Ultrastable operation of detectors for high resolution spectrographs

Antonio Manescau*[a], Marco Gullieuszik[b], Olaf Iwert[a], Hans Dekker[a], Jean-Louis Lizon[a], Gaspare Lo Curto[a], Peter Sinclaire[c], Filippo Maria Zerbi[d], Gerd Jakob[a], Dario Sosa[e], Paola Amico[a], Luca Pasquini[a]
[a]European Southern Observatory, Karl Schwarzschildstr. 2, D-85748 Garching, Germany;
[b]Royal Observatory of Belgium, Ringlaan 3, B-1180 Brussels, Belgium;
[c]European Southern Observatory, Alonso de Córdova 3107, Santiago, Chile;
[d]INAF - Osservatorio di Brera, Via Bianchi 46, I-23807 Merate, Italy;
[e]Instituto de Astrofisica de Canarias, Via Lactea s/n, E-38200 La Laguna, Tenerife, Spain

ABSTRACT

High resolution spectroscopy demands detector operation in an extremely stable mechanical and thermal environment; any tiny perturbation may affect the location of the detected spectral lines, affecting the instrument global performance. The detector stability has been identified currently as one of the limiting factors to improve radial velocity measurements accuracy, at the sub m/s level, and an activity focused in the performance understanding of the detector system and how to improve those has been developed. HARPS detector system has been adopted as baseline and the results obtained in a test campaign are described; next activities in the development to improve detector system performance are highlighted, concluding with the information gathered for setting up radial velocity error budgets for the next generation of ESO high stability and high resolution spectrographs.

Keywords: spectroscopy, detectors, radial velocity

1. INTRODUCTION

Key long-term scientific goals of the E-ELT such as indirect detection of Earth-like exo-planets, a direct measurement of the expansion of the Universe and even testing of possible hidden extra-dimensions of space require measuring the Doppler shift of astronomical objects with accuracy significantly beyond the current state of the art. Within the program for preparation for the construction of the European Extremely Large Telescope from the European Commission (Framework Program 7th, FP7) one of its activities aims to develop a breadboard which allows addressing issues to maintain radial velocity measurements accuracy at cm/sec level over several decades, since the detector system stability has been found to be one critical aspect for the global performance.

HARPS[1] represents nowadays the most stable stellar spectrograph and delivers the most accurate radial velocity (RV) measurements. The HARPS detector system has been designated as the baseline for the development of our activity and its characterization is an indispensable step to attain a better performance in the current and next generation of high accuracy spectrographs. A measurement campaign was prepared and executed on HARPS to determine its detector stability and the results are presented. A clone system is being built in the laboratory to first reproduce the measurements already done and then improve the system performance; this will be done together with a detailed computer model of the detector cryostat.

The results of the HARPS program will allow preparing RV budgets for the proposal of the new spectrographs ESPRESSO[2] for the VLT and CODEX[3] for the E-ELT. Those budgets address temperature requirements on detector cryostat system to achieve required RV accuracy for these instruments.

*amanesca@eso.org; phone + 49 89 32006142; http://www.eso.org

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2. THE HARPS STABILITY PROGRAM

A program of measurements was executed to understand the behavior and eventually improve the HARPS detector performance and other detector system in view of the VLT instrumentation and E-ELT programs. To do that a number of series of images, whose objectives are to determine the overall and internal stability of the HARPS detector array, have been obtained under various conditions to:

- Measure "natural" stability using currently valid parameters of the cooling control loop and detector readout parameters
- Look for possible drift due to a ΔT in the temperature set point (impact on drift in pix/ºC)
- Look for possible drift due to a change in dissipation of the chips (impact on drift in pix/mW)

Once completed those test with data obtained in "working conditions", further measurements will be carried out at ESO laboratories on a test cryostat resembling the HARPS setup trying to, first reproduce and then to optimize the stability. This would be done in a laboratory environment where the control parameters can be more easily changed and optimized, temperature sensors attached, etc.

