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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 therefore be used as a reference when preparing observing time proposals and the 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 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 heavily based on material provided by the ESPRESSO Consortium. It is intended for ESPRESSO users and as such is written from an astronomer's perspective. Comments and suggestions on the content of this manual 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 after it is introduced. The aim of Table 1 is to help the reader in explaining the meaning of each short expression.

1T	First temperature enclosure (convergence-point room)
3T	Third temperature enclosure (surrounding the vacuum vessel)
AD	Applicable Document
ADC	Atmospheric Dispersion Corrector
APSU	Anamorphic Pupil Slicer Unit
BCA	Blue Camera
BTM	Blue Transfer Mirror
BXD	Blue Cross-Disperser
BOB	Broker of Observation Blocks
CCD	Charge-Coupled Device
CCL	Combined Coudé Laboratory
CPL	Common Pipeline Library
CR	Coudé Room
CS	Control Software
CTE	Charge Transfer Efficiency

DAS	Data Analysis Software
DC	Dichroic
DFS	Data Flow System
DRS	Data Reduction Software
EG	Echelle Grating
ESO	European Southern Observatory
ESPRESSO	Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations
ETC	Exposure Time Calculator
FE(U)	Front-End (Unit)
FITS	Flexible Image Transport System
FL	Field Lens
FM	Field Mirror (also called RFM)
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
MC	Main Collimator
OB	Observation Block
PAE	Provisional Acceptance Europe
PLC	Programmable Logic Controller
RCA	Red Camera
RD	Reference Document
RFM	Red Field Mirror (see FM)
RTM	Red Transfer Mirror
RXD	Red Cross-Disperser
RV	Radial Velocity
S/N	Signal-to-Noise Ratio
TCCD	Technical CCD
ThAr	Thorium-Argon hollow cathode lamp
UHR	Ultra-High Resolution
UT	Unit Telescope (8.2-metre telescope at Paranal)
VLT	Very Large Telescope
VME	VersaModule Eurocard

VPHG	Volume Phase Holographic Grating
VV	Vacuum Vessel

Table 1: Abbreviations and acronyms used in this document

1.3 More Information on ESPRESSO

The complete ESPRESSO documentation is available from the ESPRESSO public web pages together 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 following public 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 installed at ESO's VLT. The instrument is in the Combined-Coudé Laboratory (CCL), and can collect light from the incoherent focus front-end units of the 4 Unit Telescopes (UTs). The telescope light is fed from each of the UTs into the instrument via a `Coudé-Train' optical system and through optical fibres. Target and reference light enter the instrument simultaneously through two separate fibres.

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. In 1-UT mode the light of the UT in operation is fed into the spectrograph; alternatively, the light from up to *all* four UTs can be fed into ESPRESSO simultaneously (4-UT mode).

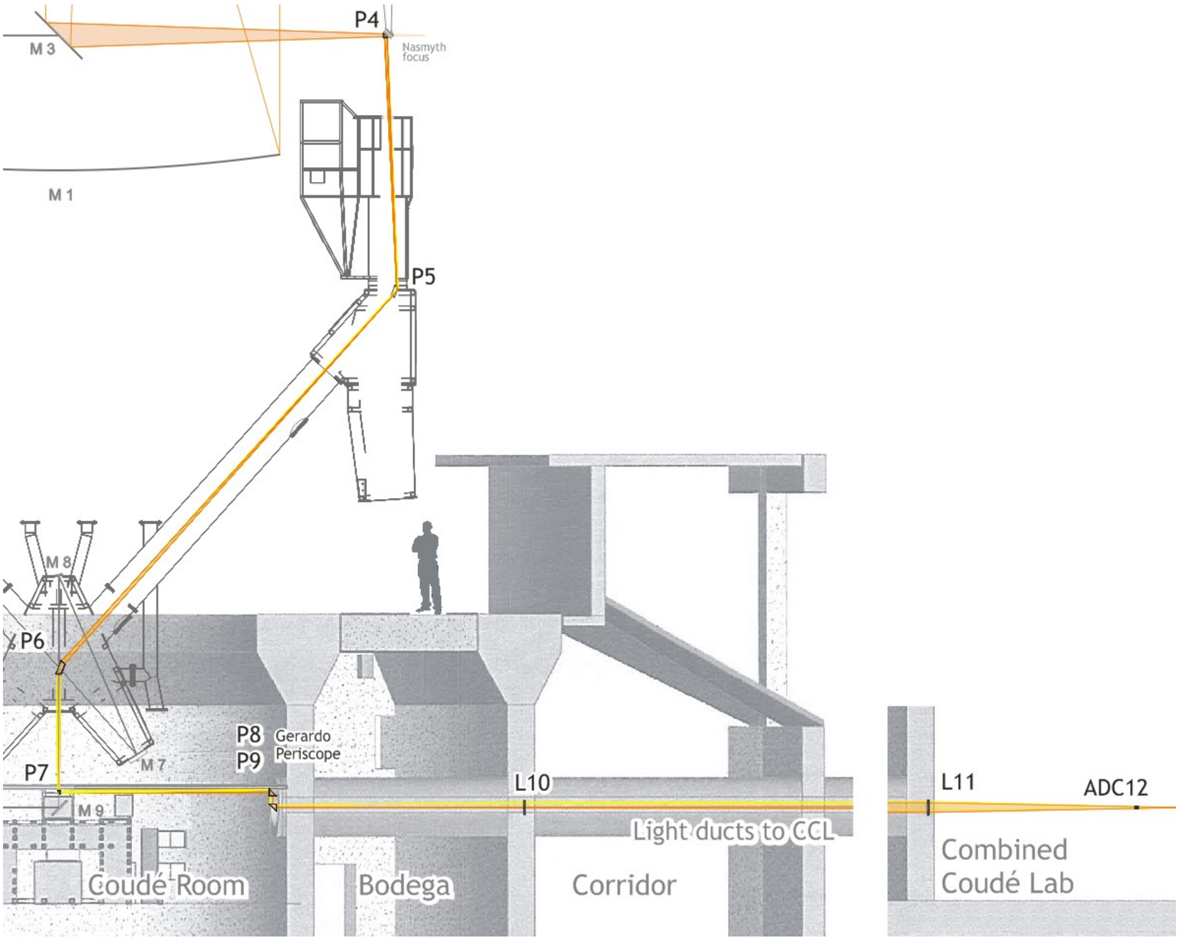


Fig. 1: UT Coudé Train and optical path to the CCL through the telescope and tunnels.

Channelling of light from the telescopes to the CCL is obtained through a full optics solution, with no use of fibre. The Coudé Trains pick up the light at the level of the Nasmyth-B platforms and redirect it with a prism through the UT mechanical structure down to the UT Coudé Rooms (CR), and then farther to the CCL along the incoherent light ducts shown in Fig. 1. The light coming from the telescopes is conveyed from the Nasmyth-B foci to the entrance of the tunnels in the CR below each UT using a set of 4 prisms. Then, the light is directed from the UT's Coudé Room towards the CCL using a 2-mirrors periscope and 2 lenses. In this way, the beams from the four UTs converge into the CCL, where mode selection and beam conditioning are obtained by a dedicated Front-End (FE) sub-system, on per UT. 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, 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 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 such beam conditioning, the FE can apply pupil and field stabilizations. These are achieved 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 used.

