ESPRESSO on VLT: An Instrument for Exoplanet Research

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Abstract ESPRESSO (Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations) is a VLT ultra-stable high resolution spectrograph installed at ESO’s Paranal Observatory in Chile at the end of 2017 and that started regular operations in October 2018. The spectrograph is located at the VLT Combined-Coudé Laboratory and is able to operate with one or (simultaneously) four 8.2 m Unit Telescopes (UTs) through four optical Coudé trains. Combining efficiency and extreme spectroscopic precision, ESPRESSO has demonstrated to gain about two magnitudes with respect to its predecessor HARPS. ESPRESSO has improved the instrumental radial-velocity precision getting close to the aimed 10 cm s$^{-1}$ level, thus opening the possibility to explore new frontiers in the search for Earth-mass exoplanets in the habitable zone of quiet, nearby G to M-dwarfs. ESPRESSO will be certainly an important development step towards high-precision ultra-stable spectrographs on the next generation of giant telescopes such as the ELT.

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Introduction

During the last decades the exoplanet science has become one of the most exciting research fields in modern astrophysics. The doppler spectroscopy or radial velocity (RV) technique (based on the determination of the projected velocity of stars in the direction of the line of sight) was the earliest method delivering the first detection of low-mass companions (e.g. HD114762 b – Latham et al. 1989). This technique provided in 1995 the first discovery of a Jupiter-mass exoplanet orbiting the solar-type star 51 Pegasi (Mayor and Queloz 1995). After the discovery of 51 Peg b, direct imaging, microlensing and specially transit searches both from the ground and space (Lissauer et al. 2014), together with the RV technique (Mayor et al. 2014), have produced an increasing number of detections of planets and planetary systems. The number of confirmed exoplanets discovered as of December 2023 is about 5557, among which ~ 4146 exoplanets have been detected using the transit technique, mostly from the CoRoT1 (Barge et al. 2006), Kepler (Borucki et al. 2009), K2 (Howell et al. 2014) and TESS2 (Ricker et al. 2015) space missions, with 37, 2778, 548, and 410 confirmed planets, respectively. About 1071 exoplanets have been discovered using the doppler technique on high-resolution spectrographs. Combined observations from both the transit and the RV techniques have yielded a significant statistical contribution to our understanding of exoplanet population, such as the frequency of planets (e.g. Mayor et al. 2011; Howard et al. 2012; K unmoto and Matthews 2020; Ribas et al. 2023), for different host spectral types and at different orbital distances including the habitable zone (i.e. in orbits where water is retained in liquid form on the planet surface).

Now we know there is wide variety of planetary systems with different planetary masses, sizes, orbital periods, eccentricities and different configurations of mass/size-distances to the host stars. Most of the known planets appear to be in planetary systems and a significant fraction in multiple planet systems. Examples of complex planetary systems as the Solar System are the 7-planet system orbiting the G dwarf HD10180, detected using the RV technique with six confirmed planets in the mass range 11 – 65 M\textsubscript{\oplus} and one planet candidate with a mass as small as 1.5 M\textsubscript{\oplus} (Lovis et al. 2011), or the more recent discovery using transit technique from the ground of also seven planets with similar size as that of the Earth orbiting the late M dwarf TRAPPIST-1 (Gillon et al. 2017). More recently, the discovery and characterization of a 6-planet system in a chain of Laplace resonances orbiting the late K-dwarf TOI-178 (Lelou et al. 2021) has shown the great synergy between the TESS and CHEOPS3 space missions, and the ground-based ESPRESSO@VLT facility. The discoveries have required intensive and long-term monitoring of stars and the continuous development of astronomical instrumentation (Pepe et al. 2014a). This together with significant improvement in the observational strategies has made exoplanet science quickly evolve from the discovery

1 Convection, Rotation and planetary Transits (CoRoT)
2 Transiting Exoplanet Survey Satellite (TESS)
3 CHaracterising ExOPlanets Satellite (CHEOPS)
ESPRESSO on VLT: An Instrument for Exoplanet Research

of giant planets even more massive than Jupiter to rocky planets with similar mass as that of the Earth. This is demonstrated by the discoveries of Kepler 78 b (Pepe et al. 2013), a planet with similar density as that of the Earth, and Proxima Centauri b (Anglada-Escudé et al. 2016), a planet with similar minimum mass as that of the Earth in the habitable zone of the closest star to the Sun. ESPRESSO has allowed us to go beyond the Earth-mass frontier with the discovery of some new sub-Earth mass planets such as Proxima Centauri d (Suárez Mascareño et al. 2020; Faria et al. 2022), the lowest mass exoplanet ever detected with the doppler technique, with a mass of $0.26 \pm 0.05 \, M_\oplus$, just about twice the mass of Mars, at an orbital period of $5.12 \pm 0.04$ days (0.029 AU from the star), with a RV semiamplitude of $39 \pm 7 \, \text{cm s}^{-1}$.

