European Organisation for Astronomical Research in the Southern Hemisphere

Programme: VLT

Project/WP: Science Operations

ESPRESSO User Manual

Document Number: ESO-319963

Document Version: 2

Document Type: Manual (MAN)

Released On: 2019-08-25

Document Classification: Public

Prepared by:	Pedro Figueira, Gaspare Lo Curto, and Andrea Mehner; originally prepared by Paolo Molaro and the ESPRESSO consortium
Validated by:	Mieske, Steffen
Approved by:	Kaufer, Andreas

Authors

Name	Affiliation
P. Molaro et al.	Original authors from the ESPRESSO Consortium
C. Ledoux et al.	Editors from ESO - Directorate of Operations
P. Figueira, G. Lo Curto, A. Mehner	IS team extensive editing

Change Record from Previous Versions

Issue/Rev.	Date	Affected Section(s)	Changes / Reason / Remarks
0.1	2017-02-01	All	First draft
0.5	2017-02-28	All	PAE version
0.6	2018-02-06	All	Pepe’s revision of PAE document
0.8	2018-03-01	All	First version for ESO Period 102
1.0	2018-07-01	All	First version for Phase 2 submission
1.1	2018-09-01	All	Updated version for Period 103
1.2	2018-12-18	All	Updated version for Period 103, phase 2
1.3	2019-03-04	All	Updated version for Period 104
1.4	2019-08-25	All	Updated version for Period 105

Table of Content

List of Figures

List of Tables

1. Introduction

1.1 Scope of this Document

The ESPRESSO User Manual is intended to assist users by providing the necessary information on the instrument capabilities and on its operation. This manual should be used as a reference when preparing observing time proposals and observations. For this purpose, this document provides:

- An overall description of the technical characteristics of ESPRESSO, its performances and observing modes;
- Information on the preparation of the observations;
- Information on practical aspects of the observations;
- A description of the instrument calibration plan;
- A brief introduction to the pipeline data reduction and data analysis software.

The content of this manual is based on material provided by the ESPRESSO Consortium. Comments and suggestions on it are welcome and should be addressed to the User Support Department (usd-help@eso.org).

1.2 Definitions, Acronyms and Abbreviations

This document uses several abbreviations and acronyms to refer concisely to an item, listed in Table 1.

1T	First temperature enclosure (convergence-point room)
3T	Third temperature enclosure (surrounding the vacuum vessel)
ADC	Atmospheric Dispersion Corrector
APSU	Anamorphic Pupil Slicer Unit
BOB	Broker of Observation Blocks
CCD	Charge-Coupled Device
CCL	Combined Coudé Laboratory
CPL	Common Pipeline Library
CR	Coudé Room
CTE	Charge Transfer Efficiency
DAS	Data Analysis Software
DFS	Data Flow System
DRS	Data Reduction Software
EG	Echelle Grating
ESPRESSO	Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations
ETC	Exposure Time Calculator
FE(U)	Front-End (Unit)

FP(CS)	Fabry-Pérot (Calibration Source)
GUI	Graphical User Interface
HARPS	High-Accuracy Radial-velocity Planet Searcher
HDU	Header/Data Unit
HR	High Resolution
LDLS	Laser-Driven Light Source
LFC	Laser Frequency Comb calibration source
OB	Observation Block
PAE	Provisional Acceptance Europe
PLC	Programmable Logic Controller
RV	Radial Velocity
S/N	Signal-to-Noise Ratio
TCCD	Technical CCD
UHR	Ultra-High Resolution
UT	Unit Telescope (8.2-metre telescope at Paranal)
VLT	Very Large Telescope
VPHG	Volume Phase Holographic Grating
VV	Vacuum Vessel

Table 1: Abbreviations and acronyms used in this document

1.3 Additional Information on ESPRESSO

The complete ESPRESSO documentation is available from the ESPRESSO public web pages along with the latest information on the instrument:

http://www.eso.org/sci/facilities/paranal/instruments/espresso

Information and software tools for the preparation of service- and visitor-mode observations using ESPRESSO are available at:

http://www.eso.org/sci/observing/phase2

http://www.eso.org/sci/observing/phase2/SMGuidelines.ESPRESSO

Visiting astronomers will find instructions on the Paranal Science Operations web pages as well as the dedicated ESPRESSO page:

http://www.eso.org/sci/facilities/paranal/sciops

http://www.eso.org/sci/facilities/paranal/instruments/espresso/visitor

Any publication based on observations using ESPRESSO should cite the paper:

Pepe et al., 2013, The Messenger, 153, 6: *“ESPRESSO — An Echelle SPectrograph for Rocky Exoplanets Search and Stable Spectroscopic Observations”*

2. Instrument Description

2.1 Overview

ESPRESSO is a fibre-fed, cross-dispersed, high-resolution Echelle spectrograph. The instrument is in the Combined-Coudé Laboratory (CCL), and can collect light from the incoherent focus front-end units of the Unit Telescopes (UTs). The telescope light is fed from each of the UTs into the CCL via a `Coudé-Train' optical system and then into the instrument through optical fibres. Target and reference light enter the instrument simultaneously through two separate fibres. ESPRESSO is then composed of four different subsystems: the Coude Train, the Front Ends, the Calibration Unit and the spectrograph. These are represented in the diagram below (Fig. 1).

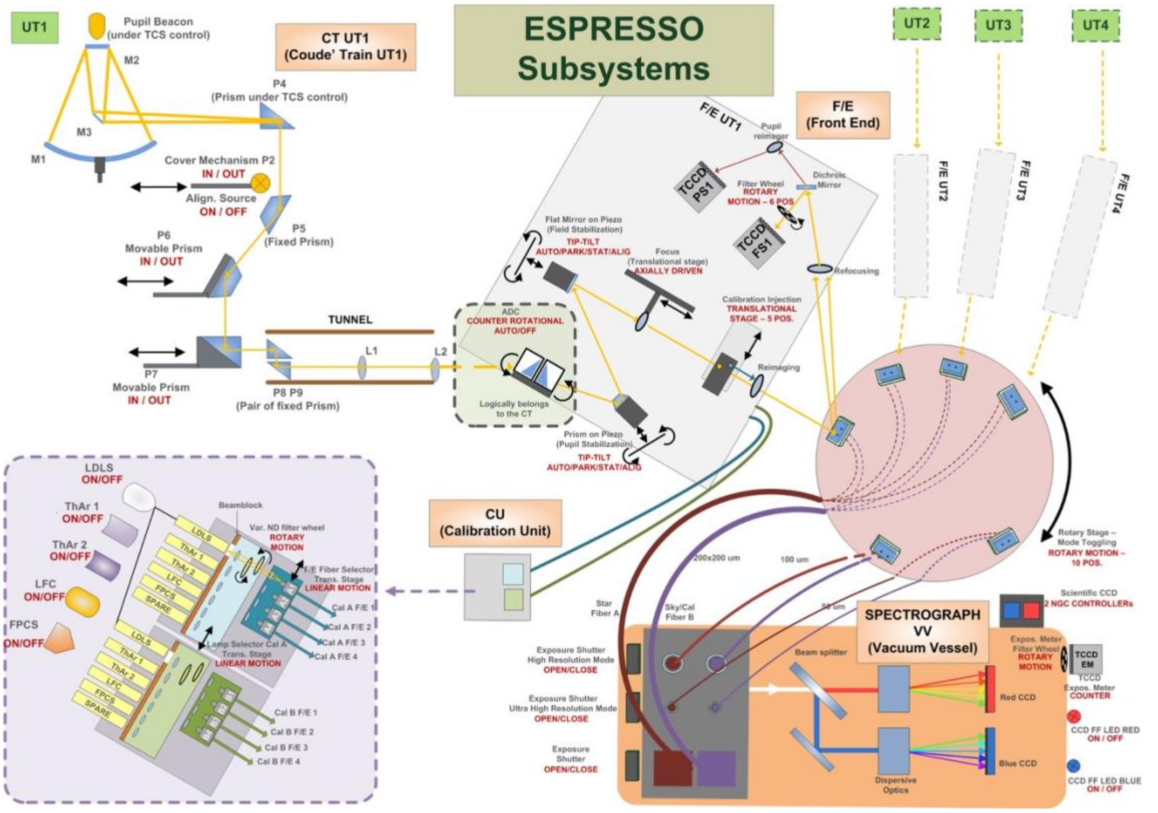


Fig. 1 ESPRESSO and its different subsystems: Coude Train, Front-End, Calibration Unit and Spectrograph.

2.1.1 A Combined-Coudé Spectrograph in 1-UT or 4-UT Mode

Although foreseen in the original VLT plan, the incoherent combined focus was put to use for the first time with ESPRESSO. The instrument can receive light from any number of the four UTs. The standard operation modes are 1-UT mode and 4-UT mode, in which light is fed from one or the 4 UTs, respectively.

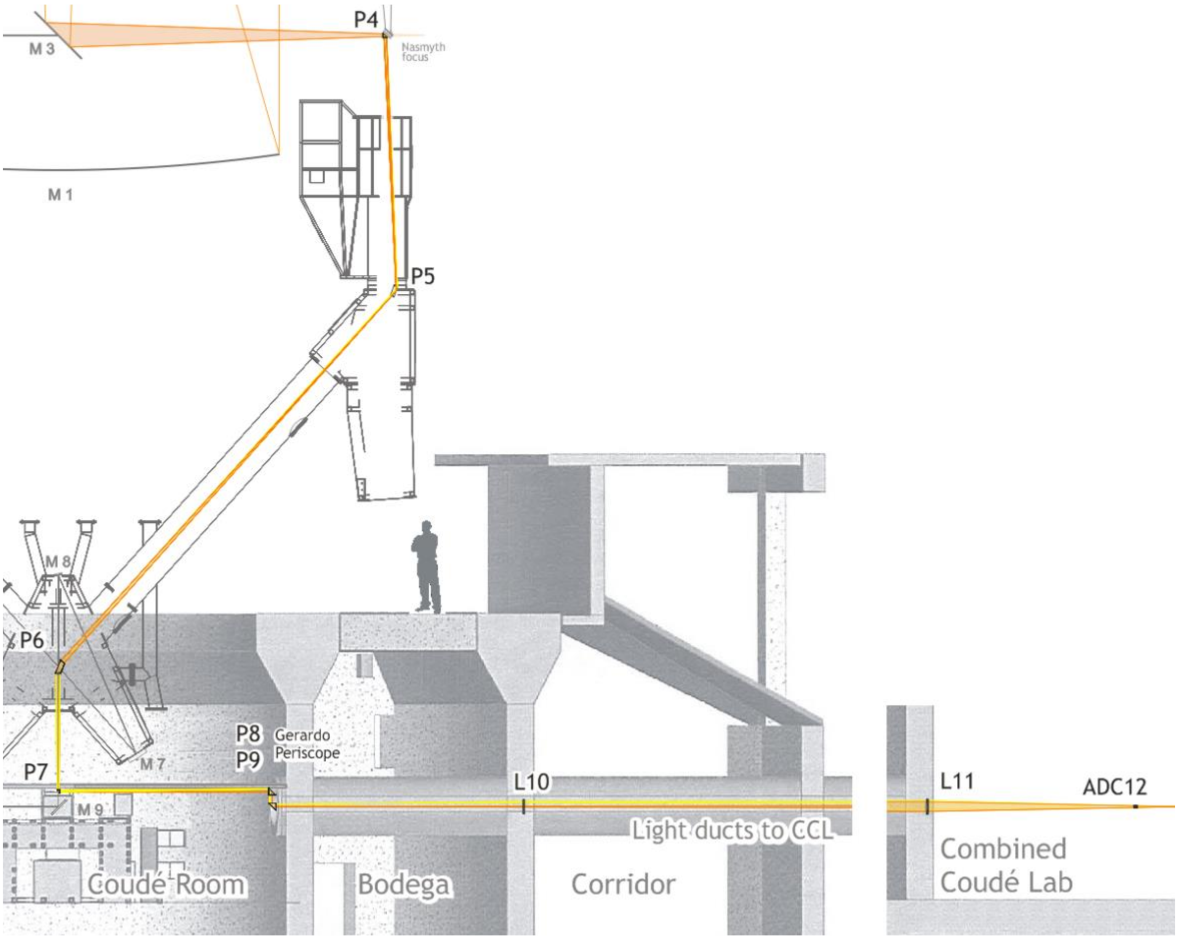


Fig. 2: UT Coudé Train and optical path to the CCL through the telescope and tunnels.