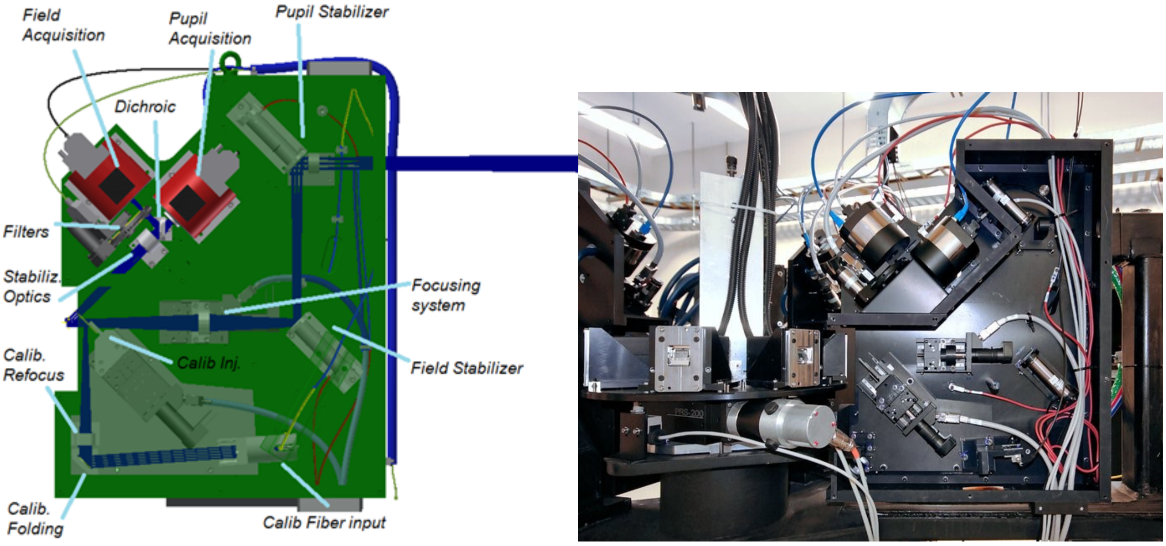


Fig. 2: Side view of an individual Front-End Unit.

In addition to these functions, the Front-End allows the injection of calibration light into the spectrograph. An inside view of a single Front-End Unit and its main components is provided in Fig. 2. 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 and a pupil camera 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. 3, together with on the right side a picture of the interior of the CCL.

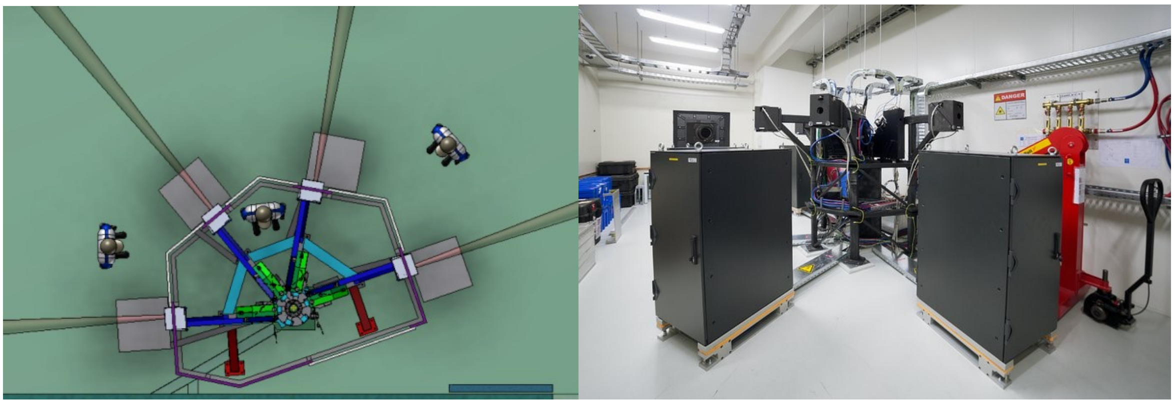


Fig. 3: Left: Top view of the Front-End Sub-System. Right: FE and the four UT beams in the CCL.

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 simultaneous wavelength 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 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 both scrambling of the near field and far field of the light beam. Modern fibers can have 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. 4. 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) shapes the beam in order to compress it in cross-dispersion direction and with a *pupil slicer* splits it up into two beams, superimposing them on the Echelle grating to minimize its size. The rectangular white pupil is then re-imaged and compressed. After the main dispersion, the dichroic beam splitter separates the beam into the blue and red spectroscopic arms, which in turn allows to optimize each arm in terms of image quality and optical efficiency. The cross-disperser has 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 space and the signal-to-noise ratio (S/N) per pixel are both 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. 5 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.

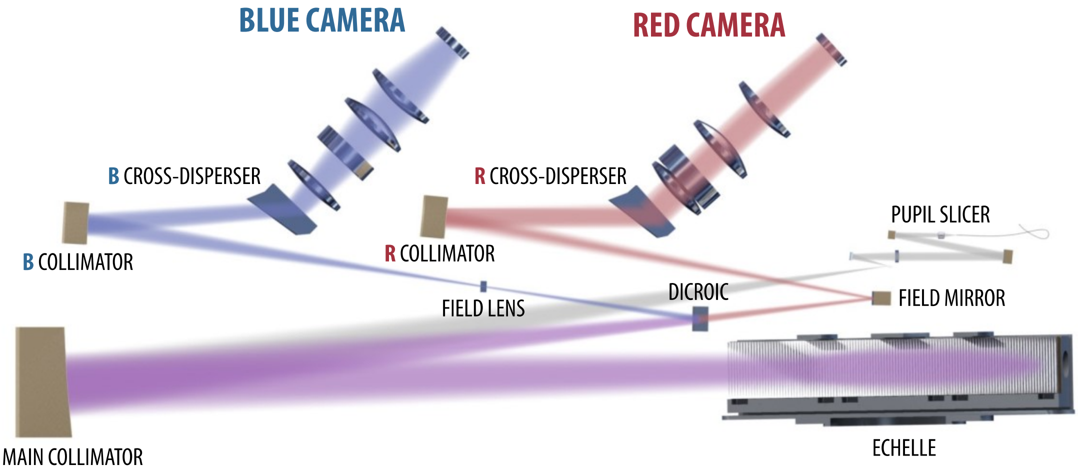


Fig. 4: Schematical layout of the ESPRESSO spectrograph and its optical elements.

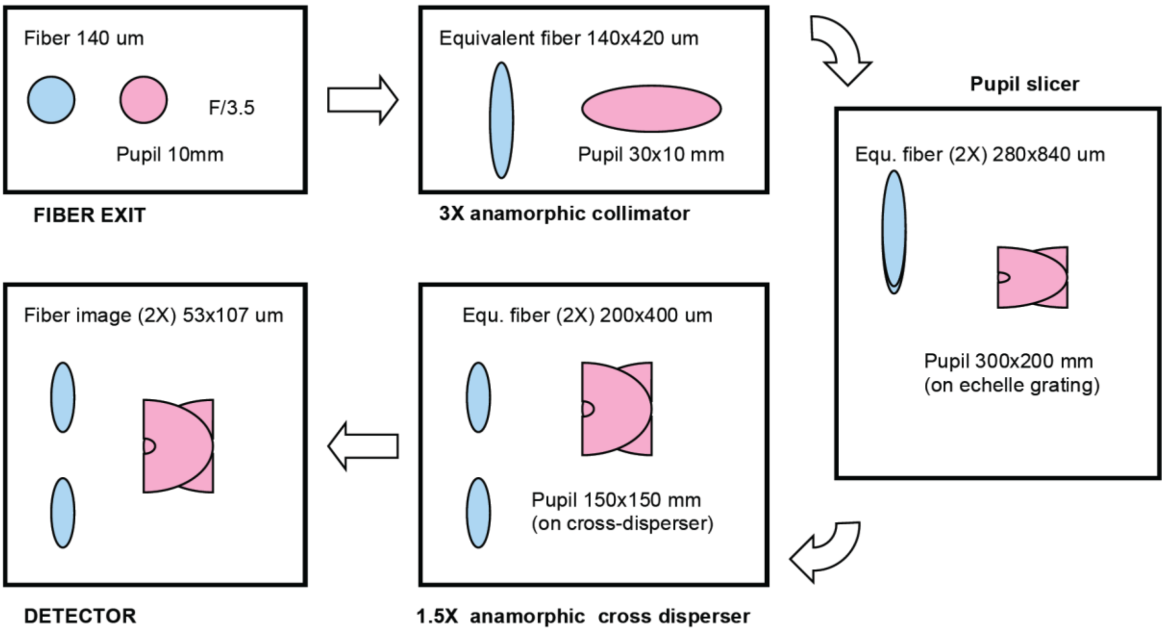


Fig. 5: Conceptual description of pupil and fibre images at key locations inside the spectrograph.

