ESPRESSO: the Echelle spectrograph for rocky exoplanets and stable spectroscopic observations

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ABSTRACT

ESPRESSO, the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations, will combine the efficiency of modern echelle spectrograph design with extreme radial-velocity precision. It will be installed on ESO's VLT in order to achieve a gain of two magnitudes with respect to its predecessor HARPS, and the instrumental radial-velocity precision will be improved to reach cm/s level. Thanks to its characteristics and the ability of combining incoherently the light of 4 large telescopes, ESPRESSO will offer new possibilities in various fields of astronomy. The main scientific objectives will be the search and characterization of rocky exoplanets in the habitable zone of quiet, near-by G to M-dwarfs, and the analysis of the variability of fundamental physical constants. We will present the ambitious scientific objectives, the capabilities of ESPRESSO, and the technical solutions of this challenging project.

1. INTRODUCTION

At its 67th Meeting in October 2007, the ESO STC recommended the development of additional second-generation VLT instruments and its detailed proposal was endorsed by the ESO Council at its 111th meeting in December 2007. Among the recommended instruments, a High Resolution, Ultra Stable Spectrograph for the VLT combined Coudé focus arose as a cornerstone to complete the current 2nd generation VLT instrument suite. Following these recommendations, ESO issued on March 2008 a call for proposal, open to member state Institutes or Consortia, to carry out the Phase A study for such instrument. Our Consortium was successfully selected to carry out the Phase A and later to conduct the ESPRESSO project, the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observation. It will be located in the Combined-Coudé Laboratory (CCL) of the VLT and will be the first instrument able of using a 16-m equivalent telescope. A detailed description of the ESPRESSO Project can be found in [1].

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The main scientific drivers for this instrument have been defined by ESO as follows:

1. Measure high precision radial velocities for search for rocky planets
2. Measure the variation of physical constants
3. Analyze the chemical composition of stars in nearby galaxies

For the capital and human investment, the Consortium will be awarded Guarantee Time Observations. 80% of the observing nights will be invested for the search and characterization of rocky planets in the habitable zone of G, K, and M stars in the 1-UT mode. A 10% of the time will be dedicated to the determination of possible variability of fundamental constants. Depending on the magnitude of the target, this programme will be carried out partially in the 1-UT, partially in the 4-UT mode. The remaining 10% will be reserved for outstanding science cases and allocated as a function of topical questions arising at the moment of the GTO Observations.

2. SCIENCE WITH ESPRESSO

2.1 Scientific Context

High-resolution spectrographs have always been at the heart of astrophysics. They form the observational basic tool for stellar physics and the interstellar and intergalactic medium. Correspondingly, such facilities have always been on high demand at major observatories (see e.g. UVES@VLT or HIRES@Keck). As telescopes get larger, the capabilities of high-resolution spectrographs extend to fainter objects, e.g. faint dwarfs in the solar neighborhood, resolved stars in local galaxies and extragalactic objects. Besides the increase in photon collecting power, another aspect has emerged in recent years: the need for high-precision spectroscopy, i.e. spectra where the instrumental effects are considerably reduced, providing thus highly repeatable observations over long timescales. One prominent technique where such considerations are particularly relevant is the measurement of high-precision radial velocities, or more generally the determination of the positions and shapes of spectral lines. The HARPS spectrograph at ESO-3.6m telescope [2] has been a pioneering instrument in this respect. It clearly appears today that high-precision spectroscopy has a great potential and many exciting discoveries are just around the corner.

The need for a ground based follow-up facility capable of high RV accuracy has been recently stressed in the ESO-ESA working group report on extrasolar planets. In fact, terrestrial planets in habitable zones are one of the main scientific topics of the next decades in Astronomy, and one of the main science drivers for the new generation of ELT. This ESO-ESA report [3] (p. 63) states: a) high precision radial velocity instrumentation for the follow-up of astrometric and transit detections, to ensure the detection of a planet by a second independent method, and to determine its true mass. For Jupiter-mass planets, existing instrumentation may be technically adequate but observing time inadequate; for Earth-mass candidates, special purpose instrumentation (like HARPS) on a large telescope would be required. The same concept is reiterated in the first recommendation: b) Support experiments to improve radial velocity mass detection limits, e.g. based on experience from HARPS, down to those imposed by stellar surface phenomena" ([3], p. 72).

