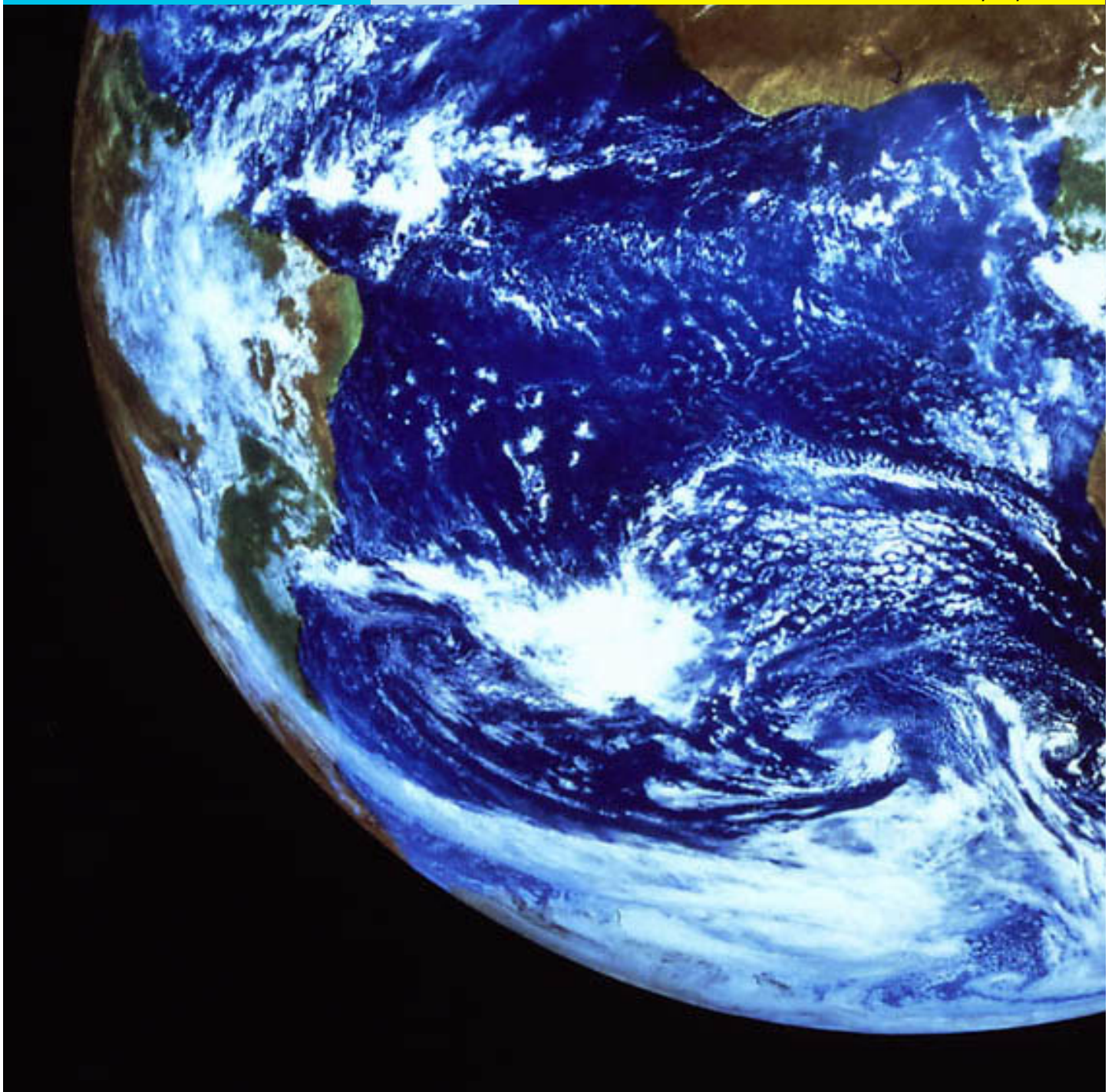




ESPRESSO

Final Design Executive Summary

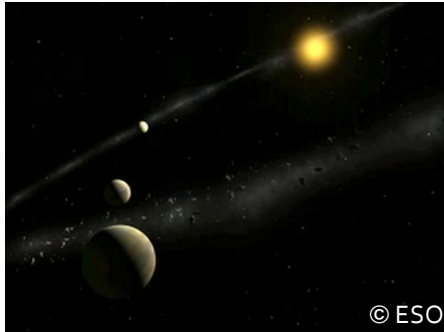
Doc. nr. VLT-TRE-ESP-13520-0037 Issue 3 26/03/2013