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 ‘only’ 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. 6.

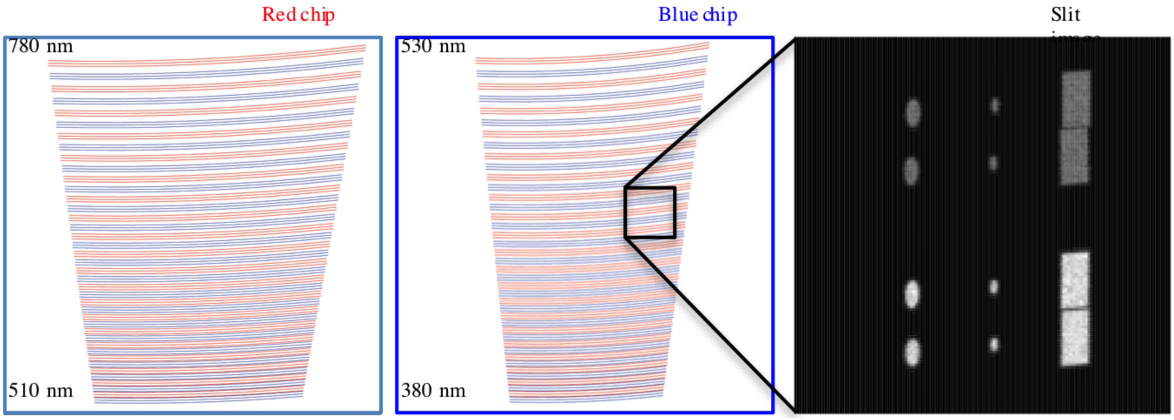


Fig. 6: Format of the red spectrum. Left and centre: format of the blue spectrum. Right: Zoom in on the pseudo-slit image. The latter shows the image of the target (bottom) and sky fibre (top). Each fibre is re-imaged into two slices. The image of the pseudo-slit on the science detectors, from left to 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 conceived to be an ultra-stable spectrograph capable of reaching RV precisions of the order of 10 cm s^{-1}, i.e., one order of magnitude better than the goal RV stability of its predecessor, HARPS. The spectrograph is therefore built in a totally fixed configuration for the highest thermo-mechanical stability. The spectrograph 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 in which a 10^{-5}-mbar class vacuum is permanently maintained. An overview of the opto-mechanics of the spectrograph is shown in Fig. 7.

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. Such an ambitious requirement is fulfilled by locating the spectrograph in a multi-shell active thermal enclosure system as depicted in Fig. 8 and Fig. 9. 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.

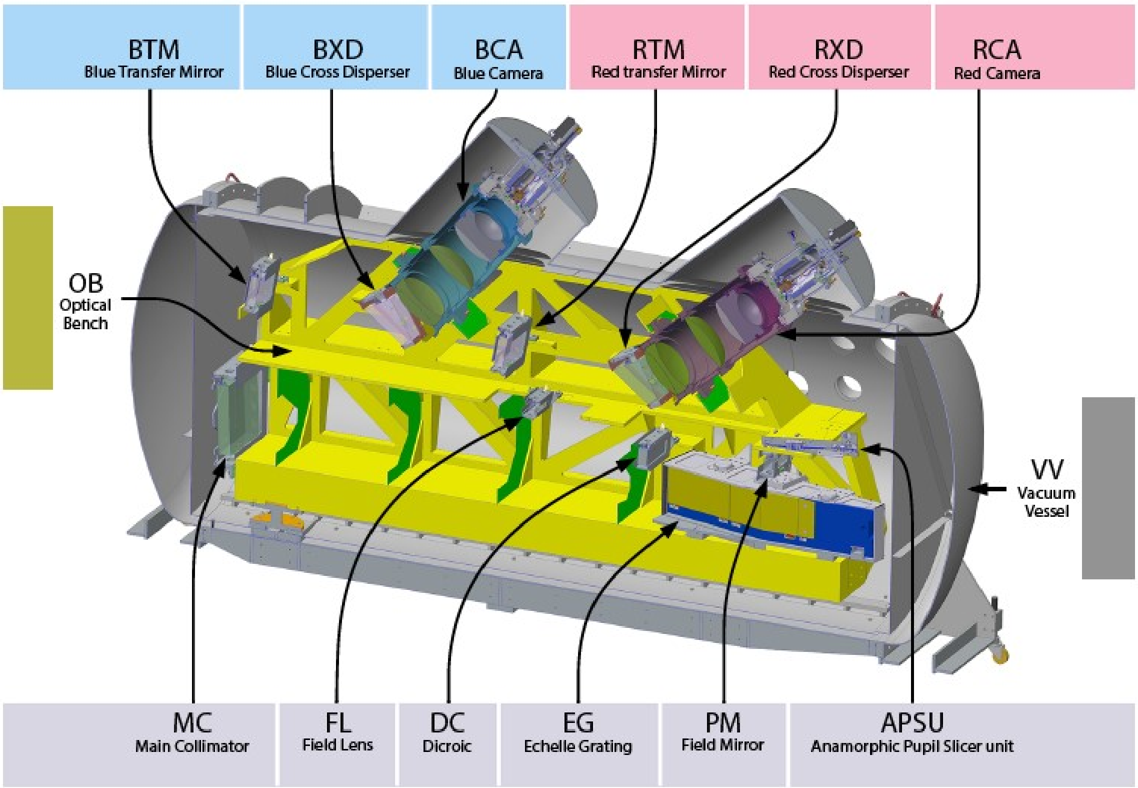


Fig. 7: Opto-mechanics of the ESPRESSO spectrograph.

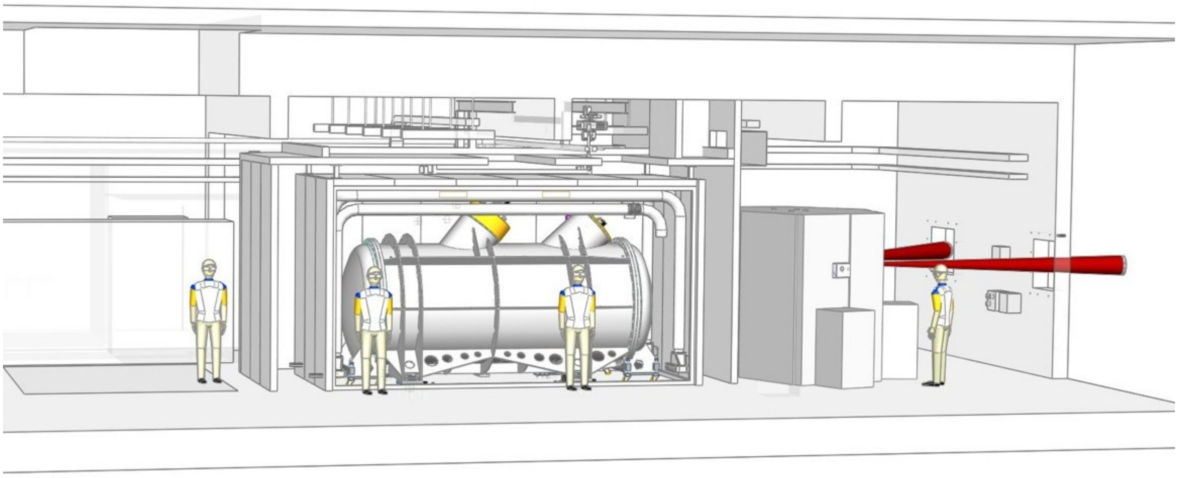


Fig. 8: Representation of ESPRESSO inside the CCL, vacuum vessel and multi-shell thermal control system, with converging light beams represented in red.