The sequence defined to obtain data which allow investigating the detector system performance in HARPS is as follows:

- Sequence A (4 – 6 hours): exposures spaced at ~ 1 minute intervals (as short as possible but using slow readout), to determine drifts possibly related to the temperature control loop and other short-term effects. Use current settings of control loop parameters.
- Sequence B (4 days): exposures spaced at say 15 minutes intervals, to determine possible drifts due to environmental effects and/or drifts in the rest of the spectrograph (due to e.g. diurnal cycle, atmospheric pressure, LN2 tank exchange, etc). No chip activity, except for one dummy dark needed to space the exposures.
- Sequence C (6 hours): Immediately after sequence B with low chip dissipation, start an observing block with high chip activity between individual exposures instead of the dummy dark, to look at the effect of chip dissipation on drift.
- Sequence D (9 hours): After a stabilization period of 24 hours with no activity, start sequence type A (1 minute between exposures). After 3 hours increase the temperature set point of the detector chip by + 0.5º while the sequence is going on, after again 3 hours change set point temperature back to nominal.

A typical image obtained during the test carried is shown in Figure 1. The signal from both optical fibers that feed the spectrograph are illuminated with the Th-Ar calibration lamp. The HARPS detector is a mosaic of two CCD's.

2.1 Execution of the program

The measurements plan was executed in HARPS in March 2008; sequences A, B and C were taken consecutively, as requested (switch between sequence B and C in day time, with telescope not moving). Sequence D needed 24 hours of no activity, and was executed latter. Vacuum vessel pumping and LN2 exchange took place during the execution of the sequence B, as these are routine activities which cannot be cancelled. Sequence A obtained 139 images, B 424 images, C 78 and D 255 images of the type shown in Figure 1.

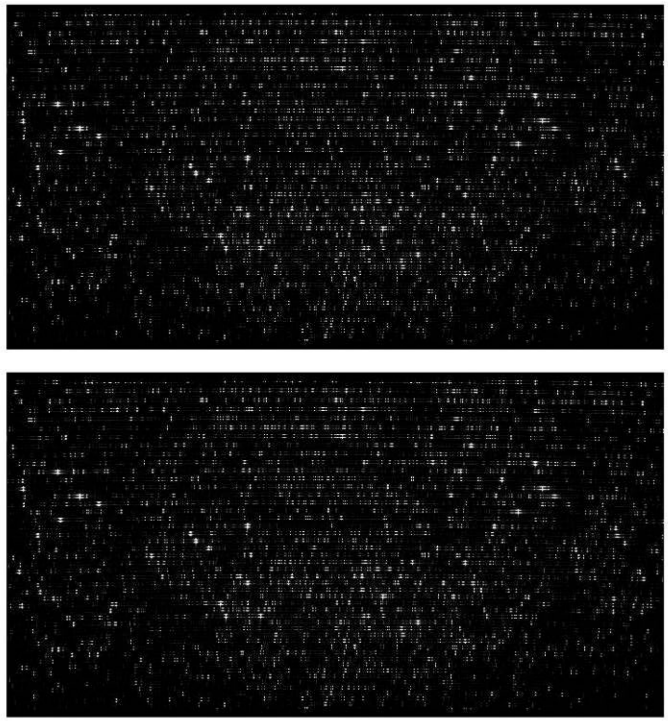


Figure 1. Spectra on the HARPS detector using the Th-Ar lamp for illumination. A mosaic of two 4k x 2k pixels CCD's are used to record the spectra; the image on top correspond to the red part of the spectrum and at the bottom to the blue.

2.2 Data analysis and results

The analysis of the images should provide the drift in X and Y (i.e. along and perpendicular to the main dispersion direction) in pixels of each chip of the mosaic individually. To detect the position of each line Sextractor[4] is used on the raw images. For the detection an absolute threshold value of 300 ADU, and a saturation level of 50.000 ADU is applied, it means that all sources with a pixel below 300 ADU after bias subtraction, or above 50.000 are rejected; with this criteria there are ~4600 and ~2900 lines for red and blue CCD's respectively.