Exoplanet research is just one trigger among many others for high-precision spectroscopy. Do the fundamental constants vary? This is one of the six big open questions in cosmology as listed in the ESA-ESO report for fundamental cosmology [4]. In the executive summary the document states: "Quasar spectroscopy also offers the possibility of better constraints on any time variation of dimensionless atomic parameters such as the fine-structure constant α and the proton-to-electron mass ratio. Presently there exist controversial claims of evidence for variations in α, which potentially relate to the dynamics of dark energy. It is essential to validate these claims with a wider range of targets and atomic tracers." This can be done only with improved spectroscopic capabilities.

ESPRESSO combines an unprecedented accuracy in the radial-velocities determination together with the largest photon collecting area available today. It will certainly provide breakthroughs on many areas of astronomical research, many of which we cannot anticipate.

2.2 The search for rocky exoplanets in the habitable zone

Since 2004, research teams using the RV technique have been making the headlines several times for their discoveries of low-mass extrasolar planets, some of which having only a few times the mass of the Earth. Of the 28 exoplanets known today having a mass below 18 Earth Masses, 23 have been discovered with HARPS (status March 2010). The rate of these discoveries increases steadily. In the present high-precision programme of HARPS it is estimated that more than 30% of the stars harbor extra-solar planets with masses below the mass of Neptune [5]. HARPS in unveiling an exoplanet population which was not known before. These discoveries were made possible thanks to the sub-m s^{-1} precision reached by this instrument. Given the faint magnitude of the star and/or their tiny radial-velocity signal induced by the planet, most of the observed objects would have remained out of reach of existing facilities that were limited to ~3m s^{-1}. On the other hand, this emerging population is supposed to be only the tip of the iceberg. Considering the observational bias towards small masses, on the one hand, and the prediction made by planet-formation models [6], on the other hand, one should expect a huge amount of still undiscovered planets, even in already observed stellar samples.

ESPRESSO is designed to explore this new domain and to enter into unknown territory. This goal can only be obtained by combining high efficiency with high instrumental precision. ESPRESSO will be optimized to obtain best radial velocities on quiet solar-type stars. A careful selection of these stars will allow focusing the observations on the best-suited candidates: non-active, non-rotating, quiet G to M dwarfs. With a precision of 10 cm s^{-1} or better it will be possible to detect rocky planets of few Earth masses in the habitable zone of solar type stars. By extending the sample towards the lighter M-stars the task becomes even 'easier'. Given its efficiency, spectral resolution and spectral domain, ESPRESSO will be most efficient up to M4 dwarfs.

The discovery and the characterization of this new population of very-light planets will open the door to a better understanding of planet formation and deliver new candidates for follow-up studies by transit, astrometry, transit spectroscopy, Rossiter-McLaugling effect, etc. Opposite, ESPRESSO will be the ideal (and maybe the only) machine to make spectroscopic follow-up of Earth-sized planets discovered by the transit technique.

2.3 Do fundamental physical constants vary?

In 1999, observations of spectral lines in distant QSOs gave the first hints that the fine-structure constant might change its value over time, being lower in the past by about 6 parts per million [7], [8]. More recently, also $\mu = m_p/m_e$ has been found to vary [9]. However, other recent results suggest no variation. The debate is still open and calls for new, more precise measurements. Only a high-resolution spectrograph which combines a large collecting area with extreme precision can provide definitive answers.

VLT's ESPRESSO, by means of its extreme stability and wavelength calibration, will provide an increase in the accuracy of the measurement of these fundamental constants by at least 1 order-of-magnitude. A confirmation of variability with high statistical significance is of crucial importance. It will open a window to new physics beyond the Standard Model and possibly shading new light on the nature of Dark Energy. On the other hand, more stringent bounds are important to constrain various theoretical models which lead to the variability of fundamental constants. Some very few objects are sufficiently bright to be observed in the 1-UT mode. For the others, the 4-UT mode will be perfectly appropriated and offers sufficient SNR to answer definitively this fundamental question.