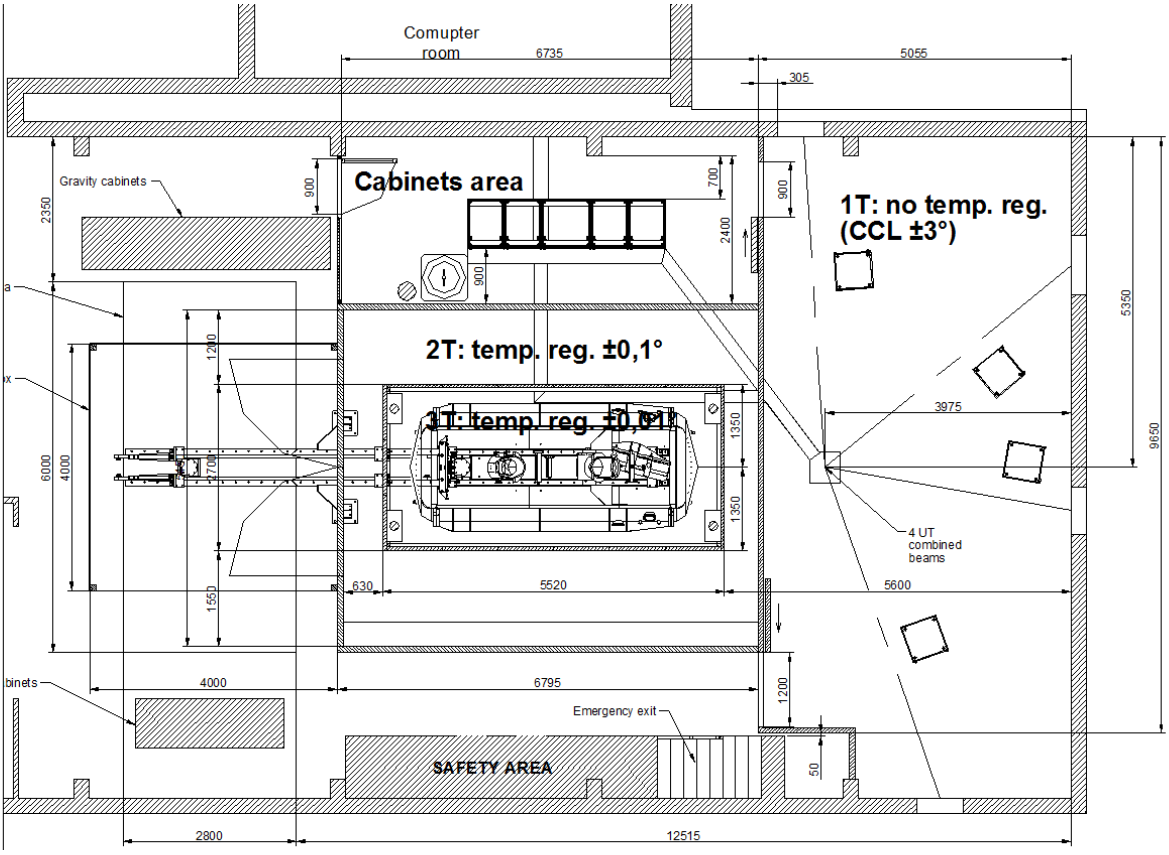


Fig. 9: Schematic diagram of ESPRESSO inside the CCL, top view.

2.2.3 Scientific Detectors

ESPRESSO also 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 further improve the stability compared to a mosaic solution like, e.g., that employed in HARPS. The CCDs have been procured from the e2v supplier. The sensitive area of the e2v chip is 92 mm x 92 mm, covering about 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, which for which an error translates directly into the RV precision and accuracy. An engineering sample is shown in Fig. 10.

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 special read-out to produce constant heat dissipation in the chips.

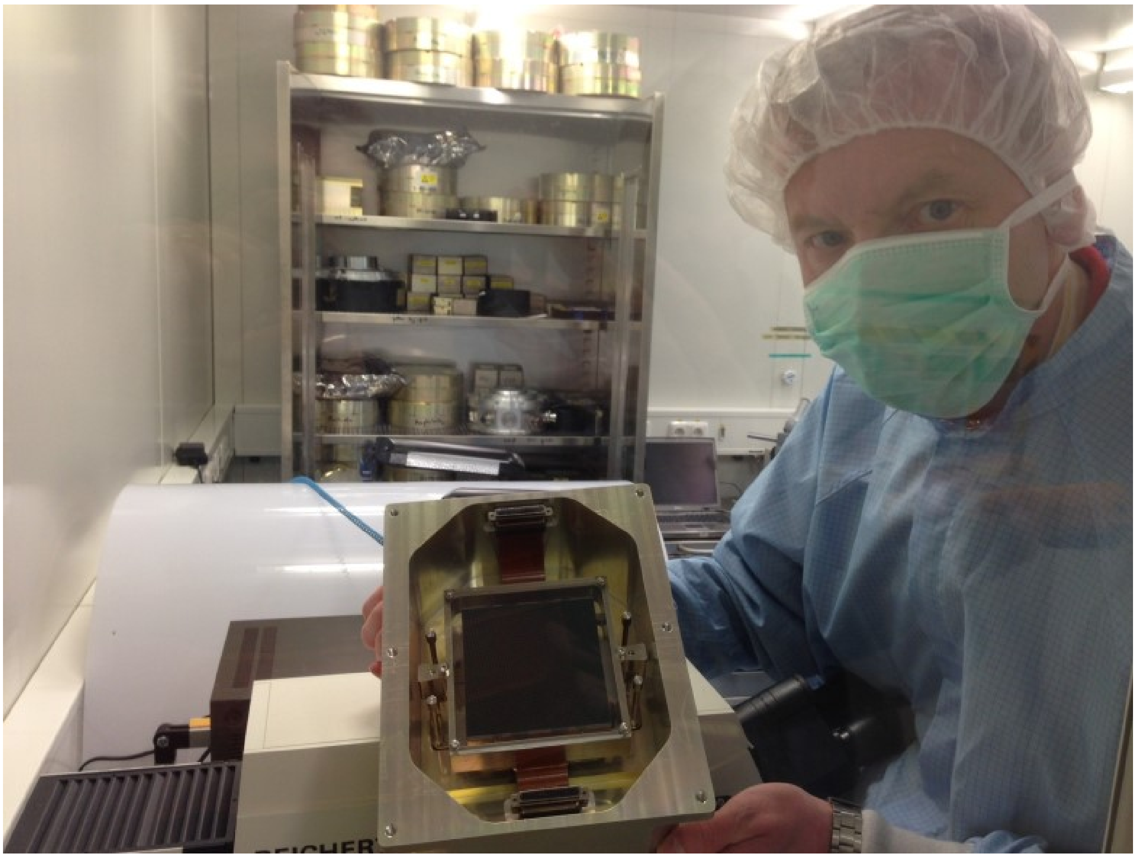


Fig. 10: The first ESPRESSO e2v CCD in its shipping container, inside the ESO cleanroom.