The Context



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 2007 a call for proposal, open to member state Institutes or Consortia, to carry out the Phase A study for such an instrument. The submitted proposal was accepted by ESO and the Consortium led by the Observatoire de Genève was selected to carry out the Phase A Study for this High-Resolution Ultra Stable Spectrograph.

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



The *Echelle S*pectrograph for Rocky Exoplanet and Stable Spectroscopic Observation, *ESPRESSO*, described in the Preliminary Design Report, is a fiber-fed cross-dispersed echelle spectrograph which can be operated with one or up to 4 UTs of ESO's VLT. It will be located in the Combined-Coudé Laboratory (CCL) of the VLT to be the first instrument able of using a 16-m equivalent telescope. The instrument design and the project organization have been chosen to comply with the main scientific drivers mentioned above, but offer many new and exciting scientific possibilities to the community.

Scientific context

High-resolution spectrographs have always been at the heart of astrophysics. In particular, they form the observational basis 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 at the VLT or HIRES at 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 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 the ESO-3.6m telescope has been a pioneering instrument in this respect. It clearly appears today that high-precision spectroscopy has a great potential for new exciting discoveries.

The need for a ground based follow-up facility capable of high RV accuracy has been stressed in the ESO-ESA working group report on extrasolar planets. In fact, *terrestrial planets in habitable zone* is one of the main scientific topics of the next decades in Astronomy, and one of the main science drivers for the new generation of ELTs. The ESO-ESA document at p. 63 states: "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: "Support experiments to improve radial velocity mass detection limits, e.g. based on experience from HARPS, down to those imposed by stellar surface phenomena" (ESA-ESO report, p. 72).

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 (Peacock et al 2006). 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 in many areas of astronomical research, many of which we cannot anticipate.

The Science



The search for rocky-planets 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. Two thirds of the exoplanets known today having a mass below 10 Earth Masses have been discovered with HARPS. The rate of these discoveries increases steadily. From the high-precision program it has been shown that 50% of the stars harbor Neptune-mass planets and super-Earths. 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 the 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 $\sim 3 m s^{-1}$. 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 predictions made by planet-formation models, on the other hand, one should expect a huge amount of still undiscovered low-mass 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 to focusing the observations on the best-suited candidates: non-active, non-rotating, quiet G to M dwarfs. With a precision of $10 cm s^{-1}$ 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-McLaughlin effect, etc. In addition, ESPRESSO will be the ideal (and maybe only) machine to make spectroscopic follow-up of Earth-sized planets discovered by the transit technique.

Do 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 (Webb et al 1999, Murphy et al. 2004). More recently, also $\mu = m_p / m_e$ has been found to vary by Ivanchik et al (2005), Reinhold et al (2006). However, other recent results suggest no variation. The debate is still open and calls for new, more precise measurements. Only a high-resolution spectrograph that combines a large collecting area with extreme wavelength precision can provide definitive clarification.

VLT 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 shed new light on the nature of Dark Energy. More stringent bounds are important to constrain various theoretical models that lead to the variability of fundamental constants.

Some very few objects are sufficiently bright to be observed with one UT. Fainter objects will greatly benefit from the possibility of using four UTs simultaneously and thus obtain sufficient SNR to answer definitively this fundamental question.

A Pandora box of science

Given its efficiency, the high spectral resolution - and in particular the $R = 220'000$ mode -, the extreme high radial-velocity precision, and the possibility of combining up to 4 UTs, 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. The original scientific report of ESPRESSO (Phase A) describes in detail additional unique and exciting sciences cases which can be addressed with ESPRESSO by the astronomical community.