Channelling of light from the telescopes to the CCL is obtained through a full optics solution, without using fibres. The Coudé Trains pick up the light at the level of the Nasmyth-B platforms and redirects it using 4 prisms through the UT mechanical structure, down to the UT Coudé Rooms (CR). It is then redirected along the incoherent light ducts into the CCL (see Fig. 2) by using a 2-mirrors periscope and 2 lenses. In this way, the beams from the four UTs converge into the CCL, and to a Front-End (FE) sub-system for each of the UTs. The implementation of the Coudé Trains required substantial changes in the Paranal Observatory infrastructure resulting in a sophisticated interface management.

The FE sub-system is composed of a rigid four-arm structure, with each arm oriented towards one of the UT's incoherent tunnels, and four FE units. The beam received from the Coudé is corrected for atmospheric dispersion by a dedicated Atmospheric Dispersion Corrector (ADC) unit (one per FE) and then redirected to the common focal plane on which the heads of the fibre-to-spectrograph feeding are located. While performing beam conditioning, the FE can apply pupil and field stabilizations via two independent control loops each composed of a technical camera and a tip-tilt stage. Due to ESPRESSO having a highly stable pupil, the pupil stabilization control loop is not currently used.

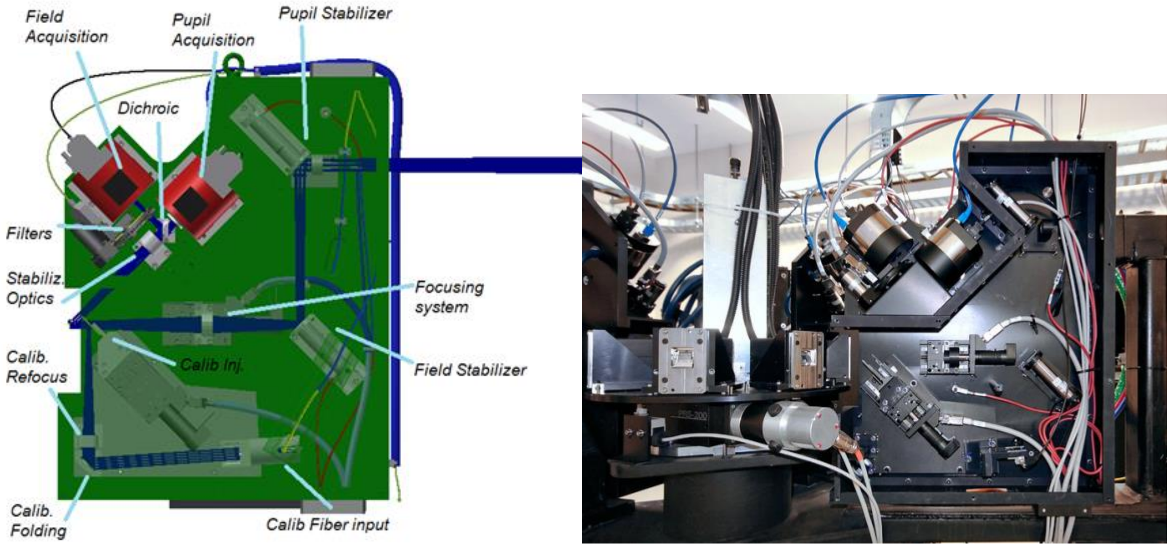


Fig. 3: Side view of an individual Front-End Unit.

In addition to these functions, the FE allows the injection of calibration light into the spectrograph. An inside view of a single FE Unit and its main components is provided in Fig. 3. In this figure, the beam arrives through the tunnel and crosses the ADC (on the right-hand side, outside of the figure). After that, the beam is deflected by the pupil- and field-stabilisation mirrors in the direction of the fibre head where the light is injected into the fibre link through a pinhole in the field mirror. A refocusing mechanism allows to focus the stellar image on the pinhole for optimum efficiency. The field mirror redirects the beam falling outside of the pinhole towards a guiding field and a pupil cameras for field and pupil visualizations, respectively, which provide a positive feedback to the pupil- and field-stabilisation mirrors. A top view of the whole FE Sub-system is shown in Fig. 4, together with a picture of the interior of the CCL.

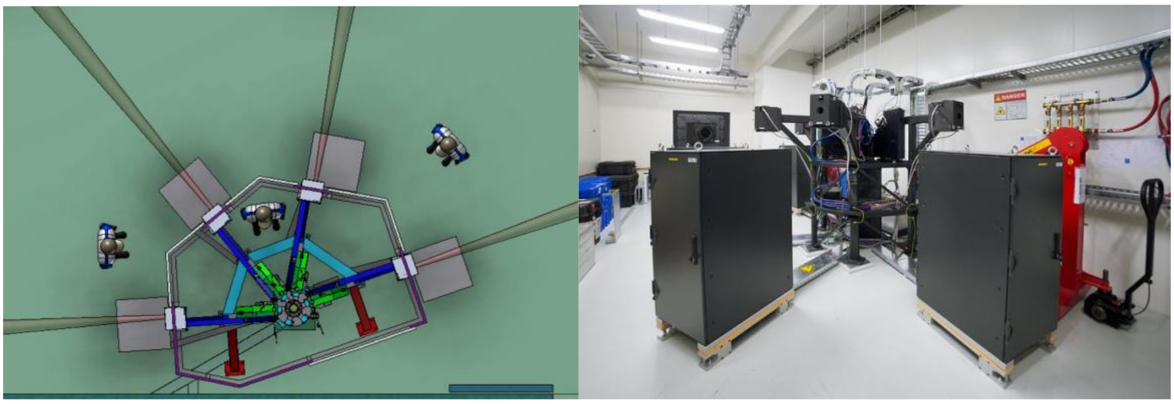


Fig. 4: Left: Top view of the Front-End Sub-System. Right: FE and the four UT beams in the CCL.

The Fibre-Link sub-system relays the light from the FE to the spectrograph. The 1-UT mode uses 2 octagonal fibres, one for the object and one for either the sky or for simultaneous radial-velocity reference.

In the 1-UT high-resolution mode (named singleHR), the fibres have a core of 140 µm that subtends 1 arcsec on the sky. In the ultra-high resolution (singleUHR) mode, the fibres' core is 70 μm wide, equivalent to 0.5 arcsec on the sky. The two fibre pairs are located in separate bundles that are brought to the focal plane of the specific FE of the corresponding UT.

In the 4-UT mode (multiMR), four object fibres and four sky/reference fibres converge from the four UTs. The four object fibres, all with a core of 140 μm, are bundled together to feed a single square 280 μm object fibre; the same procedure is used for the four sky/reference fibres that feed a single square 280 μm sky/reference fibre. Thus, in the 4-UT mode, the spectrograph ‘sees’ a fibre image twice as wide as in the case of the 1-UT fibres.

An essential task performed by the Fibre-Link sub-system is light scrambling. The use of a double-scrambling optical system ensures scrambling of both the near field and the far field of the light beam. Modern fibres are manufactured with a polygonal cross-section to break the radial symmetry and attain an improved scrambling. A high scrambling gain is crucial for high radial-velocity (RV) precision and is best achieved using octagonal fibres (Chazelas et al, 2012, SPIE, V. 8450, p9).

2.2 The Spectrograph

2.2.1 Optical Design

The optical design of the spectrograph is shown in Fig. 5. Several innovative optical solutions have been used to obtain simultaneously high spectral resolution and high efficiency without sacrificing mechanical stability.

In order to minimize the size of the optics, particularly of the collimator and the Echelle grating, ESPRESSO implements *anamorphic* optics. At the spectrograph entrance, the Anamorphic Pupil Slicing Unit (APSU) compresses the beam in cross-dispersion direction and a pupil slicer splits the pupil into two beams; the two are superimposed on the Echelle grating, that through this optical trick can have a smaller size. The rectangular white pupil is then re-imaged and compressed. After the main dispersion, the dichroic beam splitter separates the beam into two blue and red spectroscopic arms, which in turn allows to optimize each arm in terms of image quality and optical efficiency. The cross-dispersers have the function of separating the overlapping dispersed 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 spacing and the signal-to-noise ratio (S/N) per pixel are maximized. Both functions are accomplished using Volume Phase Holographic Gratings (VPHGs) mounted on prisms. The shape and size of both the pupil and fibre images are shown in Fig. 6 for various locations along the optical beam of the spectrograph. Finally, two optimised camera lens systems image the full spectrum from 380 nm to 788 nm on two large 92 mm x 92 mm CCDs with 10 μm pixels.

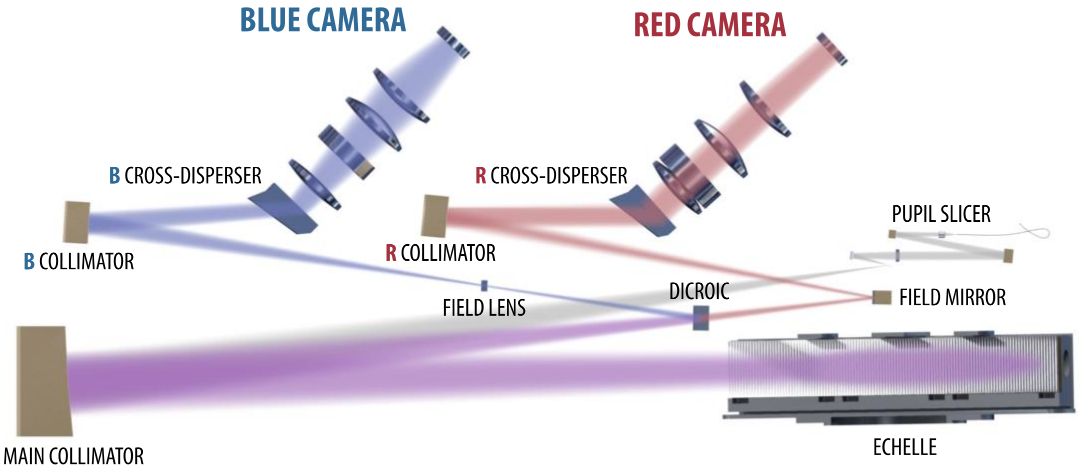


Fig. 5: Schematic layout of the ESPRESSO spectrograph and its optical elements.

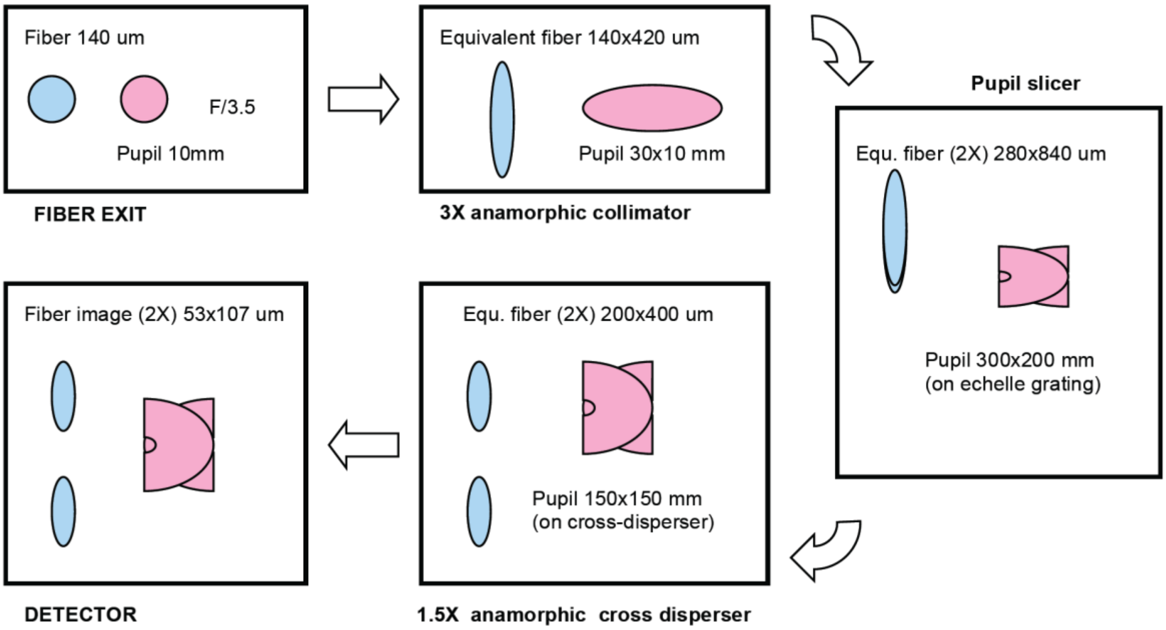


Fig. 6: Conceptual description of pupil and fibre images at key locations inside the spectrograph.