2.2.4 The Calibration Unit

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

- A Laser-Driven-Light Source (LDLS) for order localization (plus 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 500-720 nm. The extension of the wavelength calibration over the full spectral range is performed using the FP source.

  The LFC is currently not operational. 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, i.e., 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 extreme RV precision and very high RV accuracy required by ESPRESSO's science goals is obtained 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 improve light scrambling, radial symmetry of the fiber is broken by using non-circular fibre shapes. 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 and correction. 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. It is assumed that in this mode the measurement is photon-noise limited and 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 record the sky spectra. By doing so one can measure accurately sky background and detector noise contributions, which provides a significant contribution for the error budget for 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	~9%	~4%	~9%
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, 1x1 pixel binning is offered to provide fast read-out and maximize the duty cycle (open-shutter time) when the read-out noise does not contribute significantly to the error budget. On the other hand, for low S/N measurements, in order to reduce the readout noise, a 2x binning factor in the spatial direction and a slow read-out are used. Given the usually long exposure times used on faint targets, the longer readout time of this configuration is not expected to 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 Observing Software assembles the spectrum 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.

Detector mode	Binning (spaxel x spectral)	Read-out speed	RON (Blue)	RON (Red)	Conversion factor	Read-out ports	Read-out time
FAST	1x1	500 kpx s^{-1}	8 [e^-/pixel]	5 [e^-/pixel]	1.1 [e^-/ADU]	2x8	22s
SLOW	2x1, 4x2, 8x4	100 kpx s^{-1}	3 [e^-/pixel]	2 [e^-/pixel]	1.1 [e^-/ADU]	2x8	40s, 16s, 9s

Table 3: ESPRESSO detector modes.

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 all the available setups.

Observing mode	Purpose	Templates	Detector	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

3.4 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.

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

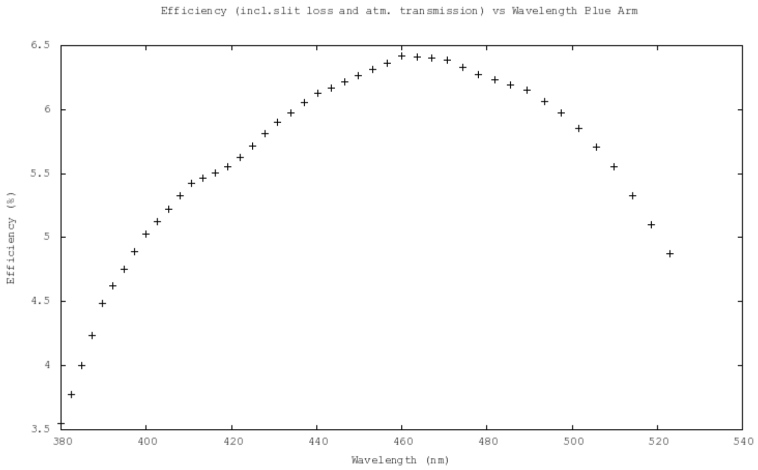
127	481.79	3.79	479.90	483.69	478.19	485.57	7.38
128	478.02	3.73	476.16	479.90	474.45	481.78	7.33
129	474.32	3.68	472.49	476.16	470.77	478.05	7.28
130	470.67	3.62	468.87	472.49	467.15	474.38	7.23
131	467.08	3.57	465.30	468.87	463.57	470.76	7.18
132	463.54	3.51	461.79	465.30	460.06	467.19	7.13
133	460.05	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's slit or fiber simply because a fraction of the stellar point spread function will fall outside the slit or loss. We refer the interested reader to ESPRESSO's ETC for a detailed explanation on the calculation of slit losses. From the definition of slit losses, it follows that these depend on the fiber diameter as seen on the sky Similar efficiencies are expected for the HR and MR modes as they both use 1-arcsec fibres, while the UHR mode is expected to lead to a lower total transmission due to its 0.5-arcsec fibre, especially under poor seeing conditions. In Fig. 11 and Fig. 12, 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.



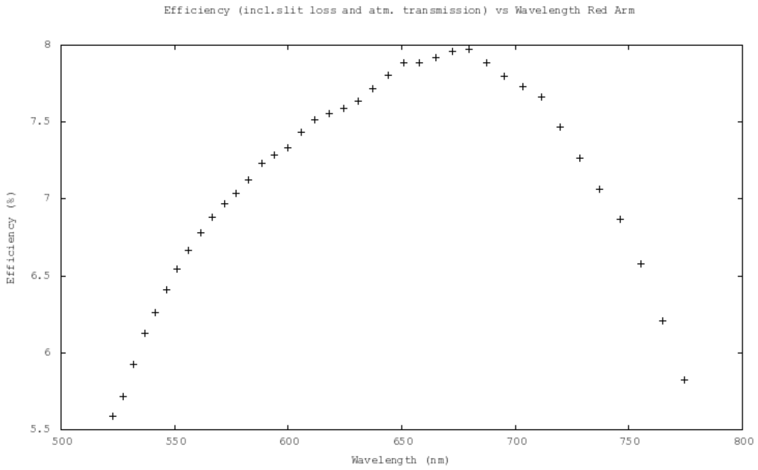


Fig. 11: Total transmission of ESPRESSO incl. slit losses and atmospheric transmission in HR (and MR) mode for the blue (top) and red arm (bottom). A seeing of 0.8 arcsec and an airmass of 1 are assumed.

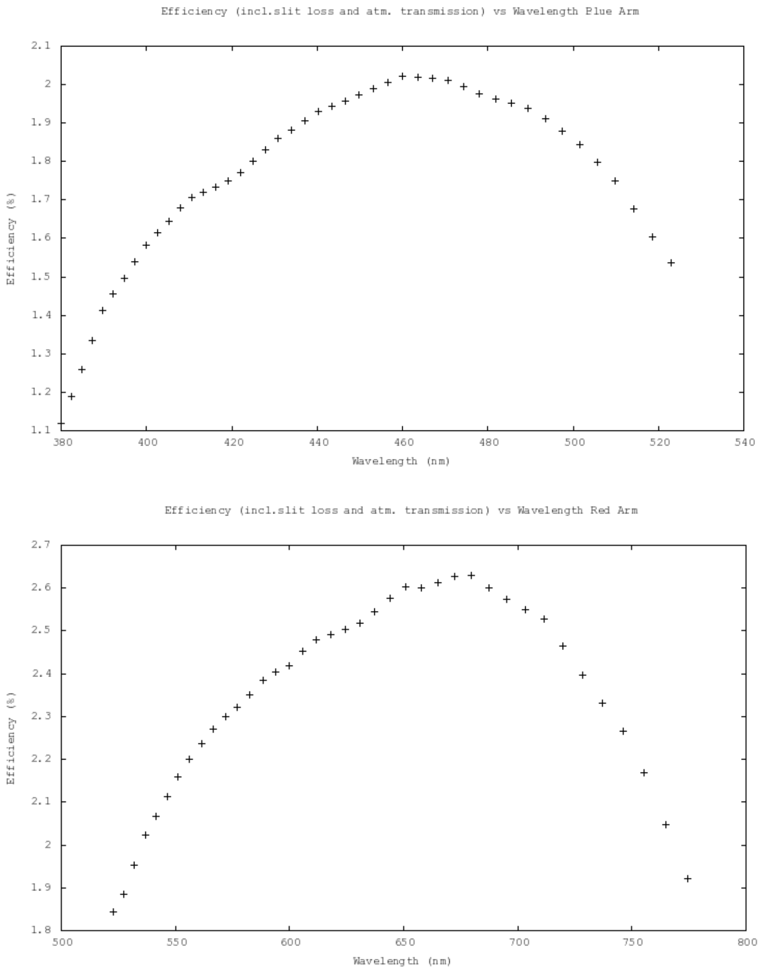


Fig. 12: Total transmission of ESPRESSO incl. slit losses and atmospheric transmission in UHR mode for the blue (top) and red arm (bottom). A seeing of 0.8 arcsec and an airmass of 1 are assumed.