- [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 and expansion of the Universe](#)
- [Further extra-solar planet science](#)
 - [The Rossiter-McLaughlin effect](#)
 - [Transmission spectroscopy](#)
 - [Planets in nearby open clusters and galaxies](#)

Use of GTO

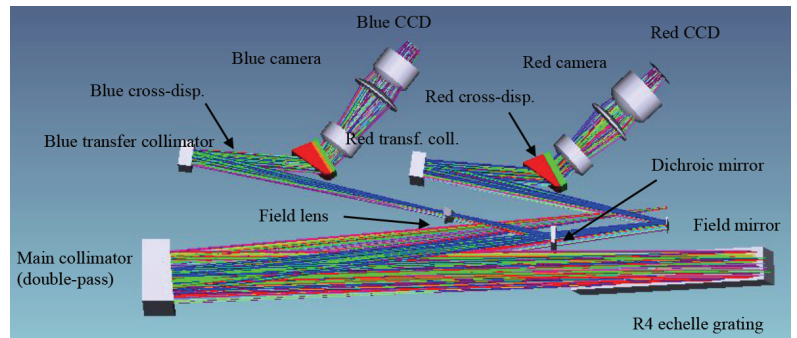
For the capital and human investment, the Consortium will be awarded Guaranteed-Time Observations. 80% of the observing nights will be invested for the search and characterization of rocky planets in the habitable zone of G, K, and M stars in the 1-UT mode. A 10% of the time will be dedicated to the 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.

Instrument and Operations



ESPRESSO – A new-generation spectrograph

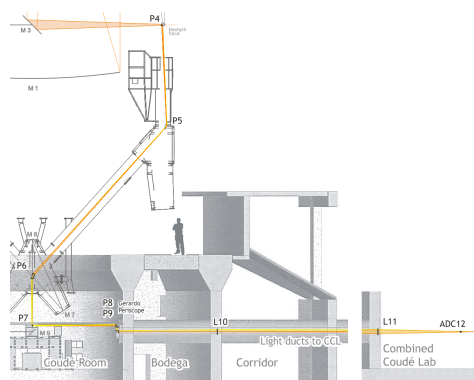
ESPRESSO is a fiber-fed, cross-dispersed, high-resolution, echelle spectrograph. The telescope light is fed to the instrument via a Coudé-Train optical system and fibers. ESPRESSO is located in the Combined-Coudé Laboratory (incoherent focus) where a front-end unit can combine the light from up to 4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



Several optical 'tricks' are used to obtain high spectral resolution and efficiency despite the large size of the telescope and the 1 arcsec entrance aperture of the instrument. At the spectrograph entrance the 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 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 large 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, such that the inter-order space and the SNR per pixel are both maximized.

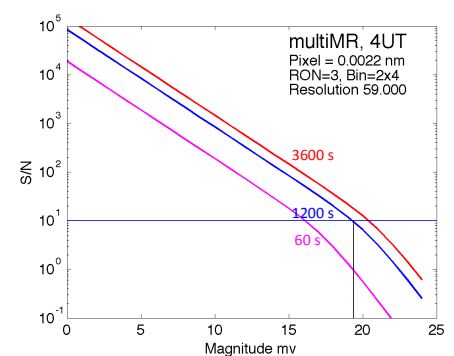
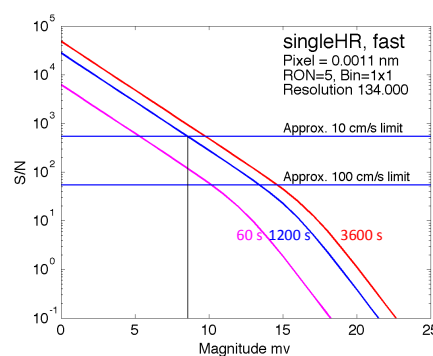
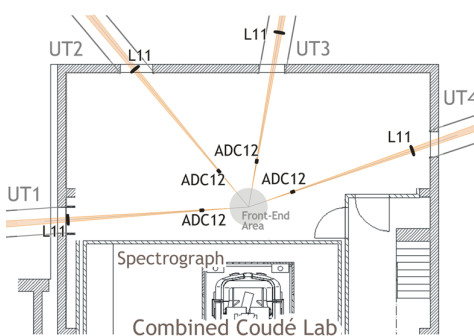
Feeding and operating the instrument with up to 4 UTs

