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CRIRES+ User Manual

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1. Introduction

1.1 Scope

The aim of the CRIRES User Manual is to provide information on the technical characteristics of the instrument, its performance, observing, calibration and data reduction procedures.

The document is structured as follows:

- Section 3 provides a technical description of CRIRES and its adaptive optics system.
- Section 4 details the instrument performance.
- Section 5 guides the users through the preparation of the observing proposal (Phase I) providing a summary of the commonly observing techniques in the infrared, and their impact on the Phase I constraints and telescope time
- Section 6 provides guidelines for Phase II preparation.
- Section 7 contains reference material. It includes a description of the calibration plan, the data format, the template reference guide and the defined reference settings.

1.2 Definitions, Acronyms and Abbreviations

Throughout this document we will use the terms CRIRES+ and oCRIRES to refer to CRIRES after and before the upgrade, respectively. However, it should be noted that the instrument name has not changed. This document employs several abbreviations and acronyms to refer concisely to an item, after it has been introduced. The following list is aimed to help the reader in recalling the extended meaning of each short expression:

AO	Adaptive Optics
APD	Avalanche photodiode
BOB	Broker of Observation Blocks
CPL	Common Pipeline Library
CRIRES	Cryogenic high-resolution infrared echelle spectrograph
CRIRES+	CRIRES upgrade project
DM	Deformable Mirror
DMO	Data management and operations division
ESO	European Southern Observatory
ETC	Exposure time calculator
FC	Finding Chart
FoV	Field of View
FPET	Fabry-Perot Etalon
FWHM	Full Width at Half Maximum
NGC	New General detector Controller
NGS	Natural guide stars
NIR	Near infrared
NIST	National Institute of Standards and Technology
OB	Observation Block
oCRIRES	Original or old CRIRES
p2	Phase II web-based preparation
p1	Phase I web-based proposal preparation and submission system



PSF	Point Spread Function
QC	Quality Control
RTC	Real Time Computer (MACAO)
RTD	Real Time Display
SDD	Software Development Division
SM	Service Mode
SNR	Signal-to-Noise Ratio
SR	Strehl Ratio
SV	Slit Viewer
SVGS	Slit View Guide Star
TC	Turbulence Category
TIO	Telescope and instrument operator
TTM	Tip-tilt mount
USD	User Support department
VLT	Very Large Telescope
VM	Visitor Mode
WF	Wave Front
WFS	Wave Front Sensor

1.3 Important websites

All CRIRES related manuals are available on the instrument web page together with the most updated information:

<http://www.eso.org/sci/facilities/paranal/instruments/crides.html>

Both Service and Visitor mode Observation Blocks (OBs) should be prepared with the latest version of the Phase 2 web-based preparation tool (p2), available at:

<https://www.eso.org/sci/observing/phase2/p2intro.html>

Information for the preparation of the Service mode observations with CRIRES are available at:

<http://www.eso.org/sci/observing/phase2/SMGuidelines.CRIRES.html>

Visiting astronomers do not need to submit OBs in advance of their observations. However, they should prepare them before arriving at the observatory or, at the latest, at the observatory the nights before their observing run. They will find further instructions on the Paranal Science Operations web page and the Paranal Observatory home page:

<https://www.eso.org/public/teles-instr/paranal-observatory/vlt/>

<http://www.eso.org/sci/facilities/paranal/sciops.html>

In particular, visiting astronomer should read the following webpage:

<http://www.eso.org/sci/facilities/paranal/instruments/crides/visitor.html>



Reference frames, static calibration frames, information regarding the CRIRES pipeline and quality control can be found at:

<http://www.eso.org/observing/dfo/quality/>

1.4 Contact Information

In case of specific questions related to proposal preparation, Service Mode observations, and the use of the pipeline please contact the ESO User Support Department:

usd-help@eso.org

For Visitor Mode observations please contact the Paranal Science Operations Team. For general information, use:

