals of many different stars (different symbols) from our planet search survey sample since the “First Light” of HARPS. The “all included” *weighted rms* is 1.6 $\mathrm{m\,s^{-1}}$, despite the fact that several critical instrument changes have been carried out between first light and the start of operations in October 2003. The error bars indicate the pure photon noise level and therefore do not take into account external errors such as stellar contributions.

In Table 3 we give an estimate of the total radial velocity error budget. It has been elaborated on the basis of the experience gained during the first year using HARPS in the simultaneous thorium reference mode. Apart from the stellar contributions the single most limiting factor remains the wavelength (or zero-point) calibration which determines the quality of the night-to-night repeatability of the measurements. Probably the noise on the computed wavelength solution is due to the insufficient knowledge of the wavelengths of the Th lines which are determined with an accuracy of typically $5 \cdot 10^{-5}$ nm (equivalent to 30 $\mathrm{m\,s^{-1}}$). This introduces a global error on the wavelength solution which can lead to an equivalent radial velocity error of about 0.5 $\mathrm{m\,s^{-1}}$. Although the error is already below the 1 $\mathrm{m\,s^{-1}}$ specification we aim at improving further the wavelength solution by building a HARPS-specific wavelength table and thus increasing the quality of the thorium catalogue.

**Table 3.** Error budget for HARPS radial velocity measurements

| Error source | Contribution | Remarks |
|---|---|---|
| Photon noise | 0.5 $\mathrm{m\,s^{-1}}$ | for an $m_V = 8$ G-K dwarf in a 4-minute integration |
| Wavelength calibration | 0.5 $\mathrm{m\,s^{-1}}$ | presently limited by the quality of the thorium lines catalogue |
| Drift measurement with sim. thorium | $< 0.1$ $\mathrm{m\,s^{-1}}$ | typically $< 0.06$ $\mathrm{m\,s^{-1}}$ |
| Atmosphere/guiding/centring | $< 0.18$ $\mathrm{m\,s^{-1}}$ | upper limit including all unknown short-term error sources |
| Stellar pulsations | 0-10 $\mathrm{m\,s^{-1}}$ | |
| Stellar activity/jitter | 0-100 $\mathrm{m\,s^{-1}}$ | |

## 6. RADIAL VELOCITY EFFICIENCY OF HARPS

The *measured* signal-to-noise ratio obtained in a 1-minute integration on an 8th magnitude star is $SNR = 45$ per spectral bin ($\lambda = 500$ nm, $\Delta\lambda = 0.00147$ nm). This value is in full agreement with the theoretical efficiency given at the beginning of the HARPS Project.[9] The respective radial velocity photon accuracy depends on how the radial velocity information is extracted but has fundamental limits given by the spectral information contained in the spectrum (amount of spectral lines, depth and width) and the flux.[10]

In HARPS, as in CORALIE and ELODIE, we determine the radial velocity of a star by cross-correlating its spectrum with a numerical mask computed for a star of similar spectral type in the rest frame of the solar system. Although this method does not fully reach the fundamental limits it has the advantage of being easily applied, fast, and *extremely* robust. The computation does neither need high signal-to-noise reference spectra of the corresponding star, nor any other a priori information except a coarse knowledge (at a level of km/s) of the stellar radial velocity. The flux level might vary strongly even above the saturation level without introducing any significant systematic error.

The achieved radial velocity precision depends however on how well the spectral types of the mask and the star match. The better this match the closer to the theoretical value will the achieved radial velocity precision be. Fig. 7 shows the obtained photon noise precision for a given $SNR = 50$. The computation has been performed for various masks and various stellar spectral types. The results are compared with the fundamental noise limit (crossed circles) which is computed on the *measured* spectrum using the formulae given by Bouchy et al.[10] At $SNR = 50$ we obtain for example a precision of 1 $\mathrm{m\,s^{-1}}$ for a non-rotating G4 dwarf. For rotating stars the fundamental precision decreases rapidly because the sharpness of the spectral features decreases. It can be shown that the precision is inversely proportional to the projected rotational velocity of the star (see Bouchy et al[10]). A difference between fundamental and achieved limits exists, especially for F-type stars, demonstrating that the radial velocity information is not extracted in the optimum way by the cross-correlation method. However, the difference is small for G-type stars and almost zero for K-type stars. The advantages provided by the cross-correlation method fully justify this small loss of precision.