ESPRESSO is located in the Combined Coudé Laboratory of the VLT (CCL). It is fed from any of the UT via the M4 mirror at Nasmyth (1-UT or *single(U)HR* mode). A full-optical system transports the beam through the telescope's Coudé path to the Coudé focus and along the 'incoherent' tunnels to the CCL. This location opens the unique opportunity to feed the instrument with the four UTs *simultaneously*, thus yielding a 16m-equivalent telescope. As such, the 4-UT combination (*multiMR* mode) will offer an important gain in collecting area and in read-out noise, since heavy binning can be applied. Given the operational constraints, it appeared interesting to offer a "reduced" multiMR mode in which only 2 or 3 UTs are fed to ESPRESSO. Operationally the instrument will have three main modes, the singleHR, singleUHR and the multiMR mode. The singleHR and singleUHR modes are identical apart from the spectral resolution given by the different fiber size. In these modes ESPRESSO will behave like any other VLT instrument. In the multiMR mode, instead, several UTs are controlled simultaneously. The spectral resolution will be lower by a factor of two compared to the singleHR mode (given twice the collecting area diameter), but efficiency and field size will be conserved.

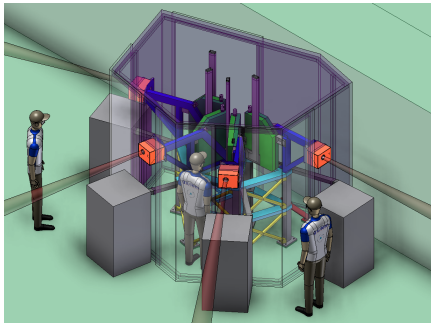


The implementation of the feed from the 4 UTs indirectly provides another major advantage for the singleHR mode: *operational flexibility*. In this mode, ESPRESSO can be fed by any of the four UTs, possibility which significantly extends the scheduling flexibility for ESPRESSO programmes and optimizes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

In the 1-UT mode a SNR of 10 per extracted pixel is obtained in 20 minutes on a $V = 16.3$ star, or a SNR of 540 on a $V = 8.6$ star. We have estimated that at $R = 134'000$ resolution this SNR value will lead to 10 cm s^{-1} radial-velocity precision for a non-rotating, K5 star. For a F8 star, the same precision would be achieved for $V = 8.0$. In the 4-UT mode, the SNR of 10 on a $V = 19.4$ star is achieved with a single 1-hour exposure. A slight gain can be achieved with higher binning (2x8).

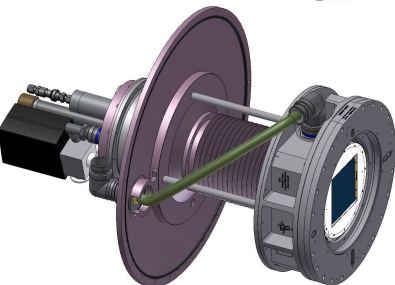
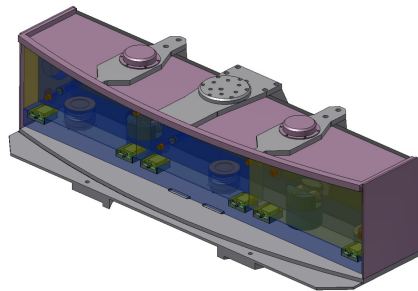
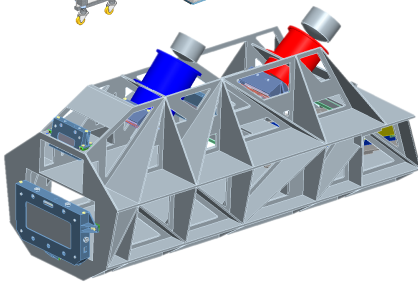
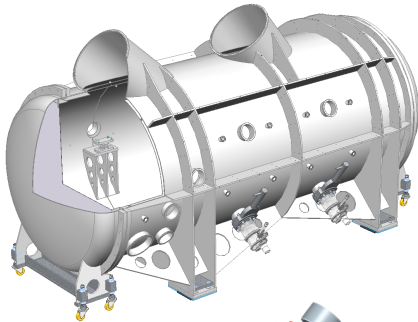


Instrument and Operations



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 that scramble the light and provide excellent illumination stability to the spectrograph. 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 a spectral reference source. Therefore, ESPRESSO will integrate a newly developed laser frequency comb that provides stability and accuracy of better than 10^{-11} , well below the cm s^{-2} regime.