2.4 A Pandora-box of other science

Given its efficiency, the high spectral resolution - and in particular the R = 225'000 mode -, the extreme high radial-velocity precision, and the possibility of combining up to 4 UTs, we expect that ESPRESSO will not only be able to fulfill the main scientific objectives, but also open a new parameter space in observational astronomy with hopefully many new and unexpected results. A preliminary and certainly incomplete list of additional unique and exciting sciences cases, which can be addressed with ESPRESSO by the astronomical community, will be given here:

- Chemical composition of stars in local galaxies
- Investigation of metal-poor stars
- Stellar oscillations, asteroseismology
- Diffuse stellar bands in the interstellar medium
- Chemical enrichment of IGM
- Galactic winds and tomography of the IGM
- Chemical properties of protogalaxies
- Cosmology
- Further extra-solar planet science
    - The Rossiter-McLaughlin effect
    - Transmission spectroscopy
    - Planets in nearby open clusters and galaxies

3. ESPRESSO – A NEW-GENERATION SPECTROGRAPH

3.1 Instrument concept

ESPRESSO is a fiber-fed, cross-dispersed, high-resolution, echelle spectrograph. The telescope light is fed to the instrument via a Coudé-Train optical system and fibers. ESPRESSO is located in the Combined-Coudé Laboratory (incoherent focus) where a front-end unit can combine the light from up to 4 Unit Telescopes (UT) of the VLT. The target and sky light enter the instrument through two distinct optical fibers which form the 'slit' of the spectrograph.