Without the application of the anamorphic pupil design, the collimator beam size would have a diameter of 40 cm and the Echelle grating would have a size of 180 cm x 40 cm. Instead, the ESPRESSO employs an Echelle grating of 120 cm x 20 cm and much smaller optical elements (collimators, cross dispersers, etc.). Due to the elongated shapes of the image of the two slices, each spectral element is covered by a larger number of detector pixels. In order to avoid increased detector noise, pixel binning is available for low S/N observations. By spreading the flux across a larger number of pixel one can reach a higher S/N per single exposure, a significant advantage in the high S/N regime. The resulting (general) spectral format covered by the blue and red chips as well as the images of the pseudo-slits on the science detectors are shown in Fig. 7.

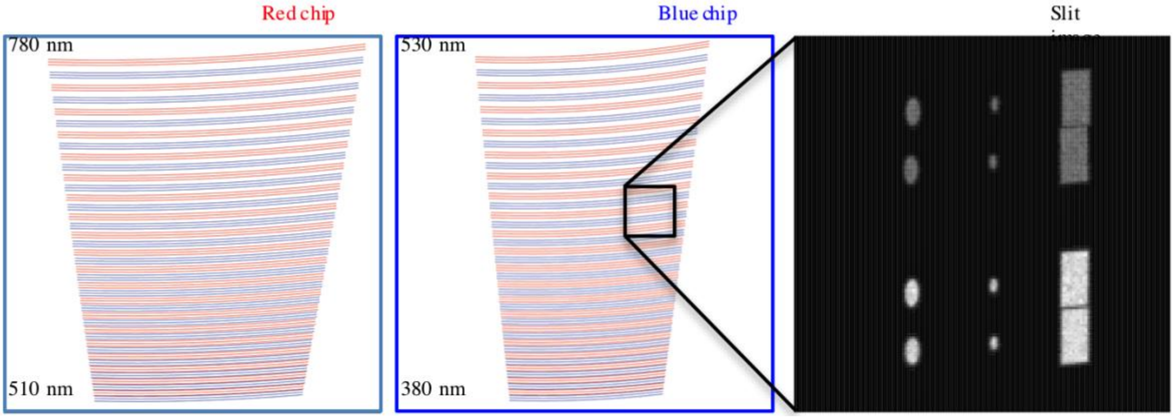


Fig. 7: Format of the spectrum. Right: Zoom in on the pseudo-slit image. The latter shows the image of the target (bottom) and sky fibre (top). Each fibre is re-imaged into two slices. The image of the pseudo-slit on the science detectors, from left to right: in the 1-UT UT mode, in the 1-UT UHR mode, and in the 4-UT MR mode, are shown together.

2.2.2 Opto-Mechanics and Thermal Control

ESPRESSO was designed to be an ultra-stable spectrograph capable of reaching an RV precision of the order of 10 cm s^{-1}, i.e., one order of magnitude better than the goal RV stability of its predecessor, HARPS. To this aim, the spectrograph is built in a totally fixed configuration for the highest thermo-mechanical stability. The optics are mounted on a tri-dimensional optical bench specifically designed to keep the optical system within the thermo-mechanical tolerances required for high-precision RV measurements. The bench is located inside a vacuum vessel inside which a 10^{-5}-mbar class vacuum is permanently maintained. An overview of the opto-mechanics of the spectrograph is shown in Fig. 8.

The temperature of the optical system is required to be stable at the mK level in order to avoid both optical index refraction variations and mechanical instabilities. This requirement is fulfilled by locating the spectrograph in a multi-shell active thermal enclosure system, depicted in Fig. 9 and Fig. 10. Each shell improves the temperature stability by a factor of 10, thus getting from typically Kelvin-level variations in the CCL down to mK stability inside the vacuum vessel and on the optical bench.

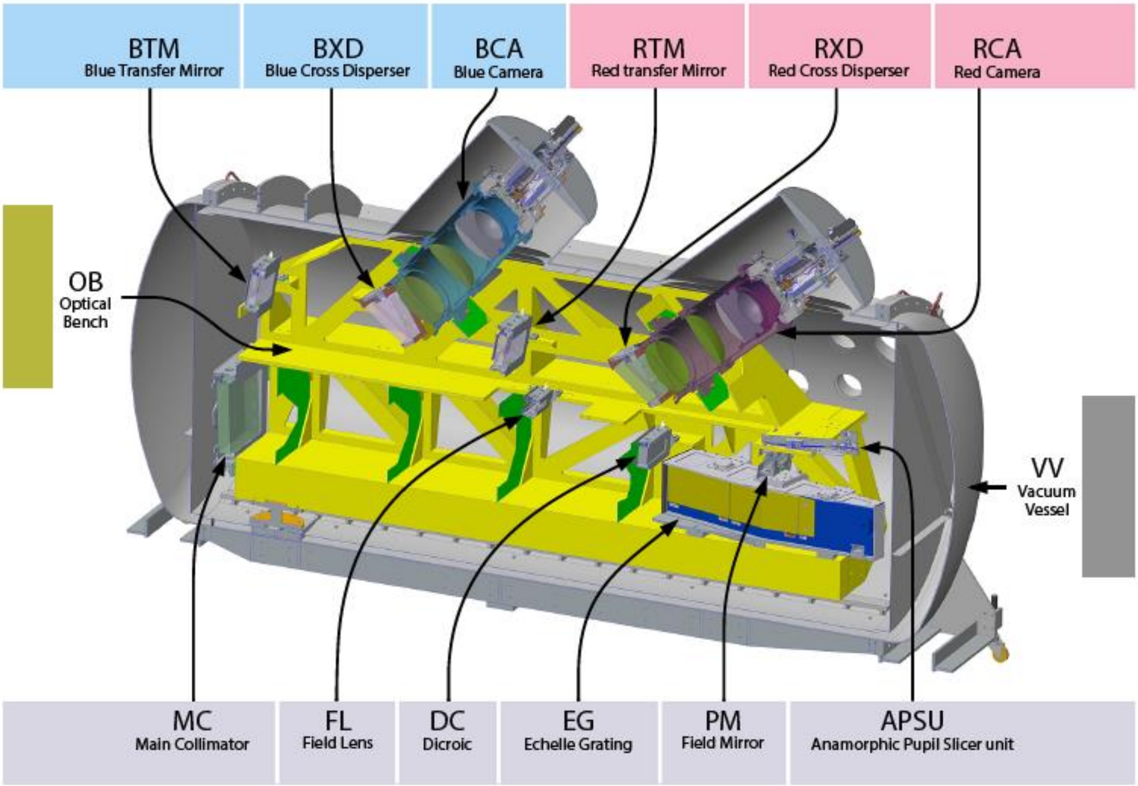


Fig. 8: Opto-mechanics of the ESPRESSO spectrograph.

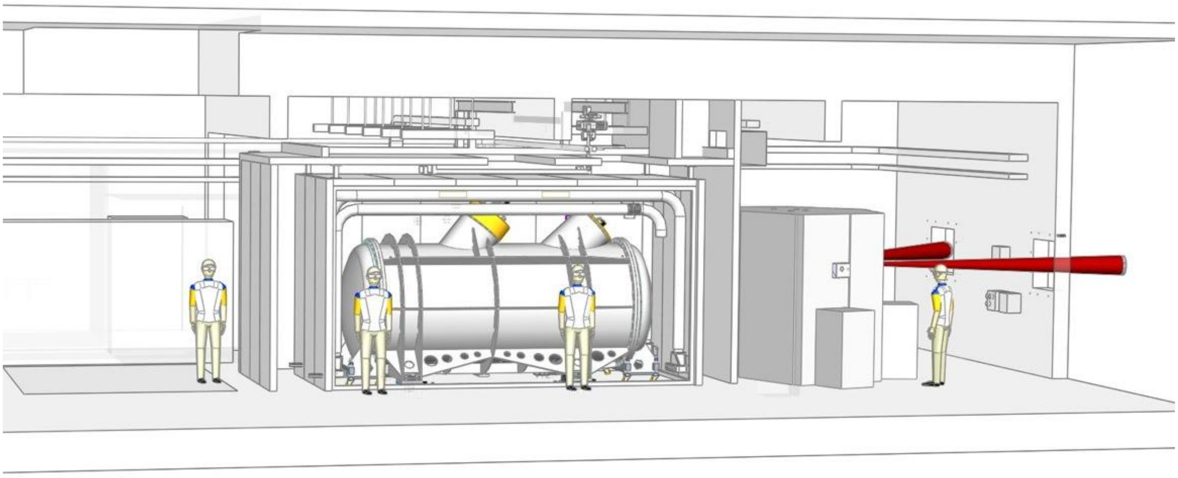


Fig. 9: Representation of ESPRESSO inside the CCL, vacuum vessel and multi-shell thermal control system, with converging light beams represented in red.

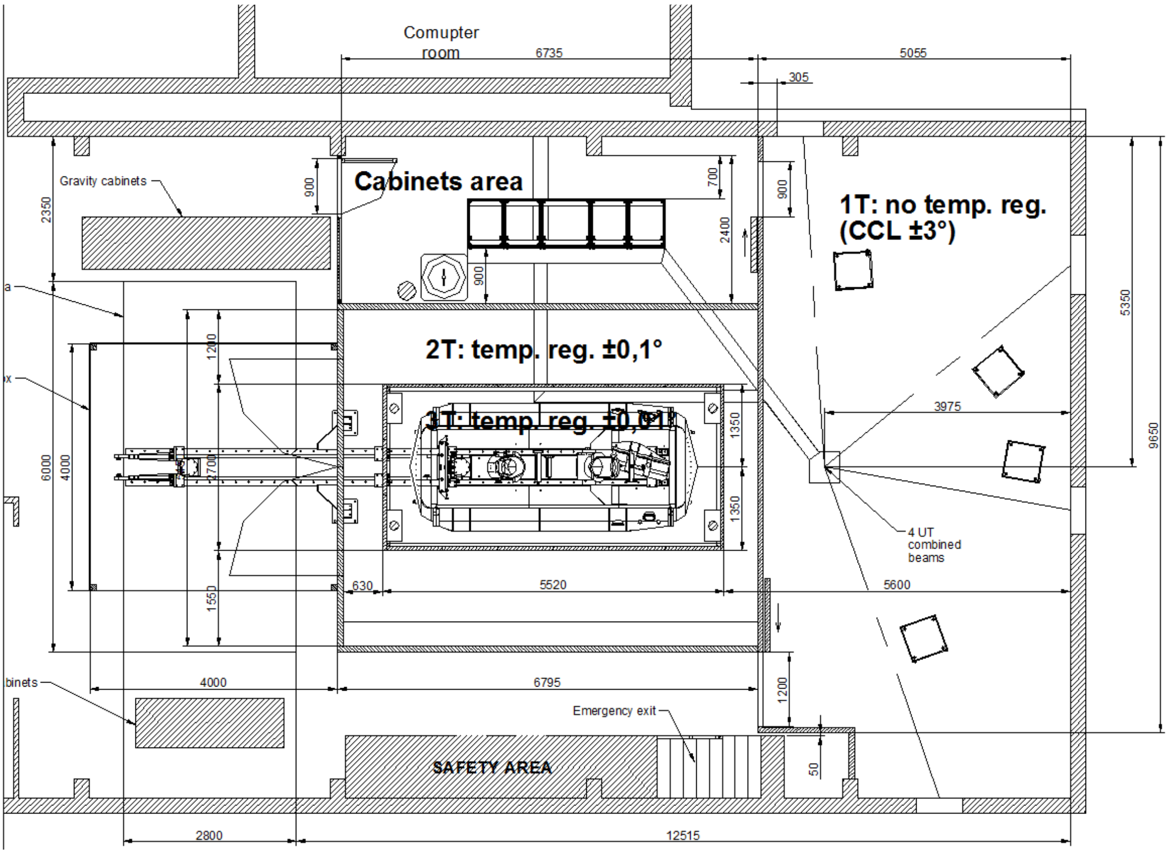


Fig. 10: Schematic diagram of ESPRESSO inside the CCL, top view.