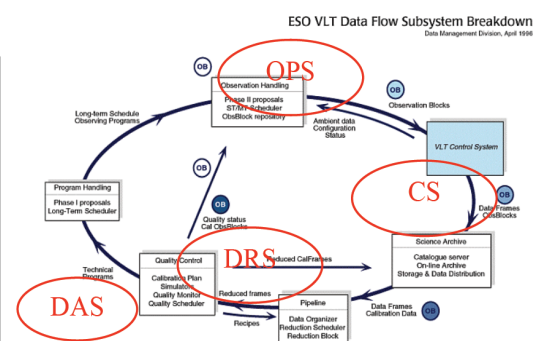
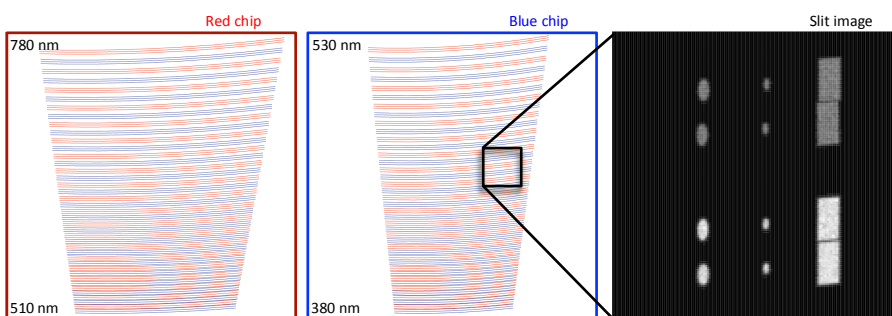
Parameter/Mode	singleHR (1 UT)	multiMR (up to 4 UTs)	singleUHR (1 UT)
Wavelength range	380-780 nm	380-780 nm	380-780 nm
Resolving power	134'000	59'000	225'000
Aperture on sky	1.0 arcsec	4x1.0 arcsec	0.5 arcsec
Spectral amplifying (average)	4.5 pixels	5.5 pixels (binned x2)	2.5 pixels
Spatial sampling per slice	9.0 (4.5) pixels	5.5 pixels (binned x4)	5.0 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	11%	11%	5%
Instrumental RV precision	$< 10 \text{ cm s}^{-1}$	$\sim 1 \text{ m s}^{-1}$	$< 10 \text{ cm s}^{-1}$

A 1 nm physical shift of the spectrum corresponds to 5 cm s^{-1} radial-velocity change. 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.

End-to-end operation

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 an observation.

All these steps will be optimally integrated into the Paranal 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.