It is also worth mentioning here that the relation between SNR and radial velocity precision for a given mask and star is strictly proportional. The employed simultaneous Th reference technique works perfectly also at very low signal-to-noise values, even when approaching SNR=1. In contrast to this, the iodine-cell technique requires

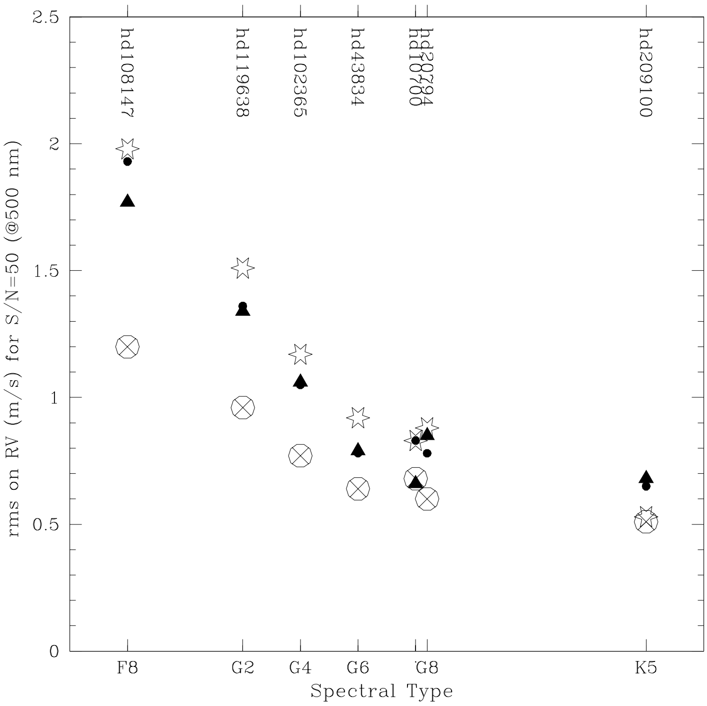


**Figure 7.** Conversion of SNR into radial velocity photon noise accuracy. The simulations have been carried out using measured HARPS spectra. The plot shows the achieved accuracy as a function of spectral type of the star and cross-correlation mask. Triangles represent a G2, filled dots a K0, and stars a K5 mask. The crossed circles show the fundamental limit computed using the formulae given by Bouchy et al.[10] It is also interesting to note that, as expected, the K5 mask is best optimised for late-type stars, while the G2 mask delivers better results for earlier-type stars

high signal-to-ratios of about $SNR = 200$ or higher to deconvolve the spectra and separate the reference signal from the stellar spectrum.

## 7. IMPACT OF HARPS IN THE DOMAIN OF EXTRA-SOLAR PLANETS

The HARPS Consortium's Guaranteed Time Observation (GTO) programme already started in July 2003. In this short run of only 9 nights HARPS already revealed all its characteristics, its optical efficiency, the unique precision and, in particular, the outstanding efficiency of the reduction pipeline. In fact, we have collected about 450 spectra and radial velocity measurements of several hundred stars. Many of them show a varying radial velocity, sometimes with a clear periodicity. Among these HD330075 was showing a radial velocity variation due to an exoplanet of $0.62\,M_{Jup}$ orbiting this star in 3.37 days (see Fig. 8). Only 10 nights of observations have been sufficient for HARPS to discover its first extra-solar planet.

The high radial velocity precision of HARPS opens new perspectives for the field of extra-solar planets, for example in the domain of low planetary masses. Only a few of the 120+ detected planets have masses less than the mass of Saturn, and due to the present precision of radial velocity surveys the distribution of planetary masses is heavily biased (or completely unknown) for masses less than half the mass of Jupiter. HARPS will offer the opportunity to search for very low-mass planets and explore the mass-function for planetary masses below the mass of Saturn and possibly down to a few Earth masses for short periods. The higher precision will also allow the discovery and study in more details of planetary systems with two or more planets.