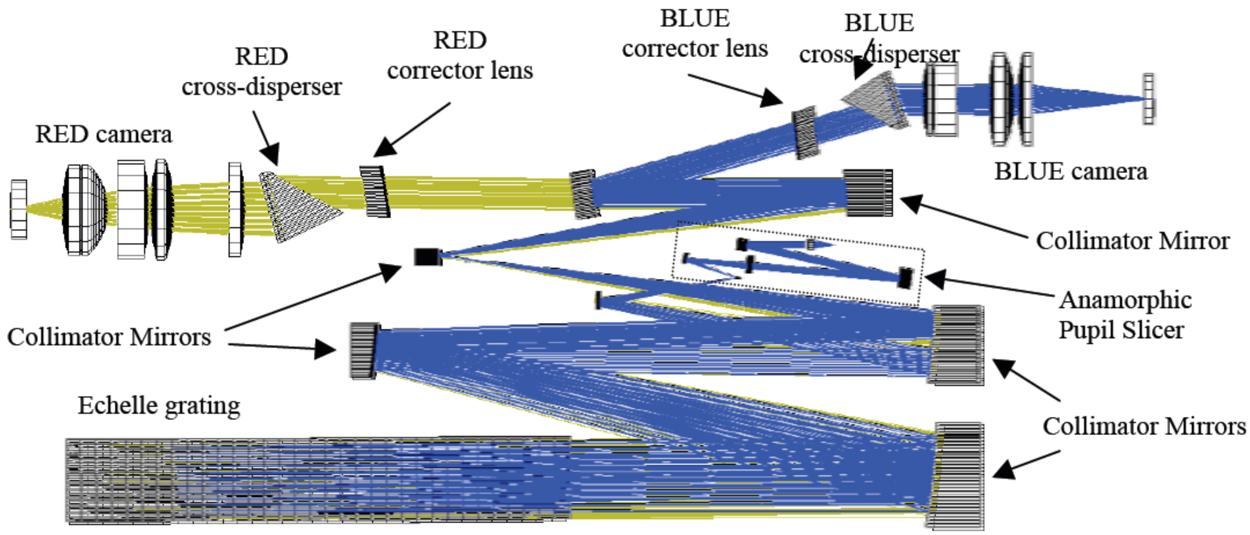

Figure 1. Optical layout of the ESPRESSO spectrograph

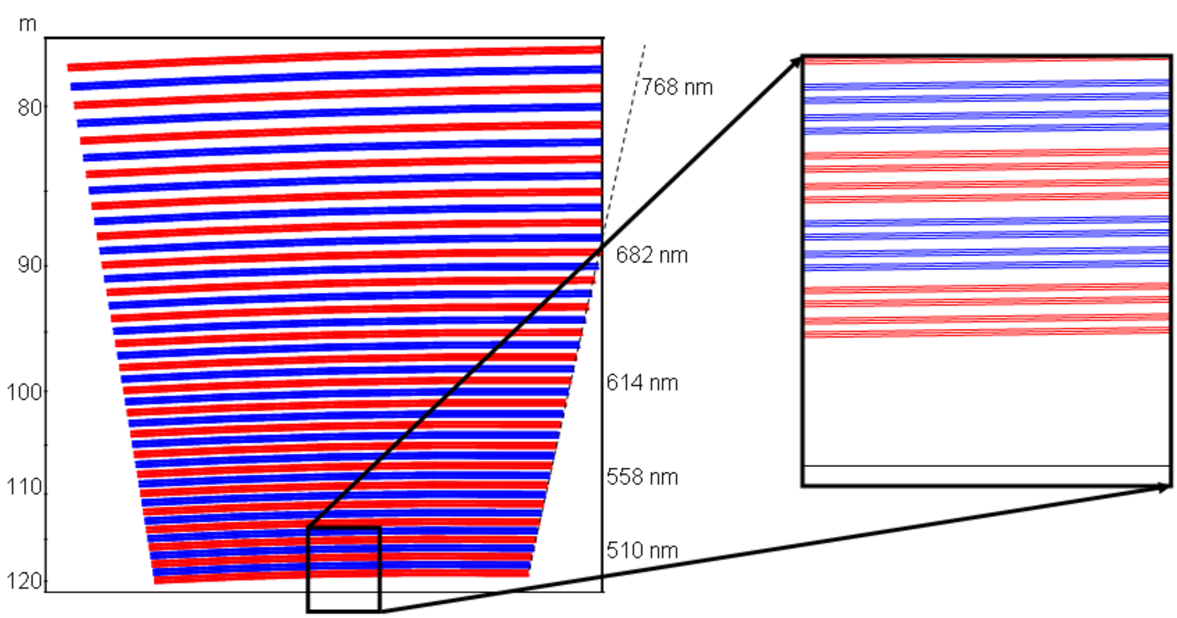

Figure 2. Spectral format of the red arm of ESPRESSO. A similar format with shorter orders is available for the blue arm. The zoom on the right side shows the four slices of each order (2 for the target and 2 for the reference fiber). Distinct orders are distinguished by different colors.

Several optical 'tricks' are used to obtain high spectral resolution and efficiency despite the large size of the telescope and the 1 arcscec field of the instrument. At the entrance of the spectrograph an anamorphic pupil slicing unit (APSU) shapes the beam in order to compress the beam in cross-dispersion direction but not in main-dispersion direction, where the full resolving power is required. In the latter direction, however, the pupil is sliced and superimposed on the echelle grating to minimize its size. The rectangular white pupil is then re-imaged and compressed. Given the wide spectral range and the high number of spectral channels, two large 90 mm x 90 mm CCDs are required to record the full spectrum. Therefore, a beam splitter separates the beam in a blue and a red arm which in turn allows to optimize each arm for image quality and optical efficiency. The cross-disperser has the function of separating the dispersed spectrum in all its spectral orders. In addition, an anamorphism is re-introduced to make the pupil square and to compress the order width in cross-dispersion direction, such that the inter-order space is maximized. We refer to [10] for a detailed description of the optical design.

3.2 Feeding and operating the instrument with up to 4 UTs

ESPRESSO is located in the (incoherent) Combined Coudé Laboratory of the VLT (CCL). It is fed from any of the UTs, separately or simultaneously, via the M4, a fiber feed along the Coudé Train, and a beam launching optics through the tunnels. This location opens the unique opportunity to feed it with the four UTs simultaneously, thus yielding a 16m-equivalent telescope. As such, the 4-UT mode is expected to offer a gain of about 1.2-1.5 mag compared to UVES and will thus make unique science possible, which today is prevented by the readout-limited regime. Given the operational constraints, it appeared interesting to also offer a "reduced" 4-UT mode in which only 2 or 3 UTs are fed to ESPRESSO. Operationally the instrument will have only two main modes, a 1-UT and a 4-UT mode. In the 1-UT mode ESPRESSO will behave like any other VLT instrument. In the 4-UT mode, one can choose to feed any 2, 3 or 4UTs into the instrument. The spectral resolution will be reduced by a factor of two (given twice the collecting area diameter), but efficiency and field size will be conserved throughout the chosen configuration. We refer to [11] for a detailed description of the so-called Coudé path of ESPRESSO.