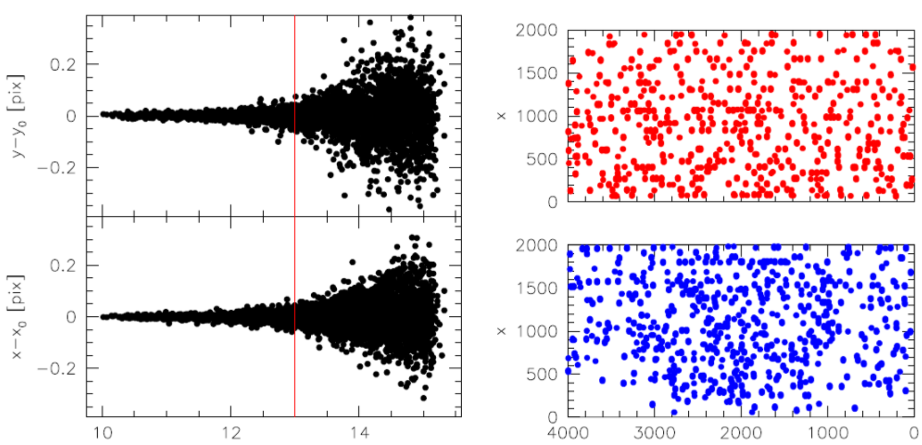


Figure 2. Left Panel: The position differences between lines in image #100 and #1 (Seq D, CCD1) as a function of the magnitude. The vertical line shows the selection criteria. Only sources brighter than mag=13 (for convenience the light intensity is expressed in magnitude) are used to evaluate the mean drifts Right Panel: The position of the final list of selected lines in the blue and red CCDs.

To evaluate the mean drift for each image, the lines with a flux greater than a threshold corresponding to magnitude 13 (see Figure 2 left) (for convenience the light intensity is expressed in magnitude), which are 950 and 850 in red and blue CCD respectively were selected. Their positions in the CCDs are shown in Figure 2 right. Finally, the mean shift in X and Y was calculated for each frame, assuming the first frame of each sequence as the reference. The dispersions of the shifts is in all cases (for all 4 sequences and for both CCDs) ~ 0.015 pix. The error on the mean shifts (taking average on all lines) is therefore ~ $0.015/\sqrt{900} = 5 \times 10^{-4}$ pixels.

- Sequence A (see Figure 3): a linear fit of the "blue" sequence in the central panel give a slope $2.16 \pm 0.36 \times 10^{-4}$ pix/h. The RMS of the fit residual is 5.93×10^{-4}, while the dispersion of the blue points in the upper panel is 3.95×10^{-4}. Both numbers are very close to the error associated to the single measure, which is ~ 5×10^{-4}, as indicated above.

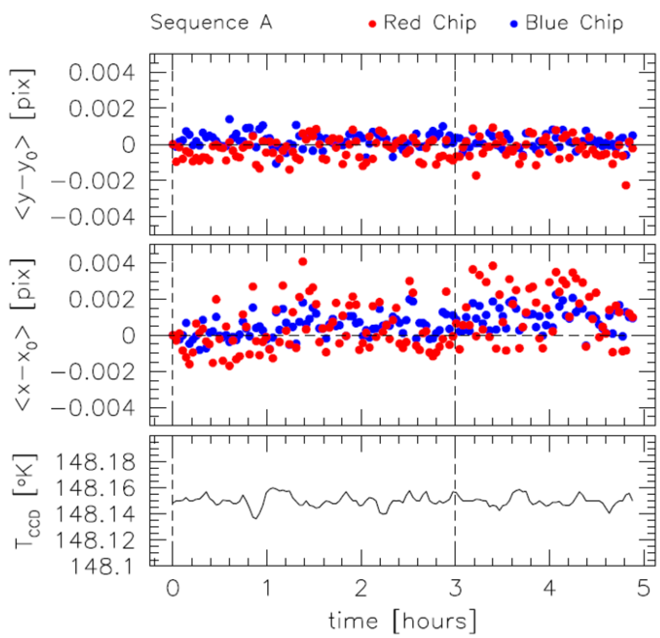


Figure 3. Mean shifts for all observations in Sequence A.

- Sequence B (see Figure 4): the shifts in the Y direction in the two detectors appear to be correlated. The discontinuities around t ~ 5h and t ~ 70h are clearly visible in both sequences. The two main peaks in the lower panel correspond with the discontinuities in the upper panel. They are correlated with the vacuum vessel pumping. The dispersion in two CCD's in the Y direction are $\sigma_{red} = 4.9 \times 10^{-4}$, $\sigma_{blue} = 5.0 \times 10^{-4}$. To test if the two sequences are correlated the difference of the two is calculated. The dispersion of the resulting values is $\sigma_{blue-red} = 5.3 \times 10^{-4}$, which is smaller than the value we would expect if they were not correlated, which is $\sqrt{\sigma_{red}^2 + \sigma_{blue}^2} = 7.0 \times 10^{-4}$. The differences between the mean shifts in the two chips are plotted in the right panel of Figure 4. The dispersion is very low also in the X direction (8.9×10^{-4}). This gives a strong indication that the mean shifts in red and blue chip are strongly correlated.