2.2.3 Scientific Detectors

ESPRESSO implements innovative solutions in the area of CCDs, their packages and cryostats. One of the world's largest monolithic state-of-the-art CCDs was selected to cover the spectral format and wavelength range of ESPRESSO and to obtain improved stability when compared to a mosaic solution like that employed in HARPS. The CCDs were procured from the e2v supplier and have a sensitive area of 92 mm x 92 mm, composed of 9k9 pixels of 10 µm size. Fast read-out of such a large chip is achieved by using its 16 output ports at high speed. The scientific CCDs have very demanding specifications, e.g., in terms of Charge Transfer Efficiency (CTE) and parameters affecting the definition of the pixel position, for which an error translates directly into the RV precision and accuracy. An engineering sample is shown in Fig. 11.

For better stability and thermal-expansion matching, the CCD package is made of Silicon Carbide. ESPRESSO's target precision of 10 cm s^{-1} requires measuring spectral-line position changes of 2 nm in the CCD plane, equivalent to only 4 times the silicon lattice constant. 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 operations are of critical importance. For these purposes, ESO has built a new "super-stable" cryostat and performs continuous wiping and applies a custom read-out pattern to produce constant heat dissipation in the chips.

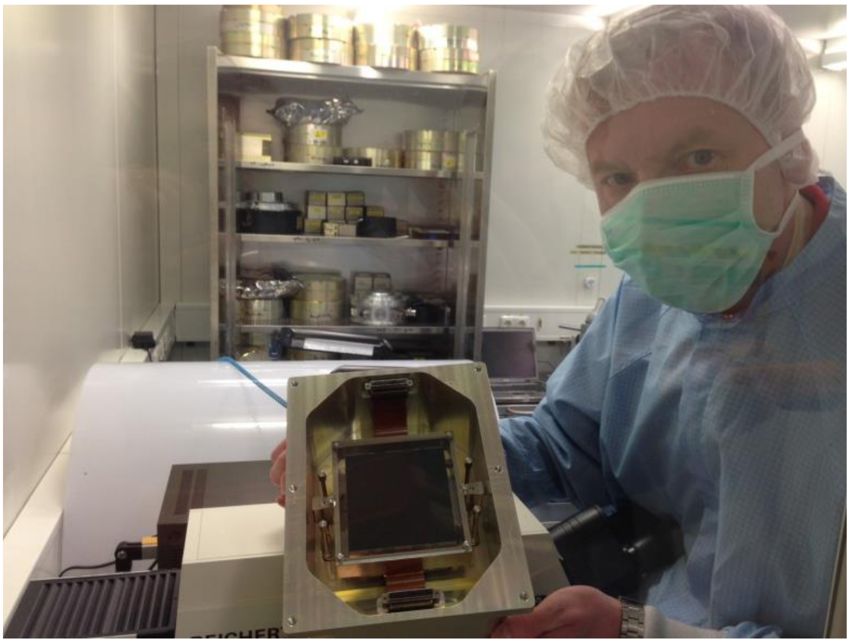


Fig. 11: The first ESPRESSO e2v CCD in its shipping container, inside the ESO cleanroom.

2.2.4 The Calibration Unit

The Calibration Unit provides a set of lamps to calibrate the instrument. These are:

- A Laser-Driven-Light Source (LDLS) for order localization, profile definition, and spectral flat-fielding;
- A Thorium-Argon hollow-cathode lamp (ThAr) for absolute wavelength calibration under regular operations;
- A Fabry-Pérot (FP)-cavity illuminated in white light for simultaneous-reference (drift) measurements. This spectral lamp is also used in combination with the ThAr to extend and improve the wavelength calibration;
- A Laser-Frequency Comb (LFC), designed for the most accurate wavelength calibration. However, the LFC currently installed only covers the wavelength range from 500 to 720 nm. The extension of the wavelength calibration over the full spectral range is performed using the FP source.

  The LFC is currently not reliable. ESO is working together with the manufacturer MENLO, in order to start regular operations as soon as possible.

The Calibration Unit (CU) feeds 8 calibration beams to the FE sub-system, 2 for each FE unit: one for the ‘object’ fibre and the other one for the ‘reference’ fibre. The light from any of the CU lamps can be injected into any of the fibres. The FE unit injection system reproduces a calibration beam identical in diameter and F-number to the scientific beam from the telescope. In the 1-UT as well as 4-UT modes, only one of the Front-End beams will receive the calibration light. Under regular operations, the FE-1 is used for calibrations for all the UTs in order to provide a common calibration reference.

3. Observing Modes

3.1 Instrument Modes

The accuracy of a measurement system is the degree of closeness between its measurements of a quantity and its real value. On the other hand, the precision of a measurement system, also called reproducibility or repeatability, is the degree to which repeated measurements under unchanged conditions lead to the same results. ESPRESSO's science goals require an extreme RV precision and high RV accuracy. This was achieved by adopting and improving on several concepts used on HARPS and now firmly established as standard in the precise RV community. The light of one or several UTs is fed by means of the FE unit(s) into optical fibres that scramble the light and provide excellent illumination stability to the spectrograph. In order to provide improved light scrambling, non-circular fibre shapes are used. By breaking the radial symmetry of our waveguide, we break the geometric regularity the internal reflections inside the fibre, attaining a more homogeneous light distribution at the exit.

The object fibre can be fed with light either from an astronomical source or from one of the calibration lamps. The reference fibre receives either sky light or light for simultaneous instrumental drift measurement. In the latter case - the so-called simultaneous-reference technique, also adopted from HARPS - it is possible to track instrumental drifts down to the cm s^{-1} level. This option was developed for the photon-noise limited regime, when the detector read-out noise is negligible, i.e., we are operating in the high S/N regime. For faint sources, or for sources for which a high spectral fidelity is preferable rather than tracking the instrument's internal drift, it is preferable to use the second fibre to measure the sky spectra. By doing so one can characterize accurately the sky background and the detector noise contributions, which provide a significant contribution to the error budget on faint sources. The user can also choose between a *Fast1x1* and *Slow2x1* readout and binning schemes that differ in terms of overhead time and binning factor in the spatial direction. The main characteristics of each observing mode are summarized in Table 2.

Parameter/Mode	singleHR (1-UT)	singleUHR (1-UT)	multiMR (4-UT)
Wavelength range	380-788 nm	380-788 nm	380-788 nm
Resolving power (median)	140'000	190'000	70'000
Aperture on sky	1.0 arcsec	0.5 arcsec	4x1.0 arcsec
Spectral sampling (average)	4.5 pixels	2.5 pixels	5.5 pixels (binned x2)
Spatial sampling per slice	9.0 (4.5) pixels	5.0 pixels	5.5 pixels (binned x4)
Number of slices	2	2	2
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 peak efficiency	~11%	~6%	~11%
Instrumental RV precision using sim. ref. (requirement)	<10 cm s^{-1}	< 5 m s^{-1}	<5 m s^{-1}

Table 2: Summary of ESPRESSO's observing modes and performances.

3.2 Detector Modes

ESPRESSO provides three observing modes: singleHR, singleUHR, and multiMR. Each mode is made available with specific detector read-out configurations optimized for low or high-S/N measurements, as detailed in Table 3. For high S/N measurements, when the read-out noise does not contribute significantly to the error budget, 1x1 pixel binning is offered to provide faster read-out and maximize the duty cycle (open-shutter time). On the other hand, for low S/N measurements a 2x1 binning factor, with binning in the spatial direction and a slow read-out is used to minimize noise contribution. Given the usually long exposure times used on faint targets, the longer readout time of this configuration does not impact significantly on the duty cycle of the observations.

The active area of each of the two detectors consists of 9216 optically active pixels in the spatial direction or cross-dispersion direction (X), and 9232 optically active pixels in the main dispersion direction (Y). The Echelle orders are thus aligned along the CCD columns (Y). The detector is read out through 2x8 ports, dividing the raw frames in 2 sections along Y and 8 sections along X. Table 4 indicates the raw-frame size provided by each individual read-out port after binning. Pre- and over-scan regions are produced in a symmetric way for each read-out port. The spectrum is assembled into a single FITS file containing two raw frames composed each of 2x8 individual sub-frames aligned according to the physical layout but separated by the pre- and over-scan regions of each sub-frame.

The total overheads contain the time spent on readout, transfer, and wiping operations. For updated information on the total overheads please refer to ESPRESSO official webpages:

https://www.eso.org/sci/facilities/paranal/instruments/espresso/inst.html

.

Detector mode	Binning (spaxel x spectral)	Read-out speed	RON (Blue)	RON (Red)	Conversion factor	Read-out ports	Total Overheads
FAST	1x1	500 kpx s^{-1}	8 [e^-/pixel]	5 [e^-/pixel]	1.1 [e^-/ADU]	2x8	45s
SLOW	2x1, 4x2, 8x4	100 kpx s^{-1}	3 [e^-/pixel]	2 [e^-/pixel]	1.1 [e^-/ADU]	2x8	68s, 41s, 36s

Table 3: ESPRESSO detector modes and associated overheads.

Binning	X	Y	PRE-X	OVER-X	PRE-Y	OVER-Y
1x1	1152	4616	24	64	0	32
2x1	576	4616	12	32	0	32
4x2	288	2308	6	16	0	16
8x4	144	1154	3	8	0	8

Table 4: Frame size provided by each individual read-out port.

3.3 Instrument Configurations

Several instrument configurations are available for different types of scientific goals. Table 5 lists the available setups.

Observing mode	Purpose	Templates	Read-Out	Binning
SINGLE_HR11	Spectroscopy and RV monitoring of bright targets (V<12) with 1 UT	singleHR	FAST	1x1
SINGLE_HR21	Spectroscopy and RV monitoring of fainter targets (V>12) with 1 UT	singleHR	SLOW	2x1
SINGLE_UHR11	Very high-resolution spectroscopy with 1 UT	singleUHR	FAST	1x1
MULTI_MR42	Spectroscopy of faint targets with 4 UTs	multiMR	SLOW	4x2
MULTI_MR84	Spectroscopy of very faint targets with 4 UTs	multiMR	SLOW	8x4

Table 5: Summary of ESPRESSO's instrument configurations

3.3.1 Binning scheme and impact on the scientific objectives

The modes HR and MR allow the user to choose from 2 different binning schemes. Binning defines how many pixels in X and Y dimension are transferred before they are read out. For ESPRESSO, in an NxM binning N pixel are clocked (transferred) in the spatial or cross-dispersed direction and M pixel in the dispersion direction, being read all at once. In this way the readout-noise contribution is accounted for once, in opposition to contributing NxM times if we did not use binning. The binning scheme is thus favorable for low S-N observations that are read-out-limited or close to it.

The price to pay is a reduced sampling of the spatial profile (by a factor of N) and a reduced sampling of the lines in the dispersion direction (by a factor of M). This latter sampling should not be confused with a lower resolution. Sampling (also termed numerical sampling) is simply the number of pixel used to record the FWHM of an unresolved line. If sampling remains above 2 pixel, then a lower sampling does not correspond to a degradation in resolution. This is always the case for ESPRESSO.

3.4 Spectral Format

The spectrum is spread over two CCDs, the blue- and the red-arm detectors, which cover the spectral ranges of 380-525 nm and 525-788 nm, respectively. Table 6 and Table 7 quantifies the spectral format of the two arms as shown by the ETC. For each order number, from left to right, the wavelength of the central column, the free spectral range (FSR) size, the minimum and maximum wavelengths, the order starting and ending wavelengths and size, and the template spectra (TS) range, are given.

Due to the presence of the APSU, for UHR and HR each order is composed of two slices with the same spectral information content but recoded on different physical pixel. For MR mode there is only one slice, created by the dispersed image of the square fibre bundle.