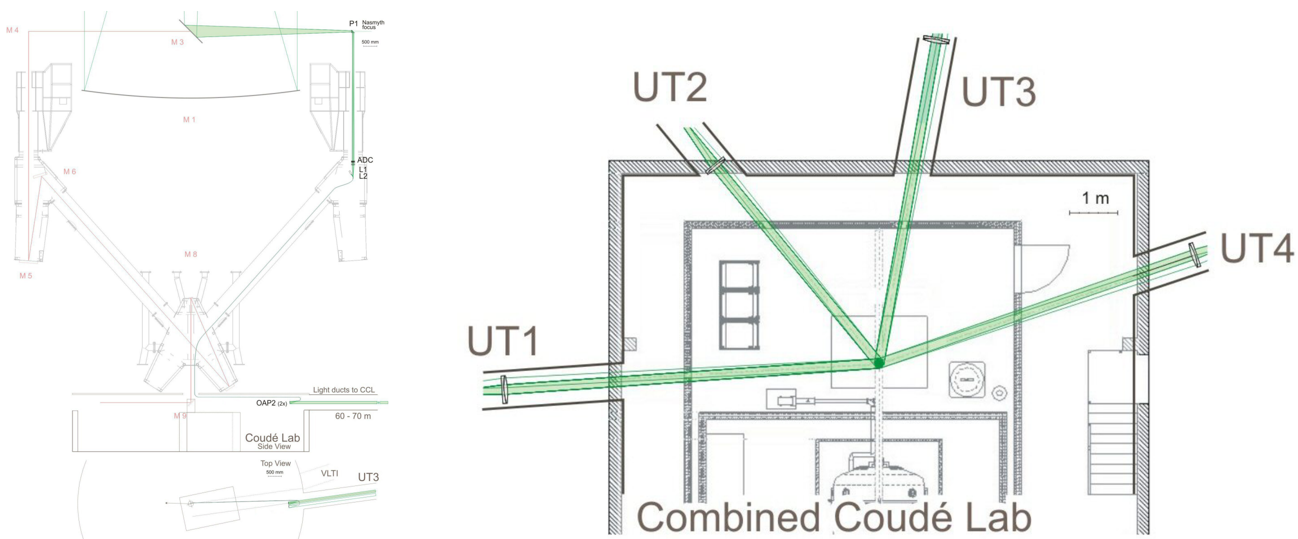

Figure 3. Left: Optical path from the M3 of an Unit Telescope (UT) of the VLT to the entrance of the light tunnels. Right: Incoherent recombination of the light beams from the four UTs in the Combined Coudé Laboratory, before being injected into a single spectrograph fiber.

The implementation of the 4-UT mode indirectly provides another major advantage for the 1-UT mode: operational flexibility. In 1-UT mode, ESPRESSO can be fed by any of the four UTs, which significantly extends the scheduling possibilities for ESPRESSO programmes and optimizes the use of VLT time in general. Scheduling flexibility is a fundamental advantage for survey programmes like radial velocity searches for extra-solar planets or time-critical programmes like studies of transiting planets. The 1-UT mode itself will thus greatly benefit from the implementation of the 4-UT mode.

4. AN INSTRUMENT FOR EXTREME PERFORMANCES

4.1 Extreme spectroscopic and radial-velocity precision

The extreme precision will be obtained by adopting and improving well-known HARPS concepts. The light of 1 or several UTs is fed by means of the front-end unit into optical fibers which provide light scrambling and thus excellent stability of the spectrograph illumination. In order to improve light scrambling non-circular fiber shapes will be considered. (Laboratory tests on octagonal fibers have demonstrated that the scrambling efficiency can be increased by a factor of 10.) The target fiber can be fed either with the light of the astronomical object or the calibration sources. The reference fiber will receive either sky light (faint source mode) or calibration light (bright source mode). In the latter case - the famous simultaneous-reference technique adopted in HARPS - it will be possible to track instrumental drifts down to the cm s^{-1} level. This technique relies on the perfect knowledge and stability of the spectral lines of the calibration source. Therefore, ESPRESSO will integrate a new developed laser frequency comb [12], [13], which provides stability and accuracy of better than 10^{-12}, well below the mm s^{-1} regime.