paranal@eso.org

2. Overview

2.1 CRIRES in a nutshell

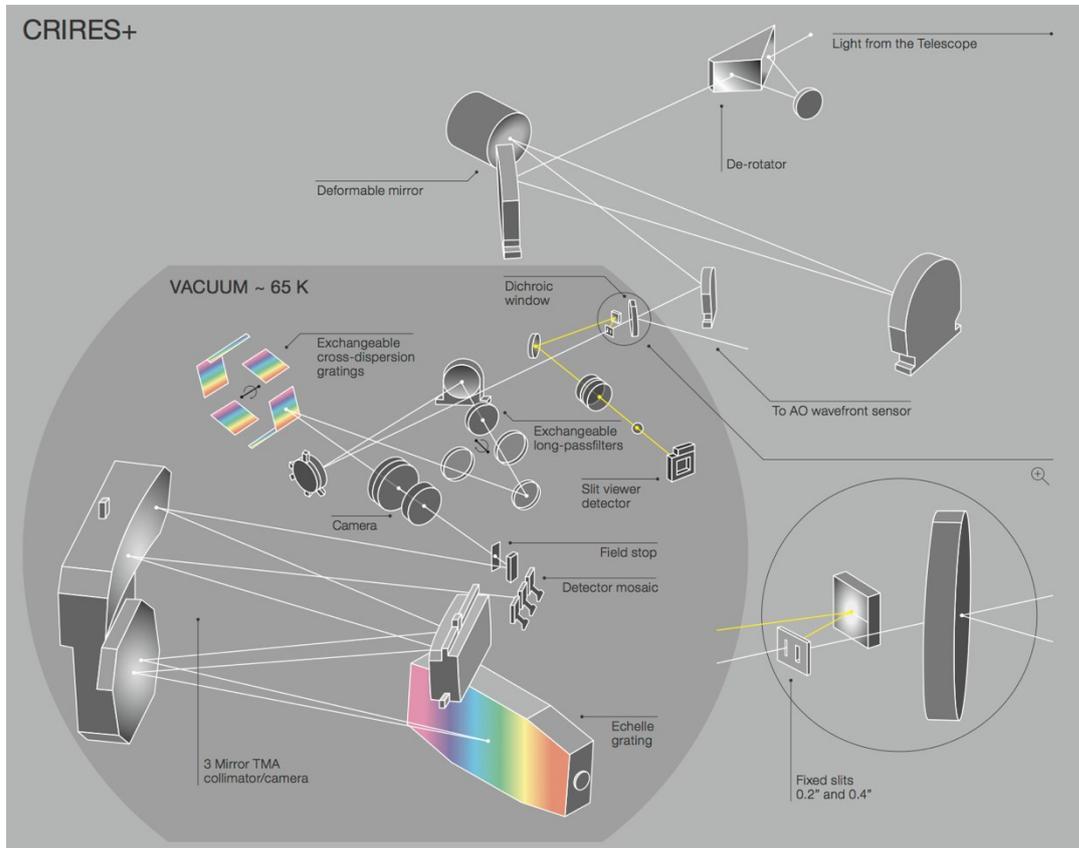


Figure 1: Optical layout of CRIRES

A basic summary of the new and main instrument parameters is given below:

Spectral resolution	50,000 and 100,000 ¹
Wavelength coverage	0.95 - 5.3 μm YJHKLM bands
RV precision	3 m/s by using gas cells
Slit length	10 arcseconds
Slit width	0.2 and 0.4 arcseconds
Slit length	10 arcseconds
Polarimetry	linear + circular (YJHK bands)
Adaptive optics	60 actuator curvature sensing (MACAO)
Cross-disperser	6 gratings (YJHKLM)

¹ See 4.4.7 for more details on ongoing analysis

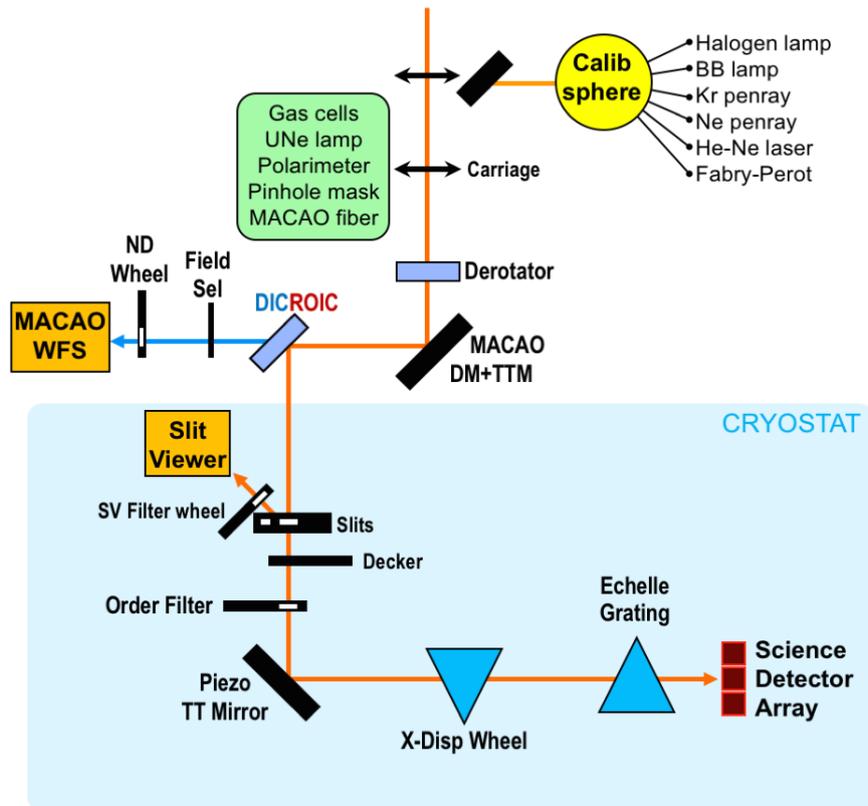


Figure 2: Light path sketch of the upgraded CRIRES.