The different fiber diameter, readout noise and pixel binning lead to a different S/N ratio per extracted pixel for the different modes. The attainable SNR for the five offered setups is shown in Fig. 13 to Fig. 15. 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 lower line density and/or 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. Fig. 15 shows similar plots for the multiMR mode. In this mode, a gain in SNR is apparent. The factor of 2 in SNR arises from the 4-times 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 of 2 or

4 in the spectral direction in the multiMR42 and multiMR84 configurations, respectively. The gain in choosing a large binning factor 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. As an example, we can indicate the following benchmark: a S/N per extracted pixel of about 15 at 550 nm is obtained on a V = 19 star within a single 1-hour exposure in the 8x4 binning mode.

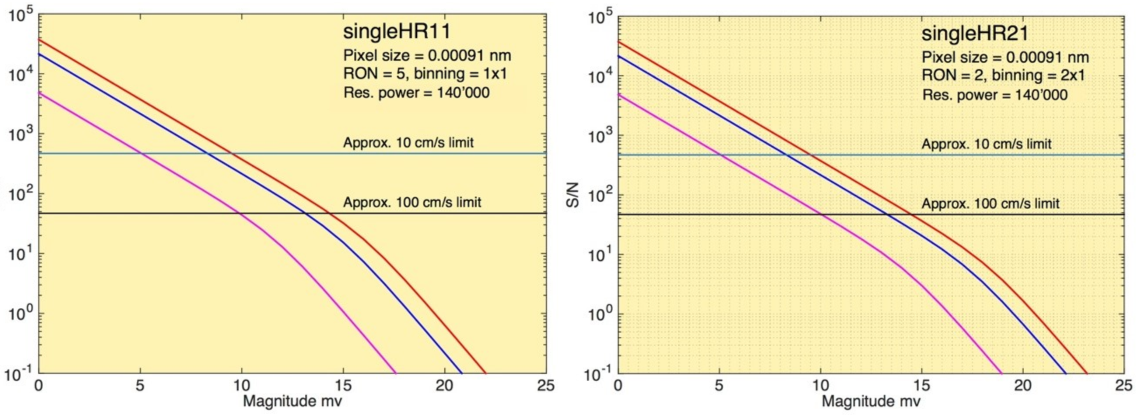


Fig. 13: Left: S/N vs. stellar magnitude obtained in the singleHR11 mode for exposure times of 60s (pink), 1200s (blue) and 3600s (red). The slope change defines the magnitude at which the measurement becomes detector read-out noise limited. S/N for 10 cm s^{-1} and 100 cm s^{-1} are shown. The values are rough estimates for slowly-rotating, inactive late-G or K dwarf stars, calculated for a seeing of 0.8 arcsec and an airmass of 1. Right: same but for the singleHR21 mode.

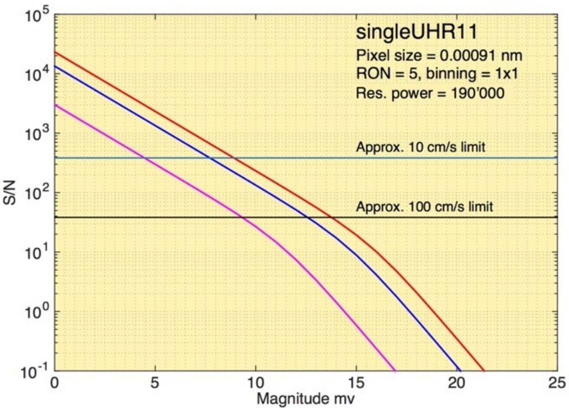


Fig. 14: Same as Fig. 13 but for the singleUHR mode.

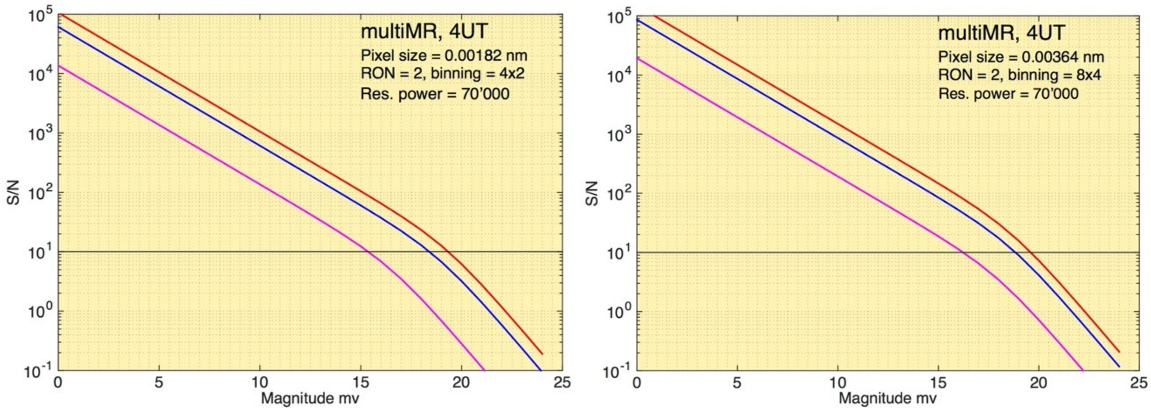


Fig. 15: Left: S/N vs. stellar magnitude obtained in the multiMR42 mode for exposure times of 60s (pink), 1200s (blue) and 3600s (red). The slope change defines the magnitude at which the measurement becomes detector read-out noise limited. Right: same but for the multiMR84 mode.

Commissioning tests have demonstrated the extreme RV precision of ESPRESSO. 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. A more detailed study will be made available in the future, after the first months of observations.

Different instrument configurations (see Sect. 0) 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 these will depend on the characteristics of the target and of the RV calculation. The take-away lesson is that the user is 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). 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 to each detector pixel a wavelength. 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.

In order to track residual instrumental drifts, ESPRESSO can use the simultaneous reference technique similarly to its predecessor HARPS (e.g., Baranne et al. 1996). This means that the spectrum of a wavelength-calibration source is recorded on the science detectors simultaneously to 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 both 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 wavelength reference. Note, however, that this reference source was designed for precision and not accuracy; programs requiring high accuracy therefore need to be calibrated against another light source.

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 is not used at night for drift measurement due to its limited wavelength range and lifetime. The LFC presents all the characteristics indispensable for an accurate wavelength calibration and provides a link to the frequency standard. However, at the time of writing of this manual the LFC is not operational. From the start of operations, a combination of ThAr frames (taken in daytime) and Fabry-Pérot exposures (taken both in daytime and simultaneous reference) provides the wavelength-calibration solution. Nevertheless, the daytime calibration plan will also include taking LFC frames systematically, as soon as is available.

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 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 detector. 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 compared to the local spectral orders can be slightly higher than that and 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. These are more easilly detected in high S/N exposures, when images of a bright spectral region are projected elsewhere on the CCD. In ESPRESSO, such ghosts are weak and only observed when exposing with the ThAr hollow-cathode lamp, which exhibits extremely strong Argon emission lines. On science exposures, ghosts have not been reported.