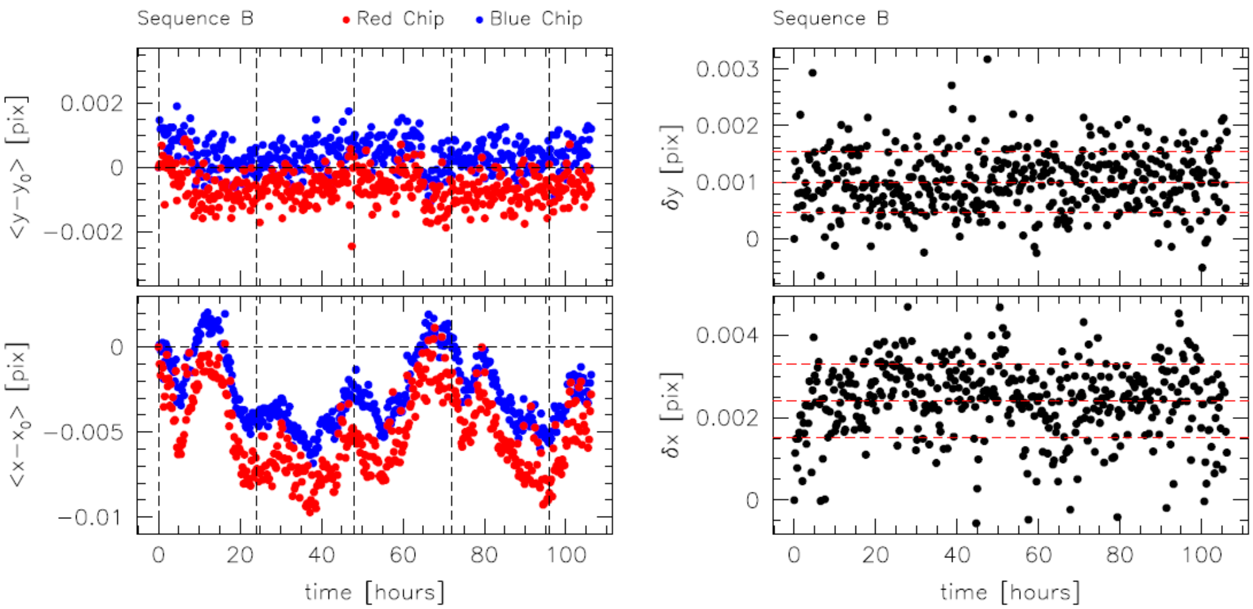


Figure 4. Left Panel: mean shifts for all observations in Sequence B. Right Panel: difference between the mean shift for Blue and Red Chip. No clear trends are present, and the RMS is similar to the measurement error, indicating a strong correlation between the mean shifts in the two chips. Horizontal lines show the mean value and the 1σ dispersion of the points.

- Sequence C (see Figure 5): the results are very similar to the obtained for Sequence A, but in this case, a linear fit of "blue" sequence in the central panel give a slope $3.16 \pm 0.25 \times 10^{-4}$ pix/h (RMS: 5.74×10^{-4}), slightly higher than that found for Sequence A, however still within the error associated to the single measure.

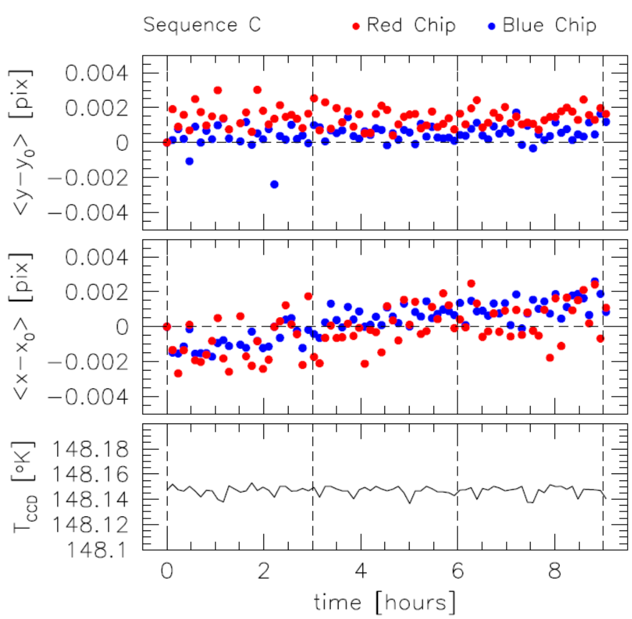


Figure 5. Mean shifts for all observations in Sequence C.