Before the upgrade, the adaptive optics (AO) assisted CRIRES instrument (oCRIRES) was an IR (0.92 - 5.2 μm) high-resolution spectrograph in operation from 2006 to 2014 at the Very Large Telescope (VLT) observatory. oCRIRES was a unique instrument, accessing a parameter space (wavelength range and spectral resolution) up to now largely uncharted. It consisted of a single-order spectrograph providing long-slit (40 arcsecond) spectroscopy with a resolving power up to $R=100\,000$. However, the setup was limited to a narrow, single-shot, spectral range of about 1/70 of the central wavelength, resulting in low observing efficiency for many scientific programmes requiring a broad spectral coverage.

The CRIRES upgrade project, CRIRES+, has transformed this VLT instrument into a cross-dispersed spectrograph with the goal to increase the simultaneously covered wavelength range by a factor of ten. A new and larger detector focal plane array of three Hawaii 2RG detectors with 5.3 μm cut-off wavelength replaced the existing detectors. For advanced wavelength calibration, custom-made absorption gas cells and an etalon system have been added. A spectro-polarimetric unit allow the recording of circular and linear polarized spectra. This upgrade is supported by dedicated data reduction software allowing the community to take full advantage of the new capabilities.

Figure 2 summarizes the overall concept of the CRIRES upgrade. The main, high resolution spectrometer unit remains untouched. The new cross-disperser unit substitutes the old re-imager and pre-dispersing sub-systems.

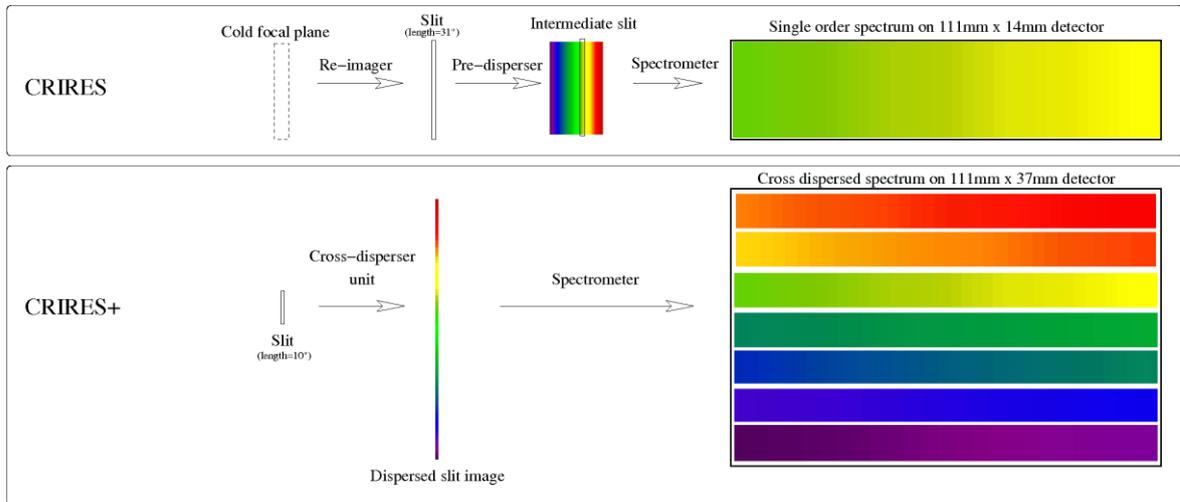


Figure 3: Schematic diagram summarizing the differences between oCRires and CRires after the upgrade

2.2 Science Drivers

A set of fundamental scientific goals were defined for CRires during the Phase A study:

2.2.1 Search for super-earth in habitable zone for low mass stars

A large fraction of all exoplanets has been discovered primarily through radial velocity (RV) measurements. However, only 5% of the planets detected so far orbit stars with stellar masses less than about $0.5 M_{\text{sun}}$. Thus, we lack key knowledge about the process of planet formation around the most numerous stars in our galaxy – M dwarfs. Low mass stars are especially interesting because these objects are cold, and the habitable zones are quite close to the star. The reflex motion of an M star ($0.15 M_{\text{sun}}$) with a $1 M_{\text{Earth}}$ planet in its habitable zone is about 1 m s^{-1} . Since M dwarfs and brown dwarfs have low effective temperatures, radiating most of their energy in the IR ($1.0 - 2.5 \mu\text{m}$), a high-resolution IR spectrograph is therefore ideal for searching for low mass planets around these objects. A new gas absorption cell to provide a stable wavelength reference as well as the increase in wavelength coverage by about a factor of ten should result in an attainable RV precision for the upgraded CRires of 3 m s^{-1} . This would enable the detection of super Earth-mass planets in the habitable zone of an M-dwarf star in the solar neighbourhood.

2.2.2 Atmospheric characterization of exoplanets

High-resolution spectroscopy of exoplanets provides us with means of studying the physical (e.g., winds) and chemical composition of exoplanetary atmospheres. CRires is well suited for the observation of close-in, highly irradiated planets that radiate most of their light in the IR. Furthermore, the IR is a spectral region where lines of molecular gases like CO, NH_3 , CH_4 , etc. are expected to be present in exoplanetary atmospheres.

2.