Table 1. Summary of the characteristics of ESPRESSO in its main modes

Parameter	Standard 1-UT	4-UT	Ultra-High Res 1-UT
Wavelength range	380-800 nm	380-800 nm	380-800 nm
Resolving power	140’000	60’000	225’000
Aperture on sky	1.0 arcsec	4x1.0 arcsec	0.5 arcsec
Sampling (average)	3.3 pixels	4.0 pixels (binned x2)	2.1 pixels
Spatial sampling	6.9 pixels	4.0 pixels (binned x4)	3.5 pixels
Simultaneous reference	Yes (no sky)	Yes (no sky)	Yes (no sky)
Sky subtraction	Yes (no sim. ref.)	Yes (no sim. ref.)	Yes (no sim. ref.)
Total efficiency	12%	12%	TBD
Instrumental RV precision	< 10 cm s^{-1}	~ 1 m s^{-1}	< 10 cm s^{-1}

In the 1-UT mode an SNR of 10 is obtained with 3 exposures of 20 minutes on a V = 17.1 star, as specified. In the 4-UT mode, the SNR of 10 on a V = 20.1 star is achieved with a single 1-hour exposure. For reference, the 10 cm s^{-1} limit is shown. We have estimated that at R = 140’000 resolution this precision is attained for a S/N of 600 per extracted pixel, while for the 4-UT mode at R = 60’000 resolution a higher S/N of 1000 would be required.

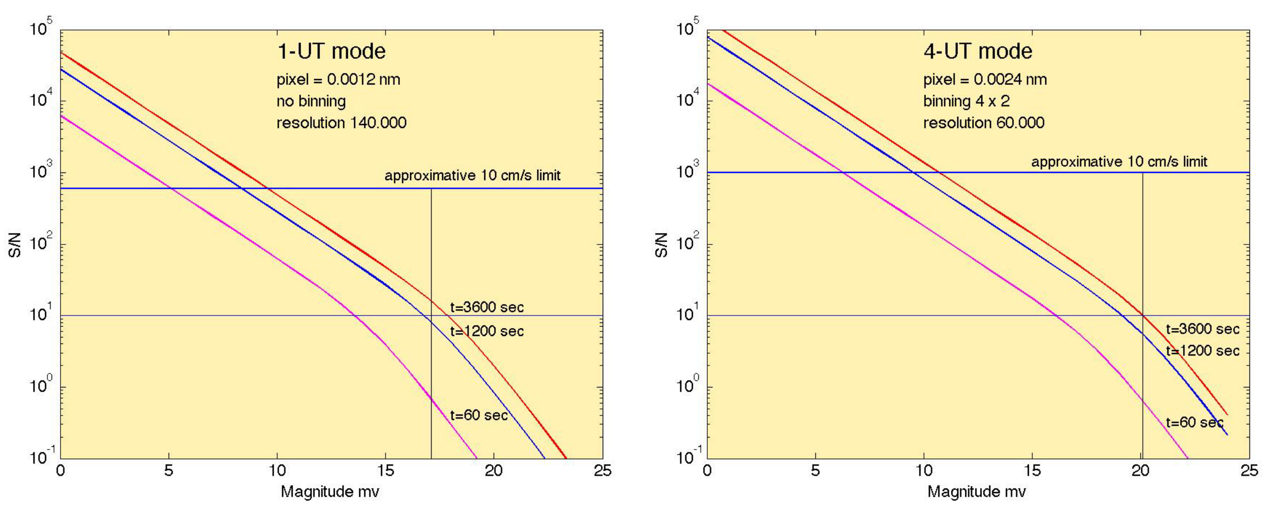

Figure 4. ESPRESSO performances in the 1-UT and the 4-UT mode

A 1 nm physical shift of the spectrum corresponds to 6 cm s^{-1} radial-velocity shift. Although the simultaneous reference is able to track potential drifts, the position of the target spectrum on the CCD shall be maintained as stable as possible in order to avoid higher-order effects. The whole spectrograph is therefore installed in a vacuum chamber and controlled in temperature. Pressure and temperature variation will be kept below 0.001 mbar and 0.001 K, respectively, such that the spectrum will not drift by more than 10 cm s^{-1} on daily basis. The detector system, which is based on a standard ESO model, will as well be optimized for thermal and mechanical stability.