- Sequence D (see Figure 6 and 7): the variation of the shift follows the variations of the recorded temperature (Figure 6, green line on top plot, rescaled to match the data points). When the temperature in increased, the shifts changes in opposite directions for the two detectors in X direction, which means the two CCDs are moving in opposite directions. Considering the CCD mounting scheme, this is an indication of an expansion of the CCD support. In the Y direction there is the same trend but the two CCDs move in the same direction. When the temperature is low (during the first 3h, and the last 3h), the shift in X is nearly constant, but during the central 3h (when the CCD temperature is higher) there is a clear slope in the plot, and this is the same for both CCDs.

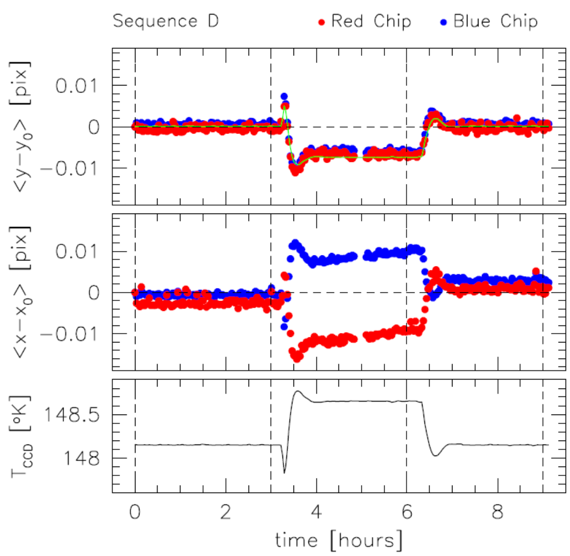


Figure 6. Mean shifts for all observations in Sequence D; the variation of the shift follows the variations of the recorded temperature (green line, rescaled to match the data points on top panel). Bottom panel show the temperature record during the series.

To better understand the results, the detectors are divided regions of 700x700 pixels and the mean shifts for every region is calculated – taking the first image of Sequence D as a reference. An example is shown in the left panel in Figure 7, where the results obtained for one image are plotted as an example. The arrows are the mean shift in each region. All arrows point toward the same point, showing an expansion of the detectors with respect to the first acquisition. From Figure 7 it is possible to conclude that the centre of expansion is located between the two detectors and slightly shifted on the right side, compatible with the real mounting scheme.

To have a more quantitative analysis and estimate the expansion factor, for every image is solved the following system:

$$
\begin{aligned}
x &= S_x + \kappa x_0 \\
y &= S_x + \kappa y_0
\end{aligned}
\qquad (1)
$$

where (x_0,y_0) are the positions in the reference image. In the right panel of Figure 7 is plotted the S_x, S_y and κ parameters for all images. The central and upper panels are very similar to Figure 6, but the S_y in Figure 7 is smaller than the mean shift in y in Figure 6. In conclusion, both plots in Figure 7 give a clear indication that both an expansion of the detector support and the detectors themselves are present.