Order	wave of central column (nm)	FSR range (nm)	FSR | Min (nm)	FSR | Max (nm)	start wave (nm)	end wave (nm)	TS range (nm)
78	784.45	10.06	779.45	789.51	778.98	790.64	11.66
79	774.52	9.80	769.65	779.45	769.11	780.65	11.54
80	764.84	9.56	760.09	769.65	759.48	770.89	11.41
81	755.40	9.33	750.76	760.09	750.10	761.38	11.28
82	746.19	9.10	741.66	750.76	740.95	752.10	11.16
83	737.19	8.88	732.78	741.66	732.01	743.04	11.03
84	728.42	8.67	724.11	732.78	723.29	734.20	10.91
85	719.85	8.47	715.64	724.11	714.78	725.57	10.79
86	711.48	8.27	707.37	715.64	706.46	717.13	10.67
87	703.30	8.08	699.28	707.37	698.34	708.89	10.56
88	695.31	7.90	691.38	699.28	690.40	700.84	10.45
89	687.50	7.72	683.66	691.38	682.63	692.97	10.34
90	679.86	7.55	676.10	683.66	675.04	685.27	10.23
91	672.39	7.39	668.71	676.10	667.62	677.74	10.12
92	665.08	7.23	661.48	668.71	660.36	670.38	10.02
93	657.93	7.07	654.41	661.48	653.26	663.18	9.92
94	650.93	6.92	647.48	654.41	646.31	656.12	9.82
95	644.08	6.78	640.70	647.48	639.50	649.22	9.71
96	637.37	6.64	634.06	640.70	632.84	642.46	9.62
97	630.80	6.50	627.56	634.06	626.31	635.83	9.52
98	624.36	6.37	621.19	627.56	619.92	629.35	9.43
99	618.05	6.24	614.95	621.19	613.65	622.99	9.34
100	611.87	6.12	608.83	614.95	607.52	616.76	9.25
101	605.81	6.00	602.83	608.83	601.50	610.66	9.16
102	599.87	5.88	596.95	602.83	595.60	604.67	9.07
103	594.05	5.77	591.18	596.95	589.82	598.80	8.99
104	588.34	5.66	585.52	591.18	584.14	593.05	8.90
105	582.74	5.55	579.97	585.52	578.58	587.40	8.82
106	577.24	5.45	574.53	579.97	573.12	581.86	8.74
107	571.84	5.34	569.18	574.53	567.76	576.42	8.66
108	566.55	5.25	563.94	569.18	562.50	571.08	8.58
109	561.35	5.15	558.79	563.94	557.34	565.85	8.51
110	556.25	5.06	553.73	558.79	552.27	560.71	8.43

111	551.24	4.97	548.76	553.73	547.30	555.65	8.36
112	546.31	4.88	543.89	548.76	542.41	550.69	8.29
113	541.48	4.79	539.09	543.89	537.61	545.82	8.22
114	536.73	4.71	534.39	539.09	532.89	541.03	8.15
115	532.06	4.63	529.76	534.39	528.25	536.33	8.08
116	527.48	4.55	525.21	529.76	523.70	531.71	8.01
117	522.97	4.47	520.74	525.21	519.22	527.16	7.94

Table 6: Spectral format of ESPRESSO's red-arm CCD.

Order	wave of central column (nm)	FSR range (nm)	FSR | Min (nm)	FSR | Max (nm)	start wave (nm)	end wave (nm)	TS range (nm)
117	522.97	4.47	520.74	525.21	519.13	527.03	7.89
118	518.54	4.39	516.35	520.74	514.72	522.57	7.84
119	514.18	4.32	512.03	516.35	510.39	518.18	7.79
120	509.89	4.25	507.78	512.03	506.13	513.87	7.74
121	505.68	4.18	503.60	507.78	501.94	509.63	7.69
122	501.53	4.11	499.49	503.60	497.82	505.45	7.64
123	497.46	4.04	495.44	499.49	493.76	501.35	7.58
124	493.44	3.98	491.46	495.44	489.78	497.31	7.53
125	489.50	3.92	487.55	491.46	485.85	493.33	7.48
126	485.61	3.85	483.69	487.55	481.99	489.42	7.43
127	481.79	3.79	479.90	483.69	478.19	485.57	7.38
128	478.02	3.73	476.16	479.90	474.45	481.78	7.33
129	474.32	3.68	472.49	476.16	470.77	478.05	7.28
130	470.67	3.62	468.87	472.49	467.15	474.38	7.23
131	467.08	3.57	465.30	468.87	463.57	470.76	7.18
132	463.54	3.51	461.79	465.30	460.06	467.19	7.13
133	460.05	3.46	458.33	461.79	456.60	463.68	7.08
134	456.62	3.41	454.92	458.33	453.19	460.22	7.04
135	453.24	3.36	451.57	454.92	449.83	456.82	6.99
136	449.91	3.31	448.26	451.57	446.52	453.46	6.94
137	446.62	3.26	445.00	448.26	443.26	450.15	6.90
138	443.39	3.21	441.78	445.00	440.04	446.89	6.85
139	440.20	3.17	438.62	441.78	436.87	443.68	6.81
140	437.05	3.12	435.50	438.62	433.75	440.51	6.76
141	433.95	3.08	432.42	435.50	430.67	437.39	6.72

142	430.90	3.03	429.38	432.42	427.64	434.31	6.67
143	427.88	2.99	426.39	429.38	424.64	431.27	6.63
144	424.91	2.95	423.44	426.39	421.69	428.28	6.59
145	421.98	2.91	420.53	423.44	418.78	425.33	6.55
146	419.09	2.87	417.66	420.53	415.91	422.42	6.50
147	416.24	2.83	414.83	417.66	413.08	419.54	6.46
148	413.43	2.79	412.03	414.83	410.29	416.71	6.42
149	410.65	2.76	409.28	412.03	407.53	413.91	6.38
150	407.91	2.72	406.56	409.28	404.82	411.15	6.34
151	405.21	2.68	403.88	406.56	402.13	408.43	6.30
152	402.55	2.65	401.23	403.88	399.48	405.75	6.26
153	399.92	2.61	398.61	401.23	396.87	403.10	6.22
154	397.32	2.58	396.03	398.61	394.30	400.48	6.18
155	394.76	2.55	393.49	396.03	391.75	397.90	6.15
156	392.23	2.51	390.97	393.49	389.24	395.35	6.11
157	389.73	2.48	388.49	390.97	386.76	392.83	6.07
158	387.26	2.45	386.04	388.49	384.31	390.34	6.03
159	384.83	2.42	383.62	386.04	381.89	387.89	6.00
160	382.42	2.39	381.23	383.62	379.50	385.47	5.96
161	380.04	2.36	378.87	381.23	377.15	383.07	5.93

Table 7: Spectral format of ESPRESSO's blue-arm CCD.

4. Performances and Characteristics

4.1 Efficiency and RV Precision

When measuring the total transmission of a spectrograph, an important factor is the slit losses. The slit losses correspond to the fraction of light that is lost at the spectrograph-telescope interface, slit or fiber, simply because a fraction of the stellar point spread function will fall outside the interface. We refer the interested reader to ESPRESSO's ETC's webpages for a detailed explanation on the calculation of slit losses. Since slit losses depend on the fiber diameter, the HR and MR modes that use 1-arcsec fibres have similar losses, while the UHR mode is affected by stronger losses due to its 0.5-arcsec fibre. The losses are exacerbated under poor seeing conditions, when the FWHM of the target's PSF becomes larger than the slit size. In Fig. 12 and Fig. 13, we show the computed total transmission of ESPRESSO for the HR (and MR) mode and the UHR mode, respectively, assuming a seeing of 0.8 arcsec. Given the sensitivity of the transmission on the astro-climatic conditions, we recommend the users to adopt a conservative approach, while preparing detailed observing strategies for variable seeing and transparency conditions.

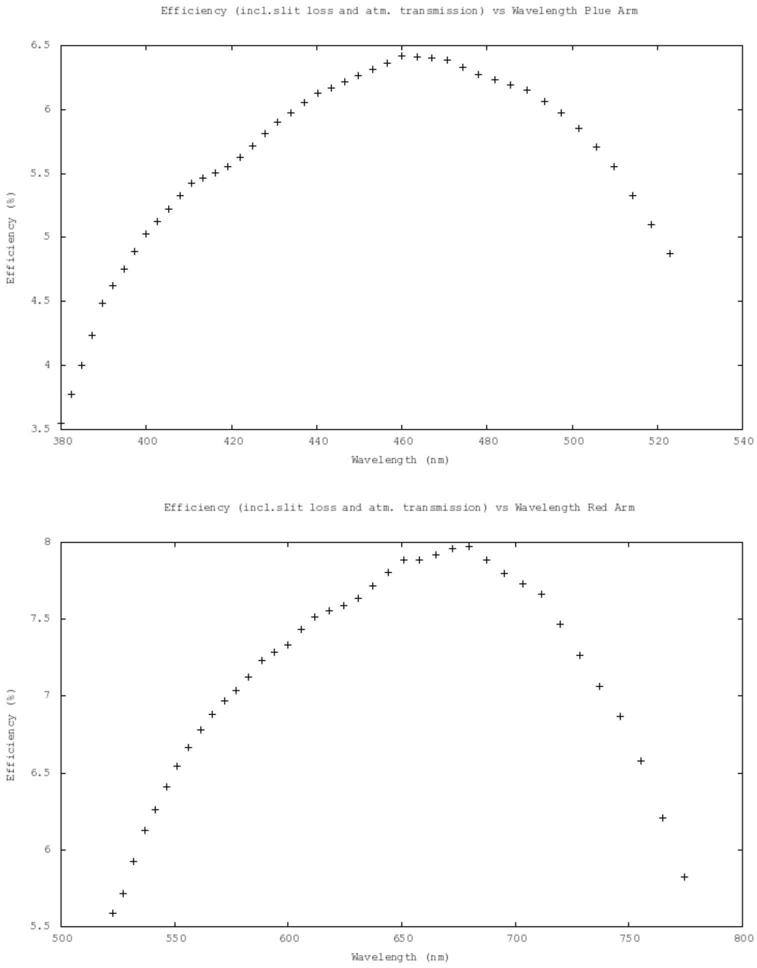


Fig. 12: Total transmission of ESPRESSO incl. slit losses and atmospheric transmission in HR (and MR) mode for the blue (top) and red arm (bottom). A seeing of 0.8 arcsec and an airmass of 1 are assumed.

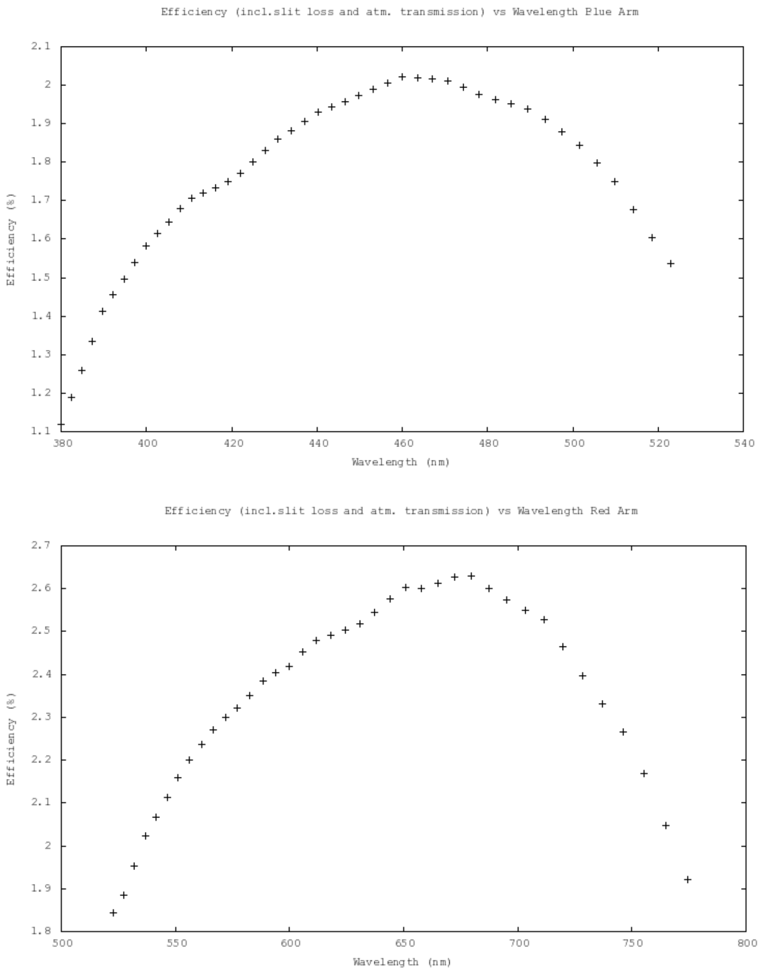


Fig. 13: Total transmission of ESPRESSO incl. slit losses and atmospheric transmission in UHR mode for the blue (top) and red arm (bottom). A seeing of 0.8 arcsec and an airmass of 1 are assumed.