On the other hand the higher efficiency combined with the simultaneous thorium reference technique allows us to go for fainter objects. Of course this is interesting for the ongoing planet search programme since it offers

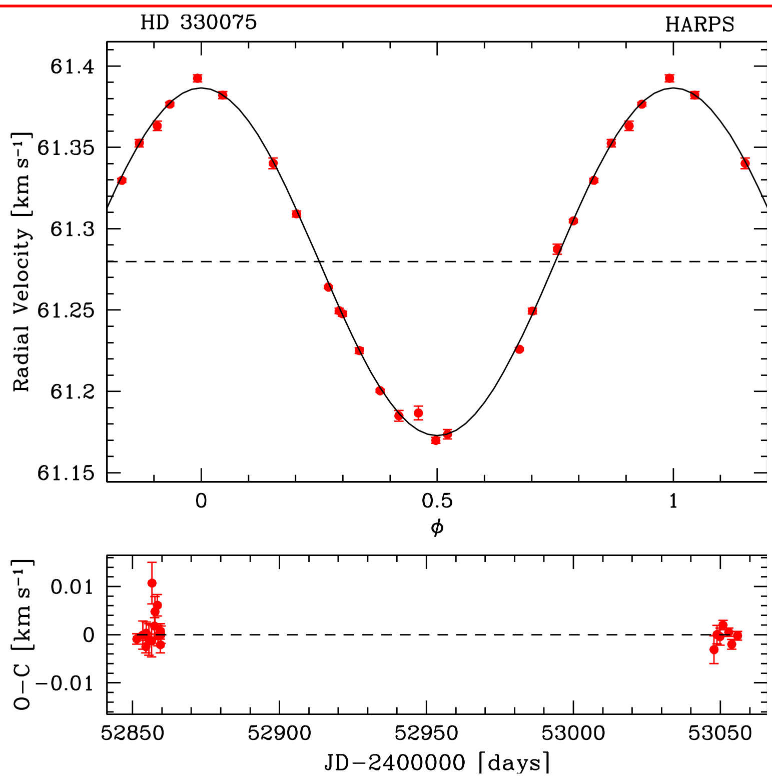


**Figure 8.** First HARPS extra-solar planet: HD330075. The planets has a minimum mass of 0.8 $M_J$ and orbits the star in 3.37 days at a distance of 0.044 AU from its parent star. It belongs therefore to the category of Hot Jupiters. The induced radial velocity variation has a semi-amplitude of 107 m s$^{-1}$. The total dispersion with regard to the orbital solution is $\sigma$(o-c) = 2.0 m s$^{-1}$ and includes photon noise, stellar pulsation and possible jitter

the opportunity to enlarge the sample to fainter stars and thus to larger distances. But it also provides the possibility to follow-up planet candidates delivered by transit search programmes, as demonstrated by the recent confirmation of two transit candidates by radial velocity measurements.[11] These measurements are of particular interest since they provide additional information not available from the transit detection alone, for example the mass of the planet. HARPS will play an important role in this field, also in the frame of the COROT space mission. Complementary ground-based spectroscopic measurements with HARPS will constrain the planetary mass and then the planet's mean density. The main scientific return for the planetary programme of the COROT mission will come from the combination of the photometric and radial velocity data.

Since not even a very good instrument is perfect we are aiming at improving HARPS even further. In order to increase the optical efficiency we installed, as announced,[6] a second pair of fibres with a diameter on the sky of 1.4 arcsec and without an image scrambler. This will sample the seeing disk better in mediocre conditions and improve the efficiency by nearly a factor of two, however at the cost of a spectral resolution reduced by about 30%. This new mode will therefore be ideal for radial velocity work on extremely faint objects ($m_V$=16) where the photon noise is by far the dominating error source (follow-up of e.g. OGLE transits), or for asteroseismology with duty cycles as short as 1 min and even for extragalactic astronomy. We expect First Light for this mode later this year.

Although many extra-solar planets are already known, more discoveries, especially at low masses, are required to get good statistics and a complete view of all possible planetary systems. This input is required for a good understanding of how planets form and evolve under various initial conditions. Thanks to its exclusive properties HARPS will contribute intensely to the acquisition of this knowledge.

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