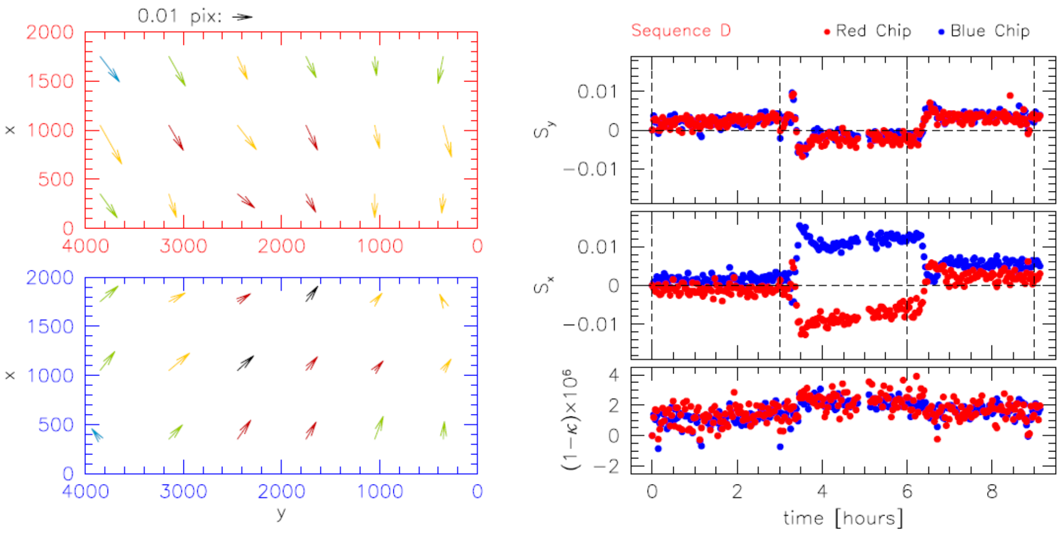


Figure 7. Left Panel: Mean shifts as a function of the position on the chip. Colors from blue to black indicate the total number of lines used to compute the mean (~20, 40, 60, 80 or 100 lines). Right Panel: Shifts and expansion factors for Sequence D (see Eq. 1)

As conclusion sequences A and C, addressing system stability and possible drift due to detector dissipation, do not show a specific trend; the shifts detected are within the error associated to a single measure. The temperature stability on the detector is critical for precise RV measurements, as come up from the sequence D.

3. DETECTOR CRYOSTAT MODEL AND HARDWARE

To continue with the development a detector system similar to the HARPS one has been prepared (see Figure 8), together with a test chamber (see Figure 9), which allows to resemble the environment where the reference image series were taken. A detector mosaic will record images projected with an optical device which generates many spots on the detector.

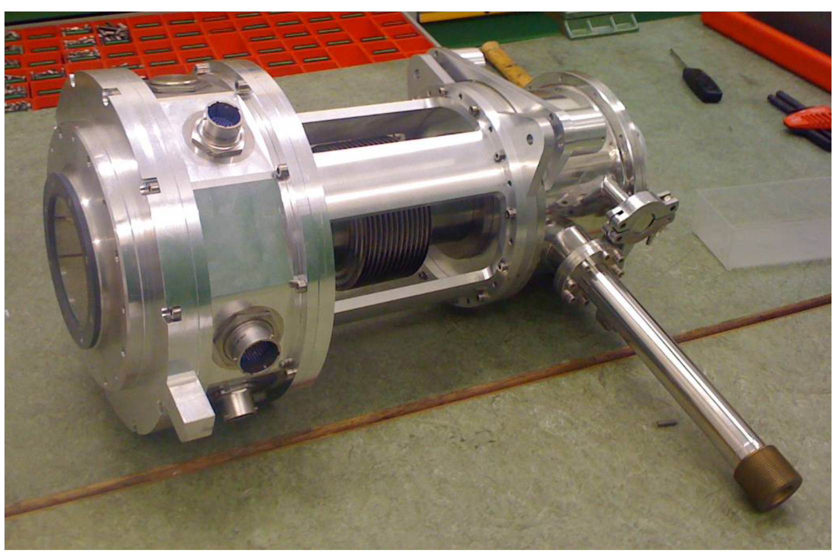


Figure 8. Detector cryostat identical to the one used in HARPS, at the ESO laboratories.