The different fiber diameter, readout noise and pixel binning lead to a different S/N ratio per extracted pixel for the different modes. The approximate S/N for the five offered setups is shown in Fig. 14 to Fig. 16. For reference, for the singleHR mode a S/N of about 100 per extracted pixel is reached in an exposure of 60 s for a V = 8 star, which should lead to a photon-noise RV precision of approximately 50 cm s^{-1} for a non-rotating, inactive K5 dwarf star, under a seeing of 0.8 arcsec and at an airmass of 1. For earlier type stars and/or rotating stars, the internal RV precision will be lower at equal S/N, as consequence of the lower line density and wider lines. The difference in S/N between the singleHR11 and singleHR21 instrument configurations will only be apparent at faint magnitudes when the detector read-out noise starts to dominate. The singleUHR mode has lower total transmission due to larger slit losses, a price to pay for the higher resolution. On Fig. 16 we notice the gain in S/N achievable using multiMR. The factor of 2 arises from the larger collecting area of the 4 UTs when compared to a single UT. An additional factor of sqrt(2) or 2 is also obtained thanks to the binning by 2 or 4 pixel in the spectral direction in the multiMR42 and multiMR84 configurations, respectively. The gain in choosing a large binning factor is evident in low S/N regime and increases closer to the limiting magnitudes, at which the observations are read-out noise limited. This represents the main advantage of the ESPRESSO 4-UT mode against four equal exposures in single-UT mode obtained sequentially. For reference, in multiMR 8x4, we can achieve a S/N per extracted pixel of about 15 at 550 nm on a V = 19 target in a single 1-hour exposure.

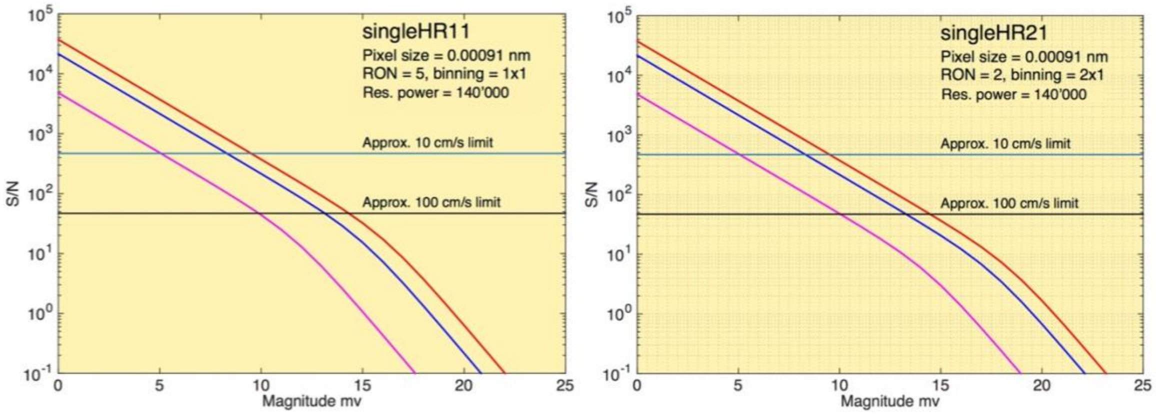


Fig. 14: S/N vs. stellar magnitude obtained in the singleHR11 and singleHR21 modes for exposure times of 60s (pink), 1200s (blue) and 3600s (red). The slope change defines the magnitude at which the measurement becomes detector read-out noise limited. S/N for 10 cm s^{-1} and 100 cm s^{-1} are shown. The values are estimated for slowly-rotating, inactive late-G or K dwarf stars, calculated for a seeing of 0.8 arcsec and an airmass of 1.

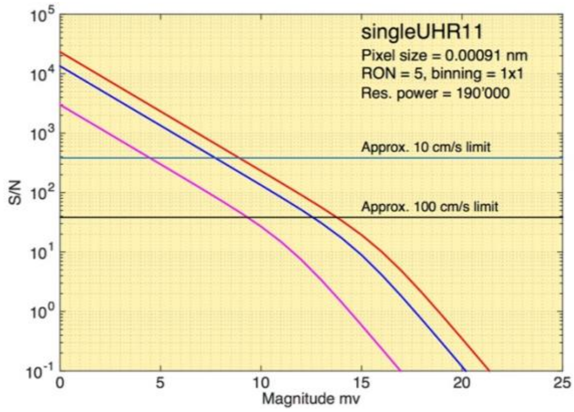


Fig. 15: Same as Fig. 14 but for the singleUHR mode.

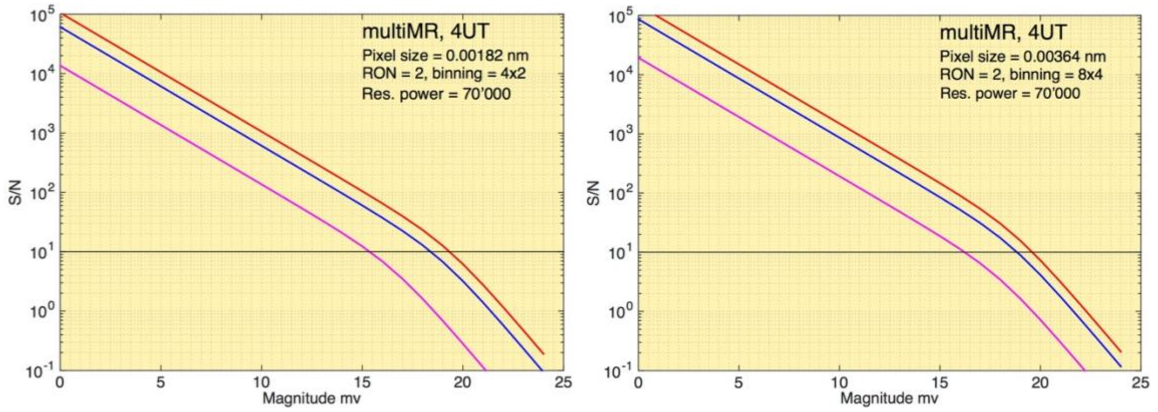


Fig. 16: S/N vs. stellar magnitude obtained in the multiMR42 and multiMR84 modes for exposure times of 60s (pink), 1200s (blue) and 3600s (red). The slope change defines the magnitude at which the measurement becomes detector read-out noise limited.

Different instrument configurations show a relative RV offset, as expected due to the properties of each setup (i.e., different spectral resolution and/or binning). The RV offsets have been measured for solar-type stars at: HR11-HR21~2.2 m s^{-1}, UHR-HR21~18 m s^{-1} and MR42-HR21~-18 m s^{-1}. However, these values are to be taken as illustrative, as they will depend on the characteristics of the target and of the RV calculation. The take-away lesson is that the user is strongly recommended to stick to the same observing mode for a given science case (i.e., for a given target and science goal).

The RV *precision* of ESPRESSO (measured within a given instrument configuration) is much higher than that. From long sequences of observations in the HR mode, it has been shown during commissioning that a precision better than 15 cm s^{-1} is achieved in the short term (i.e., within one night). The instrument can reach photon-noise limited uncertainties at the level of 10 cm s^{-1} in photon-noise-limited (i.e., high SNR) spectra of G-type stars. In the MR mode, a precision better than 1 m s^{-1} can be achieved over a few hours.

4.2 Wavelength Calibration and Drift Measurement

The wavelength calibration assigns a wavelength to each detector pixel. In ESPRESSO this is done with a repeatability of the order of $\Delta\lambda/\lambda = 10^{-10}$, leading to a very high precision in RV. A necessary condition for this precision level is the availability of a suitable wavelength-calibration source. None of the traditional used calibration sources, such as thorium-argon lamps or iodine cells, provide a spectrum with a high density of uniform and stable features, spanning the whole wavelength range of ESPRESSO. As such, alternative technical solutions were employed.

The baseline wavelength calibration adopted for ESPRESSO uses both the ThAr lamp and the Laser Frequency Comb (LFC) as part of its daytime calibrations. The LFC presents all the characteristics indispensable for an accurate wavelength calibration and provides a link to the frequency standard. However, the LFC is not yet offered to the community. Currently, a combination of ThAr frames and Fabry-Pérot exposures provides the wavelength-calibration solution. Nevertheless, the daytime calibration plan includes LFC frames whenever possible.

On top of a state-of-the art wavelength calibration, and in order to track residual instrumental drifts, ESPRESSO uses the simultaneous reference technique applied in its predecessor HARPS (e.g., Baranne et al. 1996). This means that the spectrum of a calibration source is recorded on the science detectors simultaneously with the science spectrum, using a parallel channel. The working hypothesis is that small optical path perturbations inside the spectrograph will be seen in the same way by both the target spectra and the reference spectra. These will translate into equal RV drifts on the two optical channels. For this purpose, ESPRESSO has a Fabry-Pérot unit for simultaneous drift measurement during the night. If selected by the user, this light source supplies a set of equally spaced emission lines that covers the two detectors completely; the high density of lines and spectral feature's width was optimized to deliver a precise RV reference. Note, however, that this reference source was designed for precision and not accuracy.

The LFC is not used at night for drift measurement due to its limited wavelength range and lifetime.

4.3 Dark Current, Diffuse Light, Ghosts, and Sky Background

The dark current measured on the ESPRESSO CCDs is of the order of 1 e^{-} $hour^{-1}$ $pixel^{-1}$. Dedicated dark frames are taken periodically as part of the long-term calibration plan for precise measurements of the detectors' dark current.

Scattered light is the diffuse component of the contamination on the CCDs, which is usually proportional to the total flux received in the focal plane and varies smoothly across the detectors. A maximum diffuse background below 0.1% of the peak flux has been measured. Nevertheless, in the extreme blue part of the spectrum, the diffused background can be slightly higher; this effect depends strongly on the spectral-energy distribution of the target.

Ghosts are natural features of grating spectrographs (due to the high number of optical components) and cannot be avoided. In ESPRESSO, such ghosts are weak and only observed when exposing with the ThAr hollow-cathode lamp, which exhibits extremely strong Argon emission lines. No ghosts have been seen on science exposures.

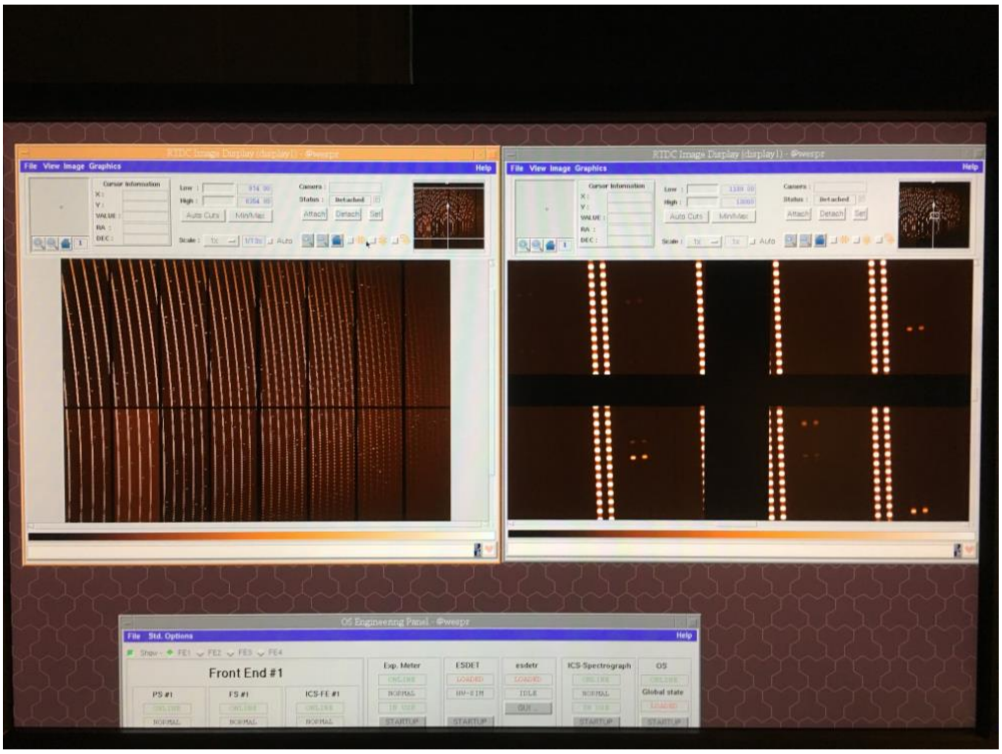


Fig. 17: Example of raw frame plus *zoom in*, on the right-hand side, from the red CCD of ESPRESSO illuminated with the ThAr lamp (in Fibre A – to the right) and the Fabry-Pérot simultaneous calibration light (Fibre B; continuous dots to the left)

When observing in simultaneous reference mode (see Fig. 17), direct contamination from the Fabry-Pérot light used in the reference fibre (Fibre B) can pollute the spectral orders of the object fibre (Fibre A). This contamination is smaller than 10^{-4} of the Fabry-Pérot light in Fibre B, but for faint targets may correspond to a large fraction of the total flux. As such, and since for faint targets sky subtraction is essential, it is recommended not to use the simultaneous reference technique for targets fainter than V~12, but rather record the sky spectrum in Fibre B (simultaneous-sky mode). The pipeline will automatically subtract the sky background from the object spectrum when observing in this mode.