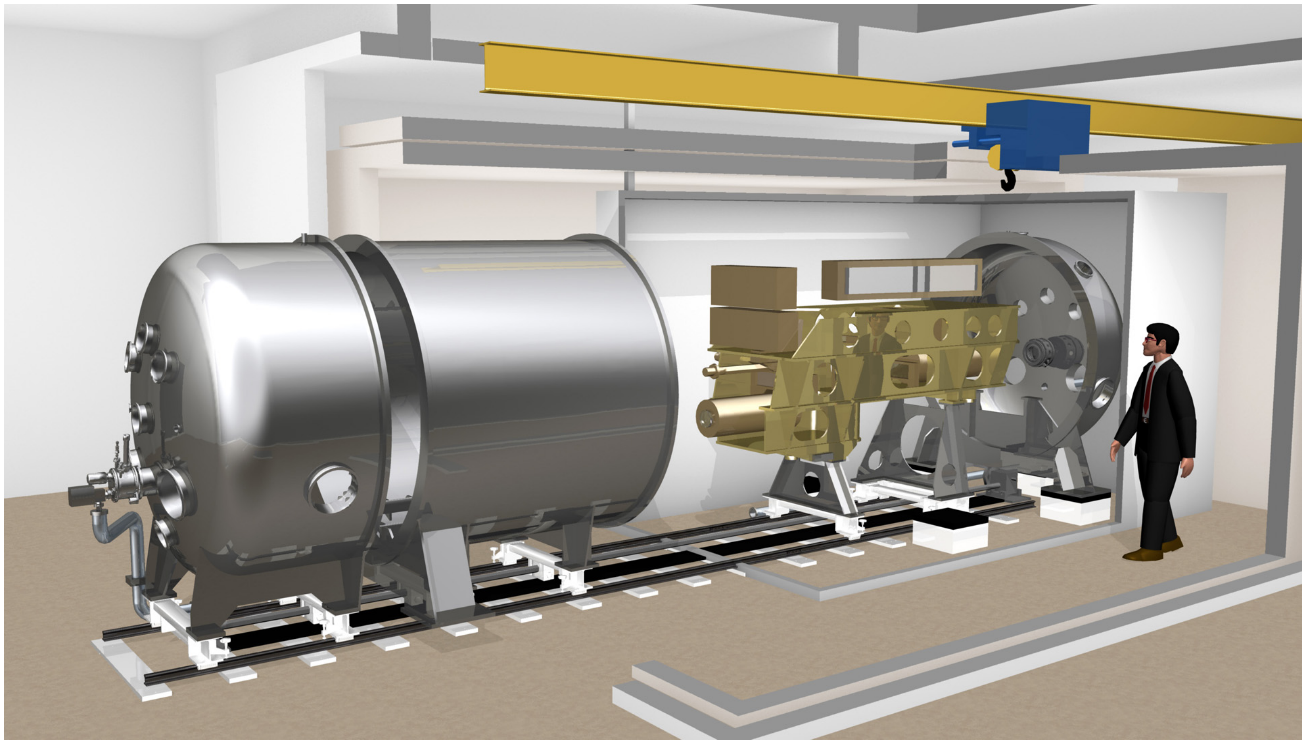

Figure 5. Mechanical layout showing the open vacuum vessel and the spectrograph, as well as a sketch of the thermal enclosure

4.2 End-to-end operations

The overall efficiency and the scientific output of long-lead programmes can be considerably increased if an integrated view of the operations is adopted. ESPRESSO shall not be considered as a stand-alone instrument but as a 'science-generating machine'. An integrated view can only be obtained if the operations consider all the aspects, from the operation preparation through the instrument operation and control SW and HW, to the data reduction and analysis, and the related data products. ESPRESSO will deliver full-quality scientific data less than a minute after the end of observations. These data, including the reduced data, will be archived and periodically reprocessed to obtain a coherent data set.