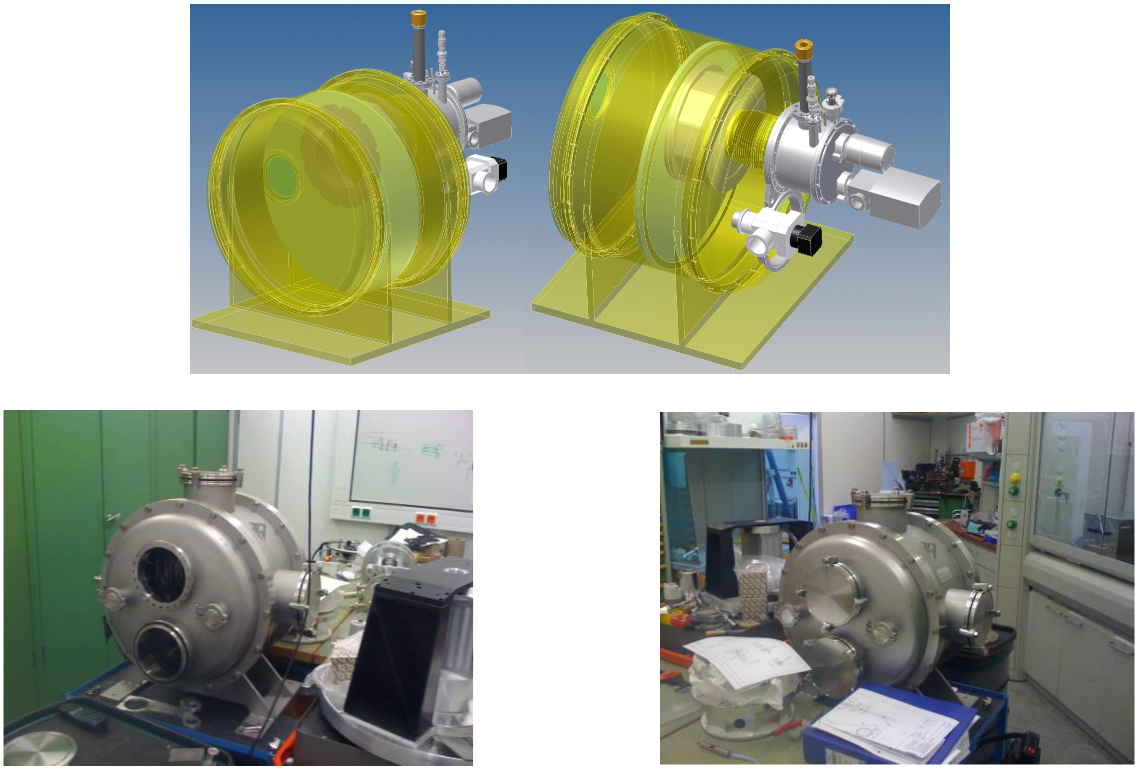
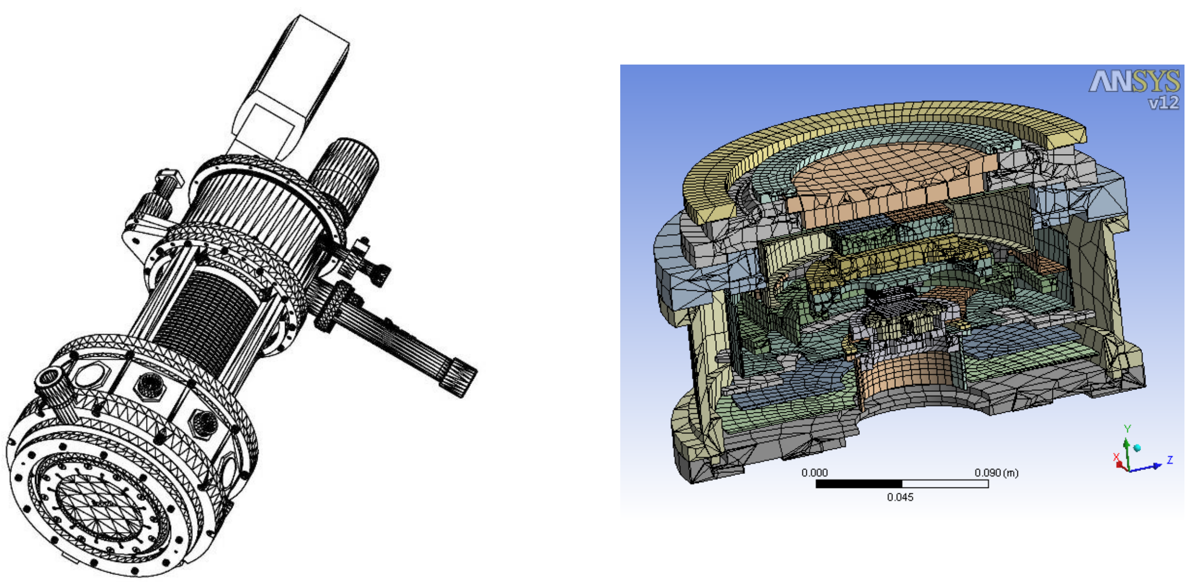


Figure 9. Test chamber to carry out the measurements at the laboratory; on top is sketched the complete setup and on bottom the chamber as received.

A detailed finite element model (F.E.M.) has been prepared (see Figure 10) to carry out performance simulations.



(a) (b)

Figure 10. (a) CAD model of the complete HARPS cryostat and (b) simplified F.E.M. model for the detector head where is clearly seen the two CCDs which forms the detector mosaic.

4. DETECTOR INSTABILITY: CONTRIBUTION TO RADIAL VELOCITY BUDGET IN NEW GENERATION OF HIGH RESOLUTION SPECTROGRAPHS

The results shown above from the data analysis of the HARPS campaign, allowed evaluating contribution of detector instability in the error budgets for radial velocity for the next generation of high-resolution spectrographs at ESO. In the next subsections it is presented the contribution from the detector system to the error in RV accuracy done for ESPRESSO[2] and CODEX[3].