Coupling the transit with the RV technique allows us to derive the mass and radius, and therefore to compute bulk density of exoplanets, a first step towards characterizing exoplanets. This in combination with detailed theoretical modelling allows us to get some insights about the bulk composition of some exoplanets and how they compared with the Earth composition (see Mayor et al. 2014; Lissauer et al. 2014, and references therein). ESPRESSO is breaking the frontier of characterizing planets smaller than the Earth, as e.g. the two super-Mercuries, less-massive but denser than the Earth, together with three super-Earths detected in the 5-planet system HD 23472. (Barros et al. 2022).

The next step is to characterize the atmospheres of exoplanets, using e.g. high-resolution spectroscopy via transmission with a technique applied to some transiting giant planets to detect Na and CO in their atmospheres (Charbonneau et al. 2002; Snellen et al. 2008, 2010; Wytenbach et al. 2015), or via spectroscopic detection of reflected light of exoplanets (Charbonneau et al. 1999; Martins et al. 2015). In spite of the difficulty of this type of analysis, ESPRESSO has managed to achieve remarkable results, demonstrating for instance the presence of rare species in the atmospheres of certain exoplanets, such as barium and lithium in the atmosphere of WASP-121 b (Borsa et al. 2021; Azevedo Silva et al. 2022; Seidel et al. 2023), and WASP-76 b (Ehrenreich et al. 2020; Borsa et al. 2021; Tabernero et al. 2021; Seidel et al. 2021; Azevedo Silva et al. 2022).

Most of the known transiting exoplanets (namely those discovered by the Kepler space telescope) orbit faint targets, which make it difficult to study their atmospheres with the current facilities. The recently found transiting super-Earth like planet in the habitable zone of the faint M dwarf LHS 1140 (Dittmann et al. 2017), discovered with MEarth (Nutzman and Charbonneau 2008) and HARPS (Mayor et al. 2003), and later confirmed with TESS and ESPRESSO (Lillo-Box et al. 2020; Cadieux et al. 2023), is an example of the need for larger telescopes equipped with high-resolution, high-precision spectrographs to investigate the atmospheres of such interesting exoplanets.

In particular, the difficulty raises when trying to find transiting Earth-like planets orbiting at the habitable zones of bright host stars. It appears quite necessary to design new techniques able to study the atmospheres of exoplanets by using the reflected light (Snellen et al. 2014), combining a high-contrast adaptive optics (AO) system with a high-resolution spectrograph to overcome the tiny planet-to-star flux
ratio in two stages. First, the AO system should spatially resolve the planet from the host star enhancing the planet-to-star contrast at the planet location and second, the light beam at the planet location passes through the high-resolution spectrographs. This technique has been applied to model the possible planetary atmospheric signal of Proxima Cen b by coupling the SPHERE high-contrast imager (Beuzit et al. 2008) and the ESPRESSO spectrograph at VLT (Lovis et al. 2017). A new instrument, RISTRETTO, for the VLT, that will provide a visible high-resolution spectrograph fed by an extreme adaptive optics (XAO) is being designed with the goal of detection and atmospheric characterization of exoplanets in reflected light, in particular, the temperate rocky planet Proxima b (Lovis et al. 2022).

The new generation of 20–40m giant telescopes such as ELT equipped with sophisticated AO systems and with stable high-precision high-resolution spectrographs will possibly be able to study the atmospheres of rocky exoplanets in the habitable zone (Snellen et al. 2015). The new optical and near-infrared ultrastable spectrograph ANDES 4 is in design phase (Marconi et al. 2022) for the ELT, and will be able to characterize the atmospheres of Earth-like planets orbiting nearby stars in the habitable zone both in transmission and reflected-light spectroscopy to search for biosignatures (Palle et al. 2023).

The need of instrumentation for exoplanet science on the 8.2-m Very Large Telescopes (VLT) was highlighted in the ESO (European Southern Observatory)-ESA(European Space Agency) working report on extrasolar planets. In October 2007 the ESO Science Advisory Committee recommended the development of new second-generation VLT instrumentation, and later endorsed by the ESO Council. Among those instruments, ESPRESSO, a high-resolution ultra-stable spectrograph for the VLT combined-Coudé focus, was proposed. The ESPRESSO (Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations) project started with the kick-off meeting in February 2011. The ESPRESSO consortium is composed of: Observatoire Astronomique de l’Université de Genève (project head, Switzerland); Instituto de Astrofísica e Ciências do Espaço/Universidade de Porto and Universidade de Lisboa (Portugal); INAF-Osservatorio Astronomico di Brera (Italy); INAF-Osservatorio Astronomico di Trieste (Italy); Instituto de Astrofísica de Canarias (Spain); Physikalisches Institut der Universität Bern (Switzerland). ESO participates to the ESPRESSO project as Associated Partner. The ESPRESSO instrument was commissioned at the VLT in Paranal Observatory in the fall 2017 and offered to the community by 2018, starting regular operations in October 2018.