5. Observing with ESPRESSO

From the operational point-of-view, ESPRESSO is a relatively simple instrument, with a fixed spectral format and five well-defined instrument configurations to select from; these correspond to the possible combinations between HR, UHR, MR and the different binning+readout schemes (see Table 5). Since Period 102, ESPRESSO has been offered for service and visitor mode operations in 1-UT mode. The 4-UT mode of ESPRESSO has been offered for operations in visitor mode since Period 103.

Once the instrument configuration is defined, the only remaining set-up choice is the light source illuminating Fibre B. The available options are FP or the SKY as reference sources. The FP source must be used if the highest RV precision is required (better than 5 m/s). For faint targets (V>12), the contamination of the science spectrum by the simultaneous reference source (at $<10^{-4}$) can be a limiting factor. In this case the RV precision will be dominated by photon noise on the target, and it is recommended not to use the simultaneous reference source, but rather to record the sky and background spectrum in Fibre B.

ThAr frames are taken during daytime to provide the absolute wavelength calibration. LFC frames are obtained on a best effort basis.

Just like for other ESO instruments, the preparation of ESPRESSO observations is done with a set of tools such as p2/vOT and the ETC.

5.1 Preparing the Observations

5.1.1 Exposure Time Calculator

The ESO Exposure Time Calculator (ETC) can be found at:

http://www.eso.org/observing/etc

that links to the ETCs of each of the La Silla/Paranal instruments. All ESO Echelle spectrographs are supported by the same model, described here:

http://www.eso.org/observing/etc/doc/helpuves.html

The ESPRESSO-specific ETC is available at:

http://www.eso.org/observing/etc/bin/gen/form?INS.NAME=ESPRESSO+INS.MODE=spectro.

The input form includes the following sections:

1 Target brightness, spectral and spatial distributions
  - The brightness can be given in the Vega system or as an AB magnitude,
  - The spectral-energy distribution can be given in the form of a stellar template, a black-body spectrum, a power-law, or a single emission line. The user can also upload a custom spectrum.

2 Sky background, including moon phase and airmass
  - The sky background is based on the Cerro Paranal advanced sky model described here:

    http://www.eso.org/observing/etc/doc/skycalc/The_Cerro_Paranal_Advanced_Sky_Model.pdf

- The user can input a turbulence category defining the seeing value observed at 550nm at zenith and the calculator will provide the corresponding Image Quality (or the other way around) using a PSF model of the atmosphere, telescope and instrument (see:

  http://www.eso.org/observing/etc/doc/helpuves.html#seeing

  for details). An estimate of the probability of realization of the requested seeing is also given dynamically.

3 Instrument configuration and number of UT telescopes feeding the instrument (either 1 or 4)
- The spectral resolution and detector mode (depend dynamically on the chosen number of UTs),
- The exposure time per detector integration.

4 Optional outputs
- Output from the ETC includes a summary of the input configuration and results are given in two tables, one for each detector.

Turbulence Categories and Constraints for P105

Since P105, observing conditions are specified in the form of Turbulence Categories. These are defined as the conditions that satisfy a given percentile of the available observing time in Paranal. For non-AO instruments like ESPRESSO, where the only relevant turbulence parameter is the seeing, these categories correspond to the following seeing thresholds.

T Category	**10%**	**20%**	**30%**	**50%**	**70%**	**85%**	**100%**
Seeing threshold	0.50”	0.60”	0.70”	0.80”	1.00”	1.30”	all

These thresholds have been computed using the cumulative distribution of the seeing, after applying a rolling 90th-percentile over 1h. For ESPRESSO OBs with a duration shorter than an hour, the probability to satisfy a given seeing constraint is Turbulence category above. For updated information on the topic please refer to

https://www.eso.org/sci/observing/phase2/ObsConditions.html

5.1.2 Phase 2

During Phase 2, the successful applicant prepares their instrument set-ups and observing strategy through the elaboration of so-called Observation Blocks and related material.

Observation Blocks

An Observation Block (OB) for a typical science observation with ESPRESSO consists of one acquisition template and one or several observation (integration) templates. The templates need to have the same instrument mode (e.g., singleHR or singleUHR).
The instrument-specific comment field of the OB should include the expected S/N at a wavelength of 550 nm, as reported by the ETC.

Main template parameters

The available templates, their parameters and options are described in detail in the ESPRESSO template manual:

http://www.eso.org/sci/facilities/paranal/instruments/espresso/doc.html

Below we describe the main choices to be made during Phase 2.

Instrument mode (singleHR vs. singleUHR)
This choice is made at the level of in the Phase 1 proposal. The median measured resolving power of the singleHR mode is 140’000 while the singleUHR mode yields *R* = 190’000. The singleUHR mode should be used if the highest spectral resolution is needed; however, the UHR mode leads to a lower S/N than the HR mode. An informed choice can be made using the ETC.

Binning modes for the singleHR mode (1x1_FAST vs. 2x1_SLOW)
Generally, the 1x1_FAST mode is used for relatively bright targets (V<10-12), while the 2x1_SLOW mode is used for fainter targets (V>10-12). For a given target, it is recommended to use always the same binning scheme.

Source on Fibre B
The available options are SKY and FPCS. The Fabry-Pérot calibration source (FPCS) is used for relatively bright targets and RV studies that require simultaneous drift measurement. The SKY option is used for faint targets for which a sky subtraction is required and/or for which a contamination from the FPCS light needs to be avoided.

Calibration associated to Fibre A
Currently, one can only choose ThAr frames to provide the absolute wavelength calibration for data reduction.

Operational airmass limit
When measuring precise RVs, the airmass limit for optimized ESPRESSO operations is imposed by the Atmosperic Dispersion Correctors (ADC’s). The ADC’s were designed for a maximum airmass of 2.2 (the value depends on the atmospheric conditions and therefore can vary slightly). If a user chooses to observe a star at a higher airmass, the ADC will fix the dispersion correction to the maximum and the remaining dispersion will be present in the observed spectrum. Since in this case the ADC’s correction is not complete, the measured RV may be affected.

As an example, at an airmass of 2.2 the amplitude of the dispersion correction residuals on the position of the star on the sky is of approximately of 0.030 arcsec. If the airmass is larger than 2.2, for every additional 0.1 in airmass the dispersion grows by approximately 0.150 arcsec.

Finding Charts

The unobstructed Field-of-View for the target acquisition has a radius of 17 arcsec. Finding charts should display a field of 30x30 arcsec in the V band.
The distance between Fibre A and Fibre B is 7.5 arcsec on sky. Due to the field rotation while observing, the Fibre B will rotate around the position of Fibre A. The finding chart generation in P2 shows an annulus for Fibre’s B possible positions on the field of view, which can be checked for potential contamination of a nearby source.

Limiting magnitude for acquisition and blind offset

Acquisition has succeeded with sources of V magnitudes as faint as 20 to 21 in dark sky. Fainter targets can be acquired using a blind offset. The convention is to provide the blind offsets in the acquisition template to move the telescope from the target to the acquisition star. The coordinates of the science target must be entered in the OB target description. In the acquisition template of the OB, the offsets of the acquisition star must be entered in arcseconds (target coordinates + offsets = acquisition star coordinates).

Defining Local Sidereal Time and Absolute time interval constraints

It is important to keep in mind that while the Local Sidereal Time (LST) constraints are defined for the entire OB, the absolute time intervals are defined for the start of the OB. This distinction is particularly important for observations aiming at covering transient events, like planetary transits.

We recommend users to request enough time to cover the target for their scientific purpose PLUS a reasonable interval in which the OB can be started (~30min). This extra time requested provides an additional baseline for observations and makes the execution of OBs easier.

5.1.3 The Effect of Precipitable Water Vapour

Precipitable Water Vapour (PWV) is the amount of water in gaseous form along a given column in the Earth atmosphere. Measured as a depth, it corresponds to the value one would measure if all the water in that column would be precipitated in rain. By knowing the PWV value during an observation as well as several other physical parameters, such as site altitude, temperature vertical profile, and humidity vertical profile, one can estimate the transmission spectra of water at any given wavelength. This predicting ability has been used extensively to measure and correct near-IR spectra, where water absorption band lines are deep and numerous.

In the ESPRESSO wavelength range, there are three main telluric absorption species: O_2, OH and H_2O. Of these, water vapour is the one that affects the widest wavelength range. Its effects are not as pronounced as in the near-IR, but may have an impact on specific science cases. For reference, the median Paranal PWV value is 2.5 mm, ranging between 0.5 mm and 20 mm in extremely favourable (dry) and unfavourable conditions (humid), respectively. For wavelengths shorter than 700 nm, water absorption amplitude is of the percent level if the PWV value is of 2.5 mm or lower, while for higher PWV values the depth of the water lines can reach up to 10%. On the other hand, the 700-800 nm wavelength range is strongly affected by water absorption, with numerous deep lines that can have an impact on the observations even in low PWV conditions. The user is referred to Querel, Naylor & Kerber (2011, PASP, 123, 222) and Kerber et al. (2014, MNRAS, 439, 247) for more information.

If aiming at a high-spectral fidelity, the user should estimate the impact of the water vapour on the lines or wavelength ranges of interest. To this end, ESO provides two public tools; the SkyCalc Sky Model Calculator:

https://www.eso.org/observing/etc/bin/gen/form?INS.MODE=swspectr+INS.NAME=SKYCALC

which allows to measure the impact of the PWV and other observing conditions based on the Cerro Paranal Sky Model (Noll et al., 2012, A&A, 543, A92; Jones et al., 2013, A&A, 560, A91),

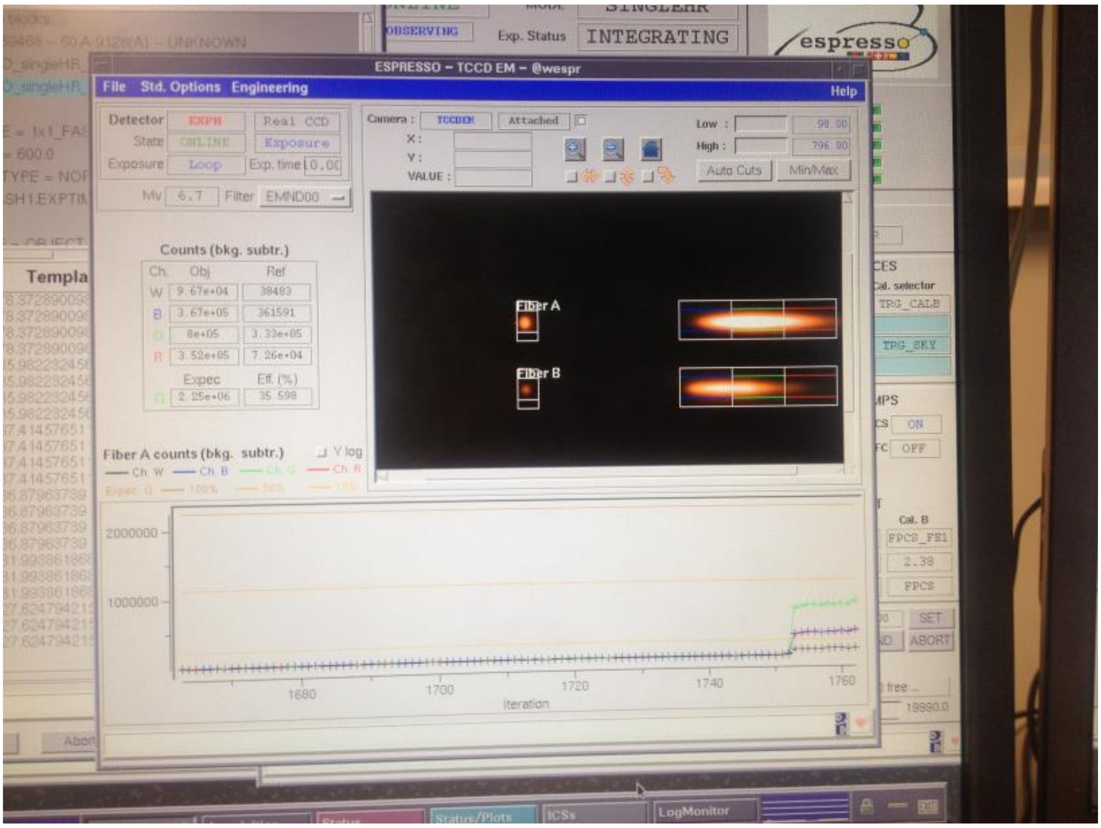
and Molecfit (Smette et al., 2015, A&A, 576, A77):

https://www.eso.org/sci/software/pipelines/skytools/molecfit which corrects astronomical observations for telluric absorption features, based on fitting synthetic transmission spectra calculated through a radiative transfer code.