Project and Management



Management

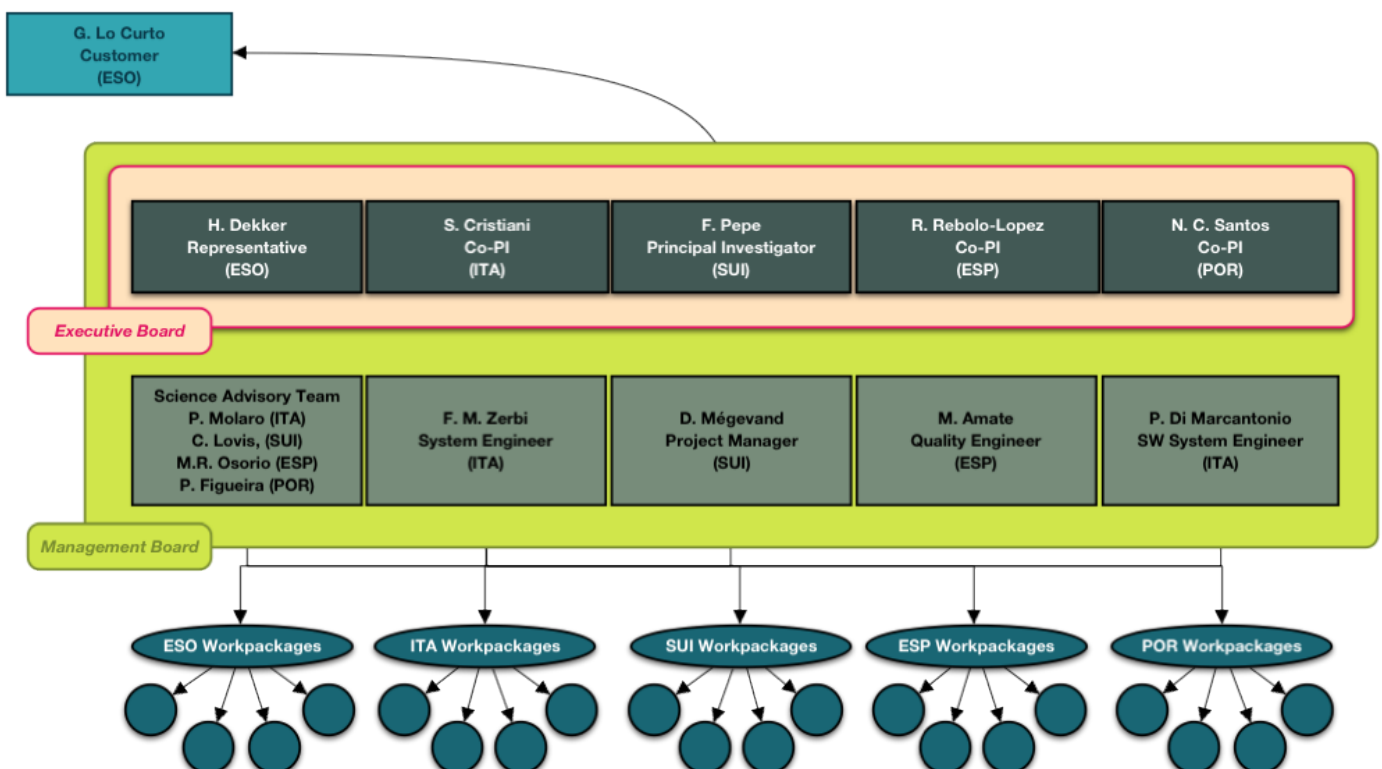
The final consumer of ESPRESSO is the astronomical community of the member states of ESO. The customer is ESO, who specifies the technical requirements for ESPRESSO. The consortium is the contractor of the instrument. It is formed of institutes of four countries. Each country is represented in the Consortium by a single point of contact for all managerial aspects, the Co-PI. The Consortium is represented in the contractual relationship with the customer, ESO, by a single point of contact, the PI. The legal aspects within the Consortium are regulated by an 'internal' Memorandum of Understanding (MoU), which describes obligations and rights of the single Institutes within the project, and defines the use of and rights over the scientific outputs of ESPRESSO.

<u>Country</u>	<u>Institute</u>	<u>Responsible</u>
Switzerland	Observatoire de Genève, University of Geneva Physikalisches Institut, University of Bern	Francesco Pepe, <i>PI</i>
Italy	INAF, Osservatorio Astronomico di Trieste INAF, Osservatorio Astronomico di Brera	Stefano Cristiani, <i>Co-PI</i>
Spain	Istituto de Astrofisica de Canarias, Tenerife (IAC)	Rafael Rebolo Lopez, <i>Co-PI</i>
Portugal	Centro de Astrofisica, University of Porto (CAUP) Faculdade da Ciências, University of Lisbon (FCUL)	Nuno Santos, <i>Co-PI</i>

The relationship with ESO is somewhat more complex because ESO is, on the one hand, the customer, and, on the other hand, a project member. This Partnership is expressed by the fact that ESO holds the responsibility for various work packages and deliverables. In order to formalize the collaboration, ESO has signed the mentioned MoU as an 'Associated Partner' with rights and obligations similar to the other Partners. ESO's work packages are bound to a unique project structure and their responsible persons communicate directly with the ESPRESSO Project Manager. The ESO's Representative is part of the Executive Board, which is composed of the Consortium's Co-PIs. The Executive Board is responsible for all decisions that concern contractual matter and the management structure of the Consortium.