Exoplanet science with ESPRESSO

The main scientific drivers of ESPRESSO are: (i) search for rocky planets; and (ii) measure the variation of physical constant. We refer to Pepe et al. (2014b, 2021) for details on (ii), as well as very challenging additional scientific topics that

4 ArmazoNes high Dispersion Echelle Spectrograph (ANDES)
ESPRESSO will address, as e.g. the use of the ESPRESSO RV stability to investigate long-period binarity in extremely iron-poor stars \cite{Aguado2022, Aguado2023, Molaro2023}.

The ESPRESSO Guaranteed Time Observations (GTO) \cite{Pepe2021} were executed between October 2018 and September 2023, and were organized in four main groups: (i) WG1: blind search for exoplanets; (ii) WG2: atmospheric characterization of giant exoplanets via transmission spectroscopy; (iii) WG3: mass measurements of transiting exoplanets discovered by K2 and TESS; (iv) WG4: fundamental constants from QSO observations.

One of the main scientific topics in the next decades is the search and characterization of terrestrial planets in the habitable zone of their host stars, and one of the main drivers of the new generation of extremely large telescopes is the detection of their atmospheres \cite{Marconi2016, Palle2023}. At the end of the 90’s and the following decade, the monitoring of stars using high-resolution spectroscopy yielded many detections of Jupiter like planets. Only after 2003, the HARPS spectrograph installed at the 3.6-m ESO telescope in La Silla Observatory (Chile) opened a new window on the domain of Neptune and super-Earth like planets \cite{Pepe2018}. This instrument (with a resolving power of $R \sim 115,000$) is contained inside a vacuum vessel and uses a simultaneous calibration reference that allows to correct for (small) instrumental drifts due to (also small) changes of temperature and pressure, providing an extreme long-term RV precision below the 1 m s$^{-1}$ \cite{Pepe2014b}. The ESPRESSO instrument has confirmed the late G-
type dwarf star $\tau$ Ceti as a RV standard where the roughly $1 \text{ m s}^{-1}$ RV variation is mostly caused by the stellar activity (see Fig. 1). Already in 2004 the discovery of a super-Earth with a minimum mass of about only $10 M_\oplus$ orbiting the G-type star $\mu$ Arae (Santos et al. 2004) demonstrated the impressive capabilities of the HARPS instrument. Since then, and thanks to its precision, HARPS has provided the discovery of most of the sub-Neptunian mass planets with masses down to a few $M_\oplus$ inducing RV semi-amplitudes as low as $0.5 \text{ m s}^{-1}$ (see e.g. Pepe et al. 2011).

The ESPRESSO instrument has improved a step further, aiming at achieving a RV precision of $10 \text{ cm s}^{-1}$, which is crucial in the path of detecting terrestrial planets in the habitable zone of host stars of different spectral types, in particular for G, and K dwarfs. The Earth induces radial velocity variations in the Sun of $\sim 9 \text{ cm s}^{-1}$, in comparison with RV signal of $12 \text{ m s}^{-1}$ induced by Jupiter. However, an Earth-mass exoplanet orbiting a M5V star in the habitable zone would cause a gravitational pull equivalent to $\sim 1.3 \text{ m s}^{-1}$, which, with the current instrument capabilities limited to $\sim 1 \text{ m s}^{-1}$, can be detected (Bonfils et al. 2013a; Anglada-Escudé et al. 2016). Thus, the quest for low-mass planets in the habitable zone has favoured RV studies on M dwarf in the last decade with numerous low-mass planets detections (see e.g. Bonfils et al. 2013a,b; Anglada-Escudé et al. 2013; Affer et al. 2016; Astudillo-Defru et al. 2017; Suárez Mascareño et al. 2017a,b). Today, several tens of planets with minimum masses below $10 M_\oplus$ have been discovered. Most of them have been detected orbiting cool dwarfs less massive than the Sun (see Fig. 2), using HARPS and HARPS-N (at 3.6-m TNG telescope located in the Observatorio del Roque de los Muchachos, La Palma, Spain; Cosentino et al. 2012) spectrographs. New dedicated instruments aiming for planet search around M dwarfs operating in the near infrared are already running such as CARMENES (at the 3.5-m telescope in the Observatorio de Calar Alto, Spain; Quirrenbach et al. 2016), NIRPS (at the 3.6-m ESO telescope in La Silla (Chile), in operations together with HARPS since April 2023; Bouchy et al. 2017), and SPIRou (at the CHFT telescope in Mauna Kea (Hawaii, USA); Donati et al. 2020).