Users interested in spectral regions affected by deep telluric lines in the 700-800 nm domain may request a specific constraint on the PWV when preparing their OBs at Phase 2. The ESPRESSO ETC includes the PWV as an input.

5.2 Observing: the Exposure Meter

ESPRESSO spectrograph is equipped with an advanced Exposure Meter (EM) that, during integrations, measures the flux entering the spectrograph as a function of time. This function is necessary to calculate the flux-weighted mean exposure time at which the precise relative Earth motion must be subtracted from the RV measurement. The EM operates by focusing the light that is not injected into the spectrograph's fiber on a simple diffraction grating that allows for a rough flux measurement in different spectral channels to identify possible chromatic effects. The use of several channels also provides a redundant, and thus more reliable, evaluation of the mean exposure time. In Fig. 18, we show the EM graphical user interface (GUI). The efficiency and flux-weighted mean exposure time are stored in the FITS header of the scientific images.



OBSERVING
Exp. Status INTEGRATING

Detector EXPH Real CCD
State ONLINE Exposure
Exposure Loop Exp. time 0.00
Mv 6.7 Filter EMND00

Camera : TCCDEM Attached
Low : 98.00
High : 796.00

Counts (bkg. subtr.)

Ch.	Obj	Ref
W	9.67e+04	38483
B	3.67e+05	361591
G	8e+05	3.33e+05
R	3.52e+05	7.26e+04
	Expec	Eff. (%)
G	2.25e+06	35.598

Fig. 18: GUI of the exposure meter during observations.

6. Calibration Plan

Each of the instrument configurations comes with its own complete set of calibrations. Science data in any configuration can be fully calibrated with a set of 11 different exposure types (see below). When processed by the ESPRESSO pipeline, each type of calibration frames generates several high-level Quality Control (QC1) parameters for instrument monitoring purposes.

The extreme precision and accuracy aimed for ESPRESSO can only be guaranteed if a full set of standard calibrations is obtained and passes quality control within 24 hours of any science observation. This 24-hour requirement is set by considering the timescales of instrument instabilities, partly based on the HARPS experience. An example is the RV drift of the spectrograph, which is kept below ~30 cm $s^{-1}h^{-1}$.

Standard calibrations in both singleHR modes are executed every day. Besides providing a full set of calibrations in these modes, these daily exposures are used for instrument health check. Standard calibrations for singleUHR and multiMR configurations will be executed within 24 hours of any science observations performed in these modes. Long-term calibrations are executed less frequently, typically once per month or less. In principle, these must be executed for all supported instrument configurations. Table 8 describes the ESPRESSO standard calibration plan.

Calibration type	Frequency	# of frames	Comments
Detector bias	Daily for singleHR modes; within 24 hours of science for singleUHR and multiMR.	10	Bias frames to measure over-scan, bias level and read-out noise.
Order definition	Daily for singleHR modes; within 24 hours of science for singleUHR and multiMR.	2 (1 per fibre)	Continuum-source spectra on both science and reference fibres to trace order/slice positions.
Flat-field, blaze and order profile	Daily for singleHR modes; within 24 hours of science for singleUHR and multiMR.	20 (10 per fibre)	Continuum-source spectra on both science and reference fibres to measure spectral flat-field, blaze function and order profile in cross-dispersion direction.
Wavelength calibration	Daily for singleHR modes; within 24 hours of science for singleUHR and multiMR.	1 per setup	Lamp setups for the two fibres: FP_FP, THAR_FP, FP_THAR, LFC_FP, FP_LFC, THAR_THAR.
Contamination by simultaneous reference	Daily for singleHR modes; within 24 hours of science for singleUHR and multiMR.	1	Depends on which source is used for the drift measurement. FP is used as baseline since P102: Fibre A: CONTAM (no light) Fibre B: FP
Detector dark current	Monthly for all modes	5 (x 3600s)	Dark frames to measure the average dark current and create a hot-pixel mask.

Detector flat-field and gain	Bi-monthly for all modes	15 (3 x 5 different exposure times)	Detector LED flat-field frames to measure the gain and create a bad-pixel map.
Fibre-to-fibre relative efficiency	Quarterly for singleHR modes and singleUHR; multiMR only when in 4-UT mode (VM).	1	Blue-sky observations with both fibres to measure the relative fibre efficiency: Fibre A: SKY Fibre B: SKY
Spectro-photometric calibration	Every 120 days for both singleHR modes and singleUHR; multiMR only when in 4-UT mode (VM).	1	Observation of a spectro-photometric standard star to measure the absolute efficiency on any UT: Fibre A: spectro-photometric standard star Fibre B: SKY

Table 8: ESPRESSO standard calibration plan

The execution of standard calibration sequences and long-term calibrations from the ESPRESSO calibration plan is under the responsibility of Paranal Science Operations. OBs for any additional day or night-time calibrations beyond the ESPRESSO calibration plan should be prepared by the user. Telescope time for any additional on-sky calibrations should be included in the total time allocation of the programme.

7. End-to-End Operations

7.1 Data Flow

ESPRESSO was designed to provide the observer with a complete science-grade dataset in order to increase the efficiency and scientific output of the instrument. For this purpose, a software-cycle integrated view, from the preparation of the observations to the data reduction and analysis has been adopted. Coupled with a careful design, it also ensures optimal compatibility and easiness of operations within the existing ESO Paranal Data Flow infrastructure. The ESPRESSO Data Flow System (DFS) includes the following main components:

- ESO's p2 tool for Phase-2 preparation,
- Specific instrument control and observation templates: ESPRESSO is compliant with the usual VLT control software environment and concepts. Compared to other VLT instruments, ESPRESSO's operational complexity arises from the requirement to be able to use any combination of UTs. At the instrument control level, PLCs (Programmable Logical Controllers), as well as off-the-shelf TCCDs, place ESPRESSO at the forefront of current instrument control systems. An overview of the ESPRESSO control environment is given in Fig. 19;
- The DRS (Data Reduction Software) and DAS (Data Analysis Software): a brief description of these is given below. The interested reader is referred to the corresponding reference documents for more detailed information.

  The ESPRESSO pipeline installed at Paranal is meant for a quick assessment of data quality. It does not make use of the latest calibration projects or is optimized in any way to provide science-graded data. In order to obtain high-quality reduced data, the user should install the pipeline, and make use of the properly associated calibrations.

7.2 Data Reduction Software (DRS)

ESPRESSO has a data-reduction software (DRS) to deliver high-quality science-grade reduced spectra. The final products of the DRS are extracted wavelength-calibrated spectra, along with RV. If the fiber B is pointed to the sky, a data product will provide the sky subtracted data; if fiber B is used for simultaneous RV monitoring, the drift is calculated and applied to the calculated RV. The extracted spectra can also be flux calibrated.

7.3 Data Analysis Software (DAS)

The ESPRESSO DAS is the first dedicated data analysis system for an ESO instrument and is meant to work in close interaction with the ESPRESSO DRS. While the DRS is automatically triggered by the generation of new observational raw data files, the DAS allows users to manipulate the reduced data in an interactive way.

The DAS comprises a total of 13 recipes that are tailored to the ESPRESSO main science cases. It is split into four branches: one for the analysis of quasar spectra, and three for the analysis of stellar spectra. Each branch of the DAS is managed by a Reflex workflow. The recipes take care of complex analysis operations, e.g., for stellar spectra: the estimation of stellar activity indices and stellar parameters (effective temperature, [Fe/H] ratio), the measurement of the equivalent widths of absorption lines, the fitting of the stellar continuum, and the re-calculation of radial velocities based on user needs; for quasar spectra: the optimal co-addition of multiple exposures, the detection of absorption lines, the determination of the QSO continuum level, and the identification and fitting of absorption-line systems.

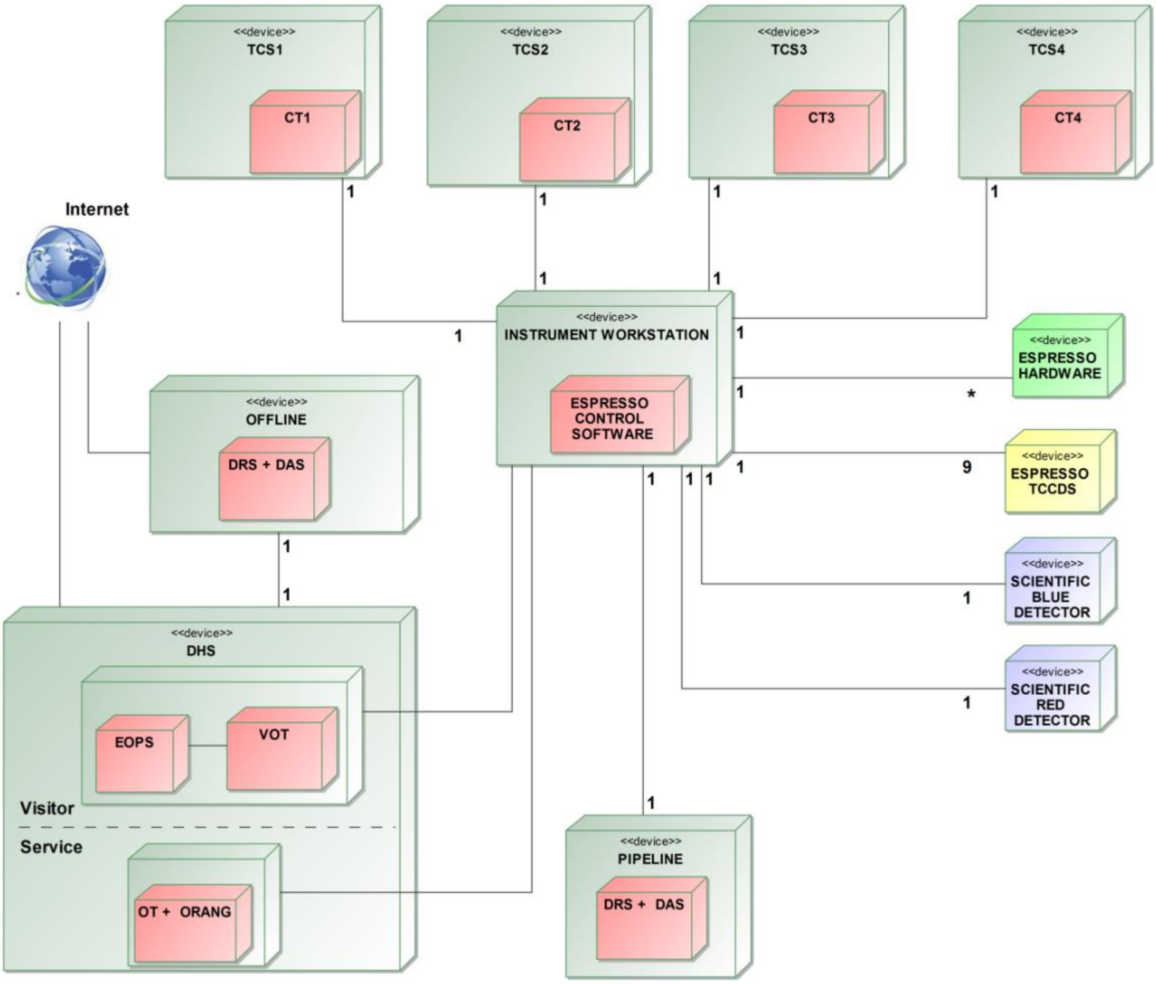


Fig. 19: Overview of ESPRESSO's control environment.

--- End of document ---