All these steps will be optimally integrated into the Paranal Observatory environment such that the result is satisfactory for the observatory and the Users. The final goal is to provide eventually the User with scientific data as complete and precise as possible.

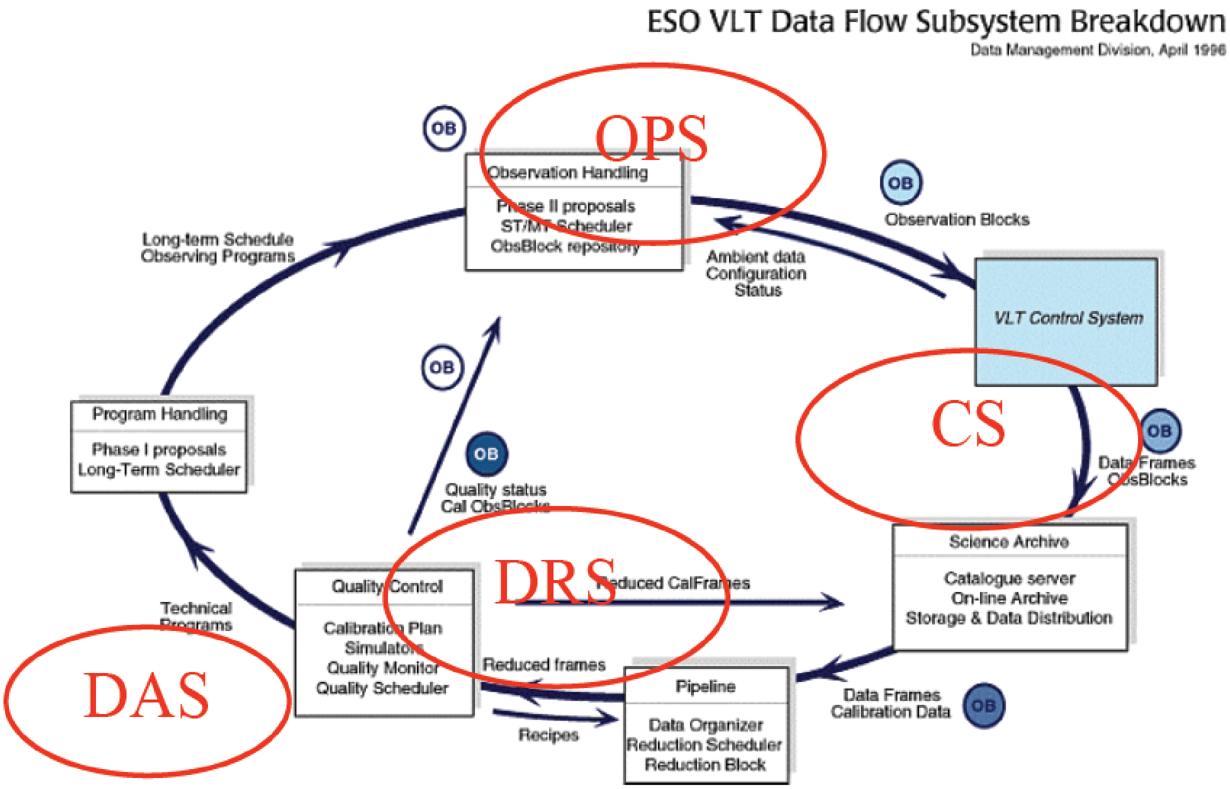

Figure 6. Data-flow system

4.3 ESPRESSO as a CODEX precursor

ESPRESSO has not to be seen as a CODEX@E-ELT [14], [15] prototype in the sense that it will not be possible to simply clone it for the E-ELT. The main reason is that CODEX will have to cope with a very different telescope size and that some design elements have been adapted to this specificity. Nevertheless, ESPRESSO can be considered as a precursor of CODEX at the E-ELT for aspects concerning technology development, operations and scientific use. Precious information and experiences have been and will be exchanged between the two projects.

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