A larger telescope size provides a lower photon noise level on Doppler signal for the same exposure time. ESPRESSO at the 8.2-m VLT at the Observatorio de Paranal is expected to achieve the $10 \text{ cm s}^{-1}$ Doppler precision and long-term stability (Pepe et al. 2021). This will open the possibility to search for Earth-mass planets at different orbital distances, including the habitable zones of solar-type stars. A carefully selected sample of non-active, non-rotating, quiet G to M dwarf will allow to explore this new domain. In the top panel of Fig. 2 we display the known planets from the NASA Exoplanet archive as of December 2023 at different orbital periods around stars. So far, most of the low-mass planets have been discovered around M dwarfs where the RV planetary signals are stronger. We have highlighted the ESPRESSO discoveries and confirmations. The larger telescope mirror of VLT and the RV precision provided by ESPRESSO is allowing to access a larger sample of fainter stars of different spectral types. The recent discovery of two temperate Earth-mass planets in the habitable zone of the relatively faint M5.5V star ($m_V \simeq 13.8 \text{ mag}$, but brighter in the near infrared, $m_J \simeq 8.3 \text{ mag}$) GJ 1002 demonstrates the capa-
Fig. 2  Top: Minimum mass vs orbital period diagram for known planets from the NASA Exoplanet archive as of December 2023 orbiting solar-type stars, together with those discovered and confirmed using ESPRESSO (green circles). Inclined solid and dashed lines show the RV semi-amplitude of planets orbiting a late M dwarf star with $0.25 \, M_{\odot}$ (green line) and a G dwarf star with $1 \, M_{\odot}$ star (blue line) assuming a RV semi-amplitude of $1 \, \text{m s}^{-1}$ and $10 \, \text{cm s}^{-1}$, respectively, and null eccentricity. Planets of the solar system (grey circles) are also labeled. Bottom: Radius vs mass diagram for known transiting planets. ESPRESSO results are highlighted using green circles. Mass-radius models are also displayed for three different bulk’s planet compositions: rocky planets with 100% Fe (red) and Earth-like rocky planets with 33% Fe (orange) and water worlds with 50% $\text{H}_2\text{O}$ (blue) (Zeng et al. 2019).
bilities of the ESPRESSO instrument (Suárez Mascareño et al. 2023). During the execution of the ESPRESSO GTO, it has been possible to break $1 \text{ m s}^{-1}$ limit and to go beyond the Earth-mass barrier, as e.g. with the discovery of the transiting multi-planet system L 98-59 with planet b of half of the mass of Venus (Demangeon et al. 2021), as well as the aforementioned blind RV detection of Proxima d with almost twice the mass of Mars (Faria et al. 2022). In the bottom panel of Fig. 2 we also display the mass-radius diagram of known transiting exoplanets, highlighting those confirmed using ESPRESSO, in comparison with models with different bulk’s compositions.

However, stellar noise or jitter, which causes different radial velocity variations at different timescales and of different magnitude (see e.g. Saar et al. 1998; Santos et al. 2000; Queloz et al. 2001; Boisse et al. 2011; Dumusque et al. 2011; Robertson et al. 2014; Rajpaul et al. 2015; Suárez Mascareño et al. 2017c), still remains the main source of error and probably the strongest limitation towards the sub-$\text{m s}^{-1}$ precision in the long term. Therefore, continuous investigation and modelling on these stellar effects at different timescales are required on the way towards finding rocky planets in the habitable zones of solar-type stars. One significant effort in this respect is the development of the PoET telescope 5, a solar telescope that will connect to ESPRESSO and allow to obtain ultra-high resolution spectra of resolved solar regions. The data will allow to understand in unique detail the different sources of stellar noise in both Doppler radial velocity measurements and transmission spectroscopy of planets orbiting sun-like stars.

![Schematic view of the four 8.2m Unit Telescopes of the VLT (multi-UT mode) feeding, through the Coudé train, the Front-End unit of the ESPRESSO spectrograph located in the Combined Coudé Laboratory.](image)

5 http://poet.iastro.pt
The discovery of a new and large population of Earth-mass exoplanets orbiting solar-type stars will expand our knowledge of planet formation, and will also deliver new candidates for follow-up observations using other techniques such as transit, astrometry, and Rossiter-McLaughlin (RM) effect. The detection with HARPS of the RM effect in occasion of the 2012 transit of Venus over the disk of the SUN provided a sort of preview of the kind of the physical information which we can hope to obtain by observing transits of exoplanets with a large telescope (Molaro et al. 2013b). ESPRESSO can also perform follow-up observations of ongoing and forthcoming transit surveys such as NGTS, MEarth from the ground or Kepler-K2, TESS and, in future PLATO (Rauer et al. 2014; Rauer and Heras 2018), from space. ESPRESSO will be possibly one of the rare instruments able to confirm long-period Earth-size transiting planets discovered by space missions like PLATO, which hopefully will provide Earth-size candidates transiting bright targets in their habitable zones.

The high resolution and stability of ESPRESSO allows for atmospheric characterization of exoplanets of different mass and size using the transmission and possibly reflection spectroscopy (Charbonneau et al. 2002; Snellen et al. 2014; Martins et al. 2015; Lovis et al. 2017; Santos et al. 2020; Casasayas-Barris et al. 2021, 2022). ESPRESSO GTO data have allowed to characterize in detail the atmosphere of the ultra-hot jupiter WASP-76 b (Ehrenreich et al. 2020; Seidel et al. 2021), which has become a benchmark target in exoplanet atmospheres, getting deeper into the structure of the iron storm. In addition, ESPRESSO observations done using 1-UT and 4-UT modes have shown the extreme capabilities of ESPRESSO (Borsa et al. 2021; Seidel et al. 2023), combining high-resolution, stability and the collecting area of the four 8.2m unit telescopes of the VLT to discover the presence of the species Ba+
in WASP-121 b and Li in both WASP-121 b and WASP-76 b (Borsa et al. 2021; Azevedo Silva et al. 2022; Tabernero et al. 2021).