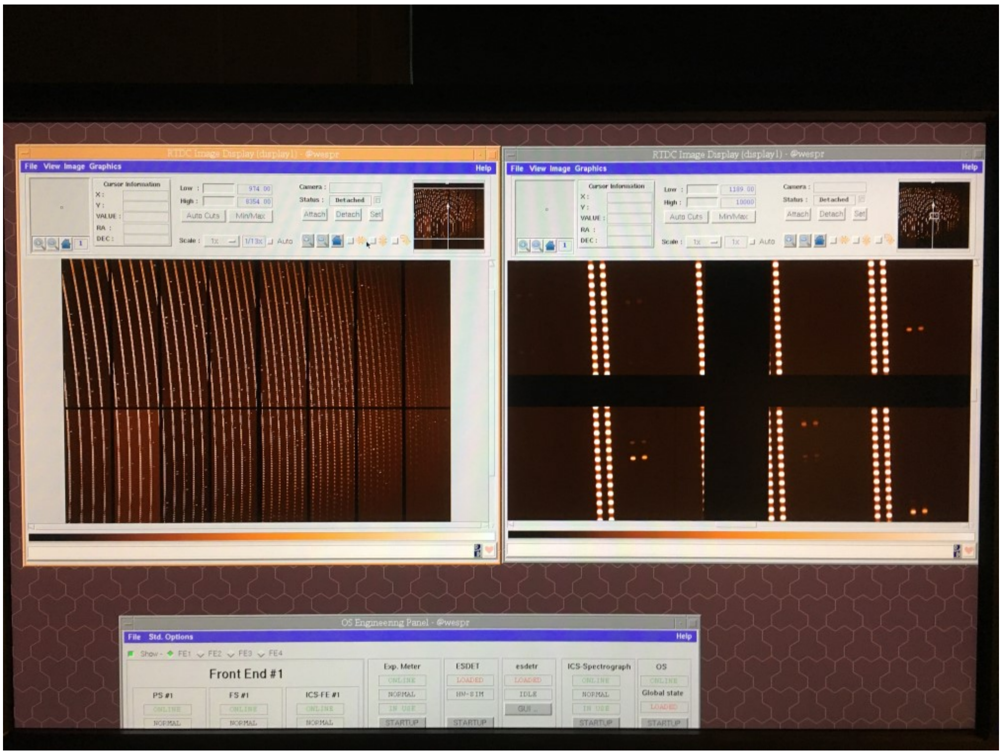


Fig. 16: Example of raw frame plus *zoom in*, on the right-hand side, from the red CCD of ESPRESSO illuminated with the ThAr lamp (in Fibre A – to the right) and the Fabry-Pérot simultaneous calibration light (Fibre B; continuous dots to the left)

When observing in simultaneous reference mode (see Fig. 16), direct contamination from the Fabry-Pérot light in the reference fibre (Fibre B) onto the spectral orders of the object fibre (Fibre A) can be observed. This contamination is smaller than 10^{-4} of the Fabry-Pérot light in Fibre B, but may correspond to a large fraction of the total flux for faint targets. Due to this, and to the fact that 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, which 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 regular operations in 1-UT mode in both of its HR configurations (1x1 and 2x1 binning) as well as in UHR mode (1x1 binning). The 4-UT mode of ESPRESSO and its Medium Resolution (MR) configurations (4x2 and 8x4 binning) have been offered for regular operations in visitor mode since Period 103.

Once the instrument configuration is defined in terms of the two above parameters, the only remaining set-up choice for the is the light source illuminating Fibre B, if any. The available options are one of the reference sources namely Fabry-Pérot or ThAr lamp, and SKY. The FP source must be used if the highest RV precision is required. On faint targets (V>12), due to the contamination of the science spectrum by the simultaneous reference source ($<10^{-4}$), the importance of sky-background subtraction, and the fact that the RV precision will be dominated by photon noise, it is recommended not to use the simultaneous reference source, but rather to record the sky spectrum in Fibre B. For the object spectrum in Fibre A, ThAr frames are taken in daytime to provide the absolute wavelength calibration (and LFC frames will start to be taken as soon as the comb is operational).

Just like for other ESO instruments, observations with ESPRESSO are aided by a set of tools such as p2/vOT and the ETC.

5.1 Preparing the Observations

5.1.1 Exposure Time Calculator

The entry point to the ESO Exposure Time Calculator (ETC) is:

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

which links to the ETCs of each of the La Silla/Paranal instruments. The user fills in an HTML/JavaScript input form, submits the parameters to the calculation engine on the server side, which in turn gives the results of the model. 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 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 seeing value @550nm @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.

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. Together with the Phase 2 documentation:

and the ESPRESSO template manual (available from:
),
the information contained in this section provides a guideline for the Phase 2 preparation process for ESPRESSO observations.

Observation Blocks

An Observation Block (OB) for a typical science observation with ESPRESSO consists of one acquisition template and one or several observation templates. Both templates need to use the same instrument mode (e.g., one of singleHR or singleUHR).
The instrument-specific comment field of the OB shoulf 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 that to be made during Phase 2.

Instrument mode (singleHR vs. singleUHR)
This choice has already been made 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 are approximately of 30 marcsec on the position of the star on the sky. After 2.2, for every additional 0.1 in the airmass the dispersion grows approximately by 135 marcsec.

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, Fibre B will move around the position of Fibre A while observing.

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)

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 largest 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 is observed to be at the percent level if the PWV value is 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.

5.2 Observing: the Exposure Meter

The spectrograph is equipped with an advanced Exposure Meter that measures the flux entering the spectrograph as a function of time, during an exposure. 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 exposure meter operates by focusing the light that is not injected into the spectrograph's fiber on a simple diffraction grating that allows 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. 17, we show the Exposure Meter graphical user interface (GUI). The efficiency and flux-weighted mean exposure time are stored in the FITS header of the scientific images for the 'green' channel.

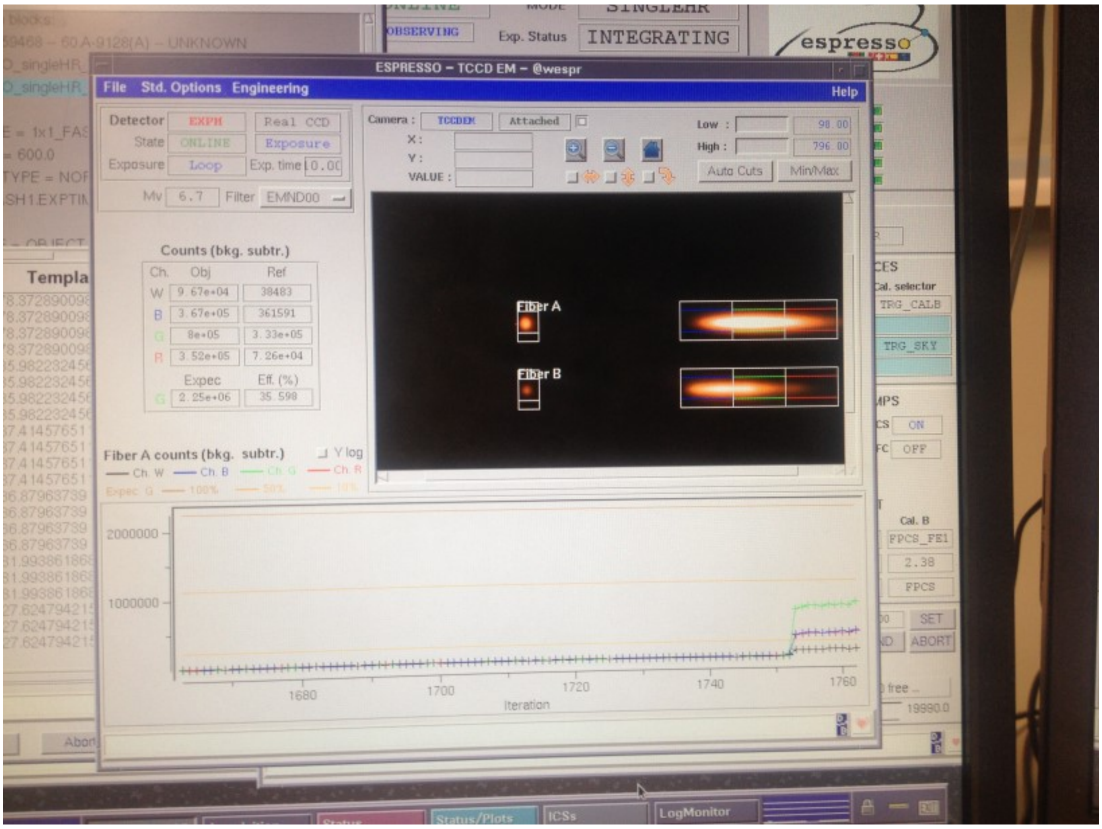


Fig. 17: GUI of the exposure meter during observations.