4.1 ESPRESSO

ESPRESSO[2] is proposed as a fiber-fed, cross-dispersed, high-resolution, echelle spectrograph for the combined focus at the VLT, which allows combining the light from up to 4 Unit Telescopes (UT). The target and sky light enter simultaneously the instrument through two distinct optical fibers, which form the spectrograph's "slit". Several optical "tricks" are used to obtain high spectral resolution and efficiency despite the large size of the telescope and the 1 arcsec fiber aperture on the sky[5].

RV accuracy for ESPRESSO is the major goal and 10 cm/sec has been established as specification. The setup of a coherent RV budget has been a major activity to which the knowledge of the detector contribution is crucial. Among the instrument subsystems the detector system will have an effect in the RV performance, which is affected by the thermal stability and the mounting of the detector chip. The required RV accuracy demands that within the time of an exposure the image centroid must be kept stable at the detector level within 2.4 nm.

The stability of the detector is linked to the thermal stability of the environment in which it is located. The plots displayed in Figure 7 have shown that a drift of the detector (conversely read as a drift in the spectrum position) is expected to occur at a rate of 0.01 - 0.02 pixel/K., i.e. 1.5 Angstroms/mK. The geometry of such drift depends on the geometry of the array mounting and the position of the cooling harness. As quoted above the total drift budget at detector level is 2.4 nm. In rough terms each mK of stability requires 10% of the total RV accuracy budget, establishing a temperature stability requirement for the ESPRESSO detector system of 1 mK. The use of the simultaneous calibration (Laser Frequency Comb, Fabry – Perot or Th-Ar lamp) could relax this requirement.

4.2 CODEX

CODEX, the proposed ultra-stable optical high-resolution spectrograph for the E-ELT, will use novel Laser Frequency Comb calibration techniques[6, 7] and an innovative design[8] to open a new era for precision spectroscopy. With its unique combination of light-collecting power and precision, CODEX will facilitate progress across a range of the burning science questions of our time. CODEX will make it possible to realize a long-held dream of cosmologists: to directly measure the acceleration of the Universe, by monitoring the cosmological redshift drift of spectroscopic features at cosmological distances. The unique combination of precision and aperture will also allow the assembly of the first sizeable sample of earth-like planets in the habitable zones of their stars with the radial velocity technique. With the increase in photon flux afforded by the large aperture of the E-ELT CODEX, will take this technique to the level of cm/sec radial velocity stability – a factor of about 50 improvement compared to current instruments.

CODEX aims to a better RV accuracy than targeted by ESPRESSO; CODEX is designed to achieve accuracy in radial velocity measurements of 2 cm/sec; this requires that within the time of an exposure the image centroid must be kept stable at the detector level within 3.2 Angstroms. In the observing mode in which the highest RV accuracy is pursued, CODEX will be used with simultaneous Laser Comb calibration[9]. The accuracy in radial velocity is linked to the differential displacement between the object spectral lines and the simultaneously recorded comb lines. The object lines can move with respect to the comb lines due to several factors such are the position of the centroid of the calibration line, position of the centroid of the spectral line, effect of the ADC and thermo-mechanical stability of the detector. Following the results and reasoning given above for ESPRESSO, for CODEX each mK of stability at the detector requires 50% of the total RV accuracy budget. However when simultaneous calibration is in use (as it is in the most challenging observing modes as regards radial velocity accuracy) what counts is the relative motion between object line and calibration line. This is about an order of magnitude less than the absolute motion and with mK temperature stability the detector system will ask for less than 10% of the budget.

5. CONCLUSION AND NEXT ACTIVITIES

The stability of the detector in for high precision spectrograph is a key aspect to achieve the higher radial velocity accuracy, which is needed in current and in the next generation of high-resolution spectrographs, to attain Doppler shift accuracies beyond the current state of the art. We reported on measured performances of the HARPS detector system, used as baseline for developing new ultra stable cryostat for detectors and described the next steps in this activity which will allow to setup in the laboratory a system resembling the one for HARPS and a computer model as a tool for study improvements in performance which will be applied in ESPRESSO[2] and even in HARPS[10].

The knowledge acquired with the HARPS measurements campaign allowed to workout error budges for radial velocity accuracy in the next generation of ESO high precision spectrographs such are ESPRESSO for the VLT and CODEX for the E-ELT.

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