A ultra-stable high-resolution spectrograph for the VLT

ESPRESSO is a fiber-fed, cross-dispersed, high-resolution échelle spectrograph located in the Combined Coudé Laboratory (CCL) at the incoherent focus, where a front-end unit can combine the light from up to four Unit Telescopes (UT) of the VLT. The so-called Coudé train optical system feeds the light of each UT to the spectrograph. The sky light and the target enter the instrument simultaneously through two separate fibers, which form together the slit of the spectrograph. ESPRESSO, unlike any other ESO instrument, is able to receive the light from any of the four 8.2-m UTs, and is able to operate simultaneously with the light of either one UT or several UTs (see Fig. 3). We refer to Pepe et al. (2021) for updated ESPRESSO instrument details and commissioning results, that we only briefly will describe below.

![Normalized, co-added ESPRESSO spectrum of τ Cet star obtained with the STAR II workflow of the data analysis software (DAS) of the ESPRESSO ESO DAS pipeline using 40 individual HR11 ESPRESSO spectra. This figure has been taken from Pepe et al. (2021).](image)

**Fig. 5** Normalized, co-added ESPRESSO spectrum of τ Cet star obtained with the STAR II workflow of the data analysis software (DAS) of the ESPRESSO ESO DAS pipeline using 40 individual HR11 ESPRESSO spectra. This figure has been taken from Pepe et al. (2021).
Observing modes and performance

The extreme precision of ESPRESSO is achieved based on well-known concepts provided by the HARPS experience. The light of one or several UTs is fed through 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 but octogonal or square fiber shapes are used (Chazelas et al. 2012). The target fiber can be fed either with the light from the astronomical object or one of the calibration sources. The reference fiber receives either sky light (faint source mode) or calibration light (bright source mode). In the latter case, the simultaneous-reference technique successfully applied in HARPS and confirmed in ESPRESSO enables to track instrumental drifts down to the cm s\(^{-1}\) level. In this mode the measurement is photon-noise limited and detector read-out noise negligible. In the faint-source mode, instead, detector noise and sky background may become significant. In this case, the second fiber allows to measure the sky background, whereas a slower read-out and high binning factor reduces the detector noise. ESPRESSO provides spectra in the wavelength range 378.2-788.7 nm with three instrumental modes: singleHR, singleUHR and multiMR, with each different detector binning (HR11, HR21, HR42, UHR11, MR42, MR84, see Table 1). They produce correspondingly different spatial and spectral sampling. The resolving power, instead, is essentially given and fixed by the instrument mode; it varies only slightly with binning. The HR and the MR modes are furthermore available with two different detector read-out modes (slow/high-gain and fast/low-gain) optimized for low and high-SNR measurements, respectively.

Table 1  Observing modes of ESPRESSO.

| Obs. Mode   | HR11 (1UT) | HR21 (1UT) | HR42 (1UT) | UHR11 (1UT) | MR42(4UT) | MR84(4UT) |
|-------------|------------|------------|------------|-------------|------------|------------|
| Wave. range| 380–790 nm | 380–790 nm | 380–790 nm | 380–790 nm  | 380–790 nm | 380–790 nm |
| Resol. Power| 138,000    | 138,000    | 130,000    | >190,000    | 72,500     | 70,000     |
| Aper. on Sky| 1.0”       | 1.0”       | 1.0”       | 0.5”        | 4×1.0”     | 4×1.0”     |
| Spec. Samp. | 4.5 pix    | 4.5 pix    | 2.25 pix   | 2.5 pix     | 5 pix      | 2.5 pix    |
| Spat. Samp. | 2×9 pix    | 2×4.5 pix  | 2×2.25 pix | 2×5 pix     | 2×20 pix   | 2×10 pix   |
| Sim. Ref. | Yes (no sky) | Yes (no sky) | Yes (no sky) | Yes (no sky) | Yes (no sky) | Yes (no sky) |
| Sky Sub. | Yes (no ref.) | Yes (no ref.) | Yes (no ref.) | Yes (no ref.) | Yes (no ref.) | Yes (no ref.) |
| Tot. Eff. | 10 %       | 10 %       | 10 %       | 5 %         | 10 %       | 10 %       |

The expected observational efficiency of ESPRESSO is shown in Fig. 4 but the updated efficiency from ESPRESSO real observations is shown in Figs. 12-16 of Pepe et al. (2021). In the singleHR mode (R \(\sim\) 140\(000\)), we estimate SNR = 10 per extracted pixel in 20 minutes on a V = 16.3 star, or a SNR = 420 on a V = 8.6 star (see Fig. 16 in Pepe et al. (2021)). We have estimated that at this resolution and a SNR \(\sim\) 420 leads to \(\sim\) 15 – 20 cm s\(^{-1}\) RV precision and reaching the 10 cm s\(^{-1}\) level at SNR > 650 for a non-rotating G8-K5 star (see Fig. 20 in Pepe et al. (2021)). In the multiMR mode, at R \(\sim\) 70000, a SNR \(\sim\) 10 is achieved on a V = 19.4 star.
with an exposure of 20 minutes, a binning $4 \times 2$ (MR42), and a slow read-out of the CCD. In the following sections we briefly describe the several subsystems of the ESPRESSO project (see also Pepe et al. 2014b; Mégevand et al. 2014; Pepe et al. 2021).