6. Calibration Plan

Since Period 103, ESPRESSO has been offered in all five instrument configurations: singleHR11, singleHR21, singleUHR11, multiMR42 and multiMR84. Each of these produces 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 probable timescales of instrument instabilities, partly based on the HARPS experience. An example is the drift of the wavelength calibration, which is not always measured through simultaneous reference mode and is kept below ~1 m s^{-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 gives details on the ESPRESSO standard calibration plan.

Calibration type	Frequency	# of frames	Comments

Detector bias	Daily for both 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 both 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 both 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 both singleHR modes; within 24 hours of science for singleUHR and multiMR.	2 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 both 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	Quarterly 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.
Detector linearity	Quarterly for both singleHR modes	20 (2 x 10 different exposure times)	Sequence of frames with FP source on both fibres using different exposure times.
Fibre-to-fibre relative efficiency	Quarterly for both 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 (and only these). 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 has been designed to provide the observer with a scientific dataset as complete and accurate as possible in order to increase the overall 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 and maintenance within the existing ESO Paranal Data Flow infrastructure both in service and in visitor mode.

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. However, compared to other VLT instruments, the internal complexity of ESPRESSO's acquisition arises from the requirement to be able to use any combination of UTs, besides the proper handling of the simultaneous reference technique. At the instrument control level, PLCs (Programmable Logical Controllers), as well as new component off-the-shelf TCCDs, contribute to placing ESPRESSO at the forefront of current instrument control systems. An overview of the ESPRESSO control environment is given in Fig. 18;
- 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.

  It is important to note, though, that the ESPRESSO pipeline installed at Paranal is meant merely 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 use install the pipeline, and make use of the latest calibrations in the reduction.

7.2 Data Reduction Software (DRS)

ESPRESSO has a fully automated data-reduction pipeline with the aim of providing the observer with high-quality reduced spectra. The DRS on Paranal is triggered by the arrival of raw FITS files, produced via the ESPRESSO Control Software. The DRS is also offered to any user for offline data processing via the periodic data releases on the website. The reference document for the pipeline is the ESPRESSO DRS User Manual which is available through the ESPRESSO public WEB pages, where the most up-to-date information can be found.

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. Both tools are installed for use in the VLT control room on Paranal. While the DRS is automatically triggered by the generation of new observational raw data files, the DAS is available to allow visiting astronomers to manipulate the reduced data and analyse these. Just like the DRS, these are provided as downloadable kits for Fedora Linux and Mac OS X platforms.

The DAS comprises a total of 13 recipes (based on CPL and fully compatible with Reflex) 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.

The description of each recipe and their usage is given in the ESPRESSO DAS User Manual, which is available through the ESPRESSO public web pages, where the most up-to-date information can be found.

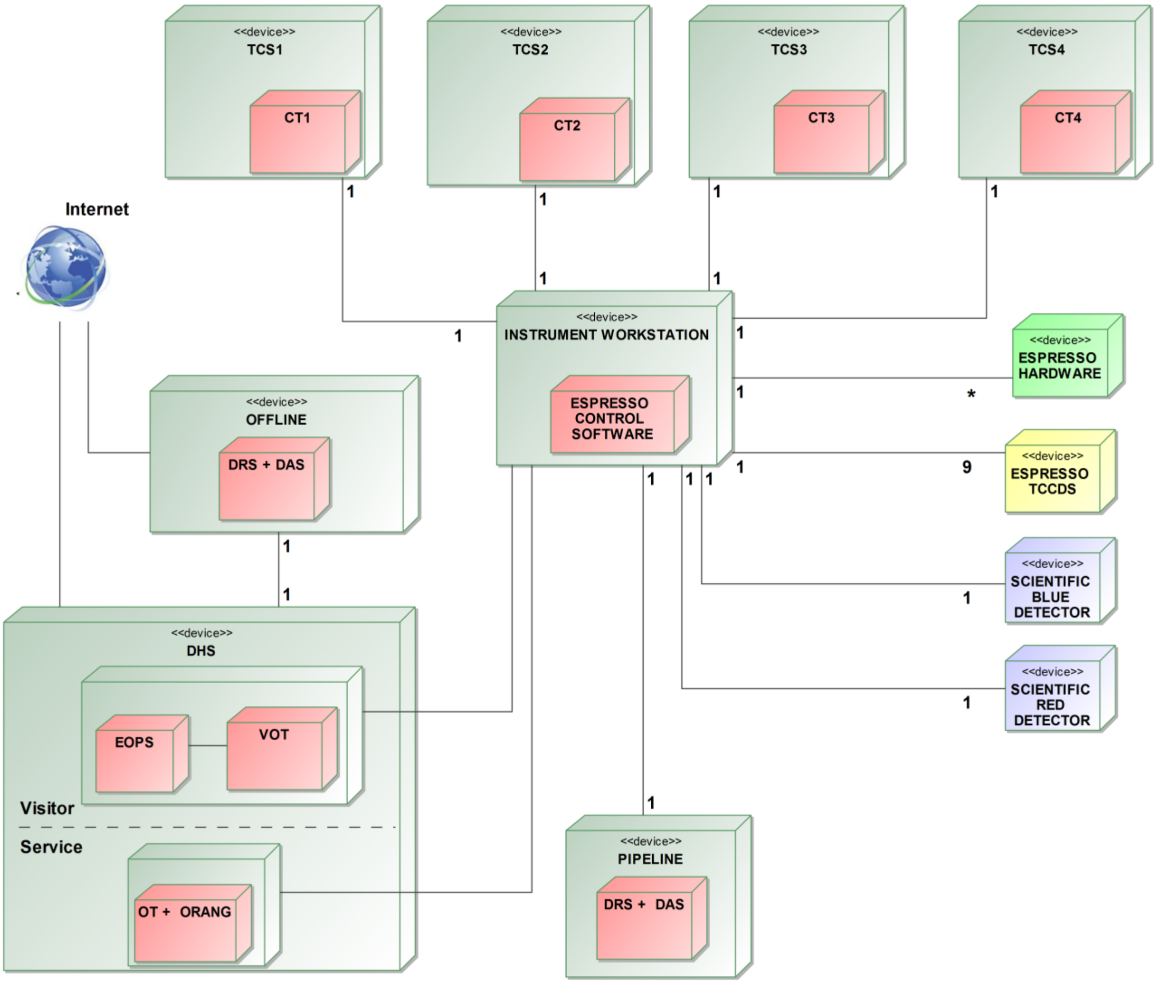


Fig. 18: Overview of ESPRESSO's control environment.

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