Project structure and phasing

The project is led by the project manager who defines the project structure (work-break down), assigns responsibilities, defines a schedule and is responsible for project controlling. He is supported by a System Engineering Team, which is responsible for the various system aspects, interfaces and products assurance. Another team, the Science Advisory Team, will continuously verify that the project evolves in the direction of the declared scientific goals and that the instrument capabilities will be eventually compliant with them. Moreover, the Science Advisory Team provides support in scientific questions such as operation and calibration, observations and scheduling, requirements definition, etc.



Project and Management



The project is broken down into 5 phases – Preliminary Design, Final Design, Subsystem MAIV, System AIV, and AIV and Commissioning in Paranal. Each phase contains several work-packages, which describes the sum of all activities necessary to successfully complete the project. Each work package is assigned to one institute and one single responsible person only. The Co-PI responsible for this institute commits to provide the WP manager with all resources necessary to complete the work package successfully.

Schedule

Milestone	From T _p	Planned Date
KOM		4-5/10/2010
TKO	T _p =01/02/2011	17-18/01/2011
PDR	T _p + 10 months	29-30/11/2011
CCD FDR	T _p + 17 months	06/2012
FDR	T _p + 28 months	05/2013
IRM	T _p + 40 months	05/2014
IRRs		07/2014 - 05/2015
Coudé-Train PAE	T _p + 48 months	02/2015
Instrument PAE	T _p + 57 months	11/2015
PAC	T _p + 70 months	12/2016
FAC	T _p + 94 months	12/2018

The official project kick-off was held in February 2011. The design phase lasted about 2.5 years and ends with the FDR in May 2013. In order to allow for early procurement of the CCD a separate FDR was held in July 2012. The engineering model has already been delivered to ESO.

The procurement of components and manufacturing of subsystems will last about 18 months. Towards the end of 2014 the subsystems will be ready for integration in Europe. The front-end unit and the spectrograph opto-mechanics will be integrated in Milano and at IAC, respectively. Together with all the other sub-systems, they shall be accepted at sub-system level and delivered for system integration at the Geneva Observatory. The system AIV phase will last about 10 to 12 months and end by the 4th quarter of 2015.

The four Coudé-Trains will be tested in Europe separately and brought, after acceptance Europe early 2015, directly to the VLT. Verification of its performances and interfaces with the telescopes will be carried out before the spectrograph arrives at the VLT.

Acceptance Europe of the instrument is foreseen to be held in Fall 2015. The transfer of the instrument to Paranal, installation and on-site commissioning will take place in 2016. Acceptance Paranal is finally planned by the end of 2016.

Project costs

	Phases A-C	Phases D-E	Total
Manpower	7.560 M€	2.920 M€	10.480 M€
FTE	94.5	36.5	131.0
Travels	0.955 M€	0.607 M€	1'562 M€
Services	0.175 M€	0.272 M€	0.447 M€
Overheads	1.950 M€	0.861 M€	2.811 M€
Components	8.252 M€	0.173 M€	8.425 M€
Total	18.892 M€	4.833 M€	23.725 M€

The general concept was adopted that each of the Partners will carry capital and human costs associated to the work packages that they are responsible for. The institutes have committed to raise capital funds at a level of about 1.5 MEUR per country for components and material and to provide the needed manpower resources. The Consortium's total capital costs, including travel and overheads, have been estimated at the level of 9 MEUR and the human effort to 117 FTE. ESO's contribution is 3.6 MEUR in capital and about 14 FTE in manpower. The project funding and cash-flow have been ensured by the various Partners and funding agencies as per original plan.





ESPRESSO:

A super-HARPS on a 10 m-class telescope

A spectral coverage from 380 to 780 nm in one shot

The highest-resolution instrument on a 10 m-class telescope

A wavelength calibration far more accurate than any other facility

An instrument producing cleanest, best-quality spectra, both at high and low SNR

A spectrograph on a 16 m telescope, the largest visible photon-collector until ELTs will be available

An ultra-high resolution mode ($R \sim 225,000$), far beyond other existing facilities on a 10 m-class telescope