**The Coudé train**

The four VLT telescope are connected to the CCL through four tunnels with a length that goes from 48 to 69 meters (see Fig. 3). A trade-off analysis among the different solutions to bring the light from the telescope to the CCL favored a full optical solution that includes prisms, mirrors and lenses. The selected design uses 11 optical elements (see Fig. 6). The Coudé train takes the light beam with a prism at the Nasmyth-B platform and conduct it through the UT mechanical structure down to the Coudé room below each UT using a set of six prisms and mirrors. The light is then routed from the UT Coudé room to the CCL, using two large lenses along the existing incoherent light ducts. The four Coudé trains relay a field of 17 arcsec around the acquired astronomical target to the CCL. The four beams from four UTs are combined in the CCL, where mode selection and beam conditioning is performed by the fore-optics of the Front-End subsystem. All four Coudé Trains provide seeing limited images to the front end that is installed at the CCL.

![Fig. 6 Schematic view of the Coudé train of ESPRESSO with the optical path through the telescope to the Combined Coudé Laboratory. The optical elements are highlighted at different positions along the path from the Nasmyth-B platform to the CCL with P (prism), R (mirror) and L (lens).](image-url)
The Front-End

The Front-End conducts the light beam received at the CCL after correcting it for atmospheric dispersion with the ADC to the common focal plane where the spectrograph fiber feeds are located. A toggling mechanism handles the selection between the possible observational modes in a fully passive way. The beam conditioning is performed applying pupil and field stabilization (see Fig. 7). These are achieved via two independent control loops each consisting of a technical camera and a tip-tilt stage. Another dedicated stage delivers a focusing function. The Front-End also handles the injection of the calibration light from the calibration unit into the fibers and then into the spectrograph. A laser frequency comb (LFC) system is foreseen as main calibration source. It produces a regular spectrum of lines equally spaced in frequency with an accuracy and stability linked to an atomic clock. The short-term Doppler shift repeatability of the LFC system has been tested in HARPS spectrograph and demonstrated to achieve the cm s\(^{-1}\) level (Wilken et al. 2012, Probst et al. 2016, 2020). The required repeatability of the order of \(\Delta \lambda/\lambda \approx 10^{-10}\) cannot be guaranteed with currently used spectral sources such as thorium argon spectral lamps, iodine cells, etc, but can be obtained with a LFC that would provide a spectrum sufficiently wide, rich, stable and uniform for this purpose (Lo Curto et al. 2012, Molaro et al. 2013a, González Hernández et al. 2020). However, the long-term stability and reliability of a LFC system has not been proved yet. We refer to Schmidt et al. (2021) for a discussion about the status of the current ESPRESSO calibration system. However, two ThAr lamps for both simultaneous reference and calibration are also available as backup calibration sources, together with one simultaneous stabilized Fabry-Pérot unit, also as a backup solution.

Fig. 7 Front-End unit and the arrival of one UT beam at the CCL. The same is replicated for the other UTs.
The Fiber-Link

The Fiber-Link subsystem transfers the light from the Front-End to the spectrograph and creates the a pseudo-slit in the output end inside the vacuum vessel. The 1-UT mode uses a bundle of two octagonal fibers each, one for the astronomical object and one for the sky or simultaneous reference. In the high-resolution mode (singleHR) mode, the fiber has a core of 140 µm, equivalent to 1" on the sky; in the ultra-high resolution (singleUHR) mode the fiber core is 70 µm, covering a field of view of 0.5". The fiber entrances are organized in pickup heads that are moved to the focal plane of the Front End when the specific bundle of the specific mode is selected. In the 4-UT mode (multiMR) four object fibers and four sky/reference fibers are fed simultaneously by the four telescopes. The four object fibers and the four sky/reference fibers finally feed two separate single square fibers of 280 µm, for the object and for the sky/reference, respectively. In the 4-UT mode the spectrograph also sees a pseudo slit of four fiber square images twice as wide as the 1-UT fibers. One essential task performed by the Fiber-link subsystem is the light scrambling. The use of a double-scrambling optical system ensures both scrambling of the near field and far field of the light beam. A high scrambling gain, which is crucial to obtain the required RV precision in the 1-UT mode is achieved by the use of octagonal fibers (Chazelas et al. 2012). The fiber link was upgraded in June 2019, thus increasing the photon-detection efficiency reaching more than 10% at seeing better than 0.75" (see Fig. 12 in Pepe et al. 2021).

Fig. 8 Layout of the ESPRESSO spectrograph and its optical elements.
Optical Design

Designing a high efficiency and high resolution spectrograph is not an easy task due to the large mirrors of the VLT telescopes and the 1 arcsec aperture of the instrument. In order to minimize the size of the optics, and in particular, that of the main collimator and échelle grating, ESPRESSO implements an anamorphic optics, the APSU, which compresses the size of the pupil in the direction of the cross-dispersion. The pupil is then sliced in two by a pupil slicer and the slices are overlapped on the échelle grating, leading to a doubled spectrum on the detector. This design reduces significantly the sizes of the optics and the échelle grating. Without this trick, the collimator beam size would have been 40 cm in diameter and the size of the échelle grating would have reached a size of 240×40 cm. The size of current échelle grating of ESPRESSO is only 120×20 cm and this also allows the use of much smaller optics (collimators, cross dispersers, etc.). The échelle grating is an R4 Echelle of 31.6 l mm\(^{-1}\) and a blaze angle of 76°. This solution significantly reduces the overall costs. The drawback is that each spectral element is covered by more detector pixels given the doubled image of the object fiber and its elongated shape on the CCD. In order to avoid to increase the detector noise, heavy binning is done in the case of faint-object observations, especially in the 4-UT mode.

The main components of the optical design are (see Fig. 8):

- **The Anamorphic Pupil Slicing Unit (APSU).** At the spectrograph entrance the APSU shapes the beam in order to compress it in cross-dispersion and splits in two smaller beams, while superimposing them on the échelle grating to minimize its size. The rectangular white pupil is then re-imaged and compressed.
- **Dichroic.** Given the wide spectral range, a dichroic 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.
- **Volume Phase Holographic Gratings (VPHGs).** The cross-disperser enables to separate 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 height such that the inter-order space and the SNR per pixel are both maximized. Both functions are accomplished using Volume Phase Holographic Gratings (VPHGs) mounted on prisms.
- **Fast Cameras.** Two optimised camera lens systems image the full spectrum from 380 nm to 780 nm on two large 92×92 mm CCDs with 10-µm pixels.

A sketch of the optical layout is depicted in Fig. 8. The spectral format covered by the blue and the red chips as well as the shape of the pseudo slit are displayed in Fig. 9. In order to precisely compute the relative Earth motion to be able to properly correct the RV measurement, it is necessary to calculate the weighted mean time of exposure. Thus, the spectrograph is also equipped with an advanced exposure meter that measures the flux entering the spectrograph as a function of time. Its innovative design (based on a simple diffraction grating) allows a flux measurement and an RV correction at different spectral channels, in order to cope with possible chromatic effects that could occur during the scientific exposures. The use of various channels
also provides a redundant and thus more reliable evaluation of the mean time of exposure.

Fig. 9 Spectral format of the red (left panel) and blue (middle panel) spectra, and a zoom of the pseudo-slit (right panel), showing the image of the target (bottom) and sky (top) fibers. Each fiber is re-imaged into two slices. The three sets of fibers, corresponding (from left to right) to the standard resolution 1-UT mode, ultra-high resolution 1-UT mode and the mid-resolution 4-UT mode (shown simultaneously for comparison). This figure has been taken from Pepe et al. (2014b).

The opto-mechanics

ESPRESSO has been designed to be an ultra-stable spectrograph enabling RV precisions of the order of 10 cm s\(^{-1}\), i.e. one order of magnitude better than its predecessor HARPS. ESPRESSO is therefore built with a totally fixed configuration and with the highest thermo-mechanical stability. The spectrograph optics are mounted in an optical bench specifically designed to keep the optical system within the thermo-mechanical tolerances required for high-precision RV measurements. The bench is mounted in a vacuum vessel in which \(10^{-5}\) mbar class vacuum is maintained during the entire duty cycle of the instrument. An overview of the opto-mechanics is shown in Fig. 10. The temperature at the level of the optical system is required to be stable at the mK level in order to avoid both short-term drift and long-term mechanical instabilities. Such an ambitious requirement is obtained by locating the spectrograph in a multi-shell active thermal enclosure system as shown in Fig. 11. Each shell improves the temperature stability by a factor 10, thus getting from typically Kelvin-level variations in the CCL down to 0.001 K stability inside the vacuum vessel and on the optical bench.
Large-area CCDs

The CCDs are another innovative solution in the ESPRESSO project. Large monolithic state-of-the-art CCDs have been chosen to use the optical field of ESPRESSO and to further improve the stability compared to the mosaic solution employed in HARPS. The sensitive area of the e2v chip is $92 \times 92$ mm covering $8.46 \times 10^7$ pixels of 10 $\mu$m size. Fast read out of such a large chip is achieved by using its 16 output ports at high speed. Other requirements on CCDs are very demanding, e.g. in terms of Charge Transfer Efficiency (CTE) and all the other parameters affecting the definition of the pixel position, immediately reflected into the radial-velocity precision and accuracy. The RV precision of 10 cm s$^{-1}$ rms requires measuring spectral line position changes of 2 nm (physical) in the CCD plane, equivalent to only 4 times the silicon lattice constant. For better stability and thermal-expansion matching the CCD package is made of silicon carbide. The package of the CCDs, the surrounding mechanics and precision temperature control inside the cryostat head and its cooling system, as well as the thermal stability and the homogeneous dissipation of the heat locally produced in the CCDs during operation are of critical importance. ESO has thus built a new superstable cryostat that has already demonstrated excellent short-term stability.
Fig. 11 Schematic view of the Combined Coudé Laboratory where ESPRESSO spectrograph is located inside the vacuum vessel, and several thermal enclosures in a multi-shell control system.

Data flow system

The ESPRESSO project has the final goal to provide the user with scientific data as complete and precise as possible in a short time (within minutes) after the end of an observation, to increase the overall efficiency and the ESPRESSO scientific output. For this purpose a software-cycle integrated view, from the observation preparation through instrument operations and control to the data reduction and analysis has been adopted. Coupled with a careful design this ensures optimal compatibility and facilitates the operations and maintenance within the existing ESO Paranal Data Flow environment both in service and visitor mode. ESPRESSO Data Flow System presents the following main subsystems:

- **The ESPRESSO Observation Preparation Software (EOPS):** a dedicated visitor tool (able to communicate directly with the VOT - Visitor Observing Tool) to help the observer to prepare and schedule ESPRESSO observations at the telescope according to the needs of planet-search surveys or other scientific programs. The tool allows users to choose the targets best suited for a given night and to adjust the observation parameters in order to obtain the best possible quality of data.

- **The Data Reduction Software (DRS):** ESPRESSO has a fully automatic data reduction pipeline with the specific aim of delivering to the user high-quality reduced data, science ready, already in a short time after an observation has been performed. The computation of the RV at a precision reaching the $10 \, \text{cm} \, \text{s}^{-1}$ level is an integral part of the DRS. During the GTO, the ESPRESSO consortium has developed two codes to improve the RV computation: (i) an automatic
model-based telluric correction code \(^7\) for the ESPRESSO data reduction software \(^7\) (Allart et al. 2022); (ii) semi-Bayesian precise radial velocity computation code \(^8\) through template matching \(^8\) (Silva et al. 2022), both enabling for instance to achieve the 14, 8 and 10 cm s\(^{-1}\) precision in M-, K-, and G-type stars, respectively \(^8\). Coupled with the need to optimally remove the instrument signature, to take account the complex spectral and multi-HDU FITS format, the handling of the simultaneous reference technique and the multi-UT mode makes the DRS a truly challenging component of the DFS chain.

- **The Data Analysis Software (DAS):** dedicated data analysis software allows to obtain the best scientific results from the observations directly at the telescope (see e.g. Fig. 5). A robust package of recipes tailored to ESPRESSO, taking full advantage of the existing ESO tools (based on CPL and fully compatible with Reflex), addresses the most important science cases for ESPRESSO by analyzing (as automatically as possible) spectra of stars and quasars (among others, tasks such as line Voigt-profile fitting, estimation of stellar atmospheric parameters, normalization of stellar spectra and comparison with synthetic spectra, quasar continuum fitting, identification of absorption systems).

- **Templates and control:** compared to other standalone instruments, the main reason for the complexity of the ESPRESSO acquisition and observation templates are the possible usage of any combination of UTs, besides the proper handling of the simultaneous reference technique. ESPRESSO will contribute to open the new path for the control systems of future ESO instrumentation.

**End-to-end operation**

ESPRESSO combine an unprecedented RV and spectroscopic precision with the largest photon collecting area available today at the European Southern Observatory, and with an unique resolving power up to \(R \sim 200,000\). In the singleHR mode, ESPRESSO can be fed with the light of an astronomical object coming from any of the four 8.2m VLT telescopes, which significantly improves the scheduling flexibility for ESPRESSO programmes and surely will optimize the use of VLT time. The singleHR mode operates at a resolution of \(R \sim 140,000\) with a RV precision of 10 cm s\(^{-1}\), opening the possibility to explore a new population of rocky planets orbiting the habitable zones of solar-type stars. The scheduling flexibility is a fundamental advantage for survey programmes like RV searches for exoplanets or time-critical programmes like studies of transiting planets. The 1-UT mode also offers the possibility to enhance the resolving power up to 200,000 with a extremely stable wavelength accuracy which certainly will motivate new scientific projects e.g. high-accuracy stellar astrophysics projects. In addition, in the multiMR mode, ESPRESSO is able to collect the light of up to four UTs to generate a high-resolution

\(^7\) https://github.com/RomainAllart/Telluric_correction
\(^8\) https://github.com/iastro-pt/sBART
spectrum. The effectively larger telescope aperture of about 16m provides access to faint astronomical targets at a resolution of $R \sim 70,000$. ESPRESSO shall not be considered as a stand-alone instrument but as a science-generating machine, certainly delivering full-quality scientific data in less than a minute after the end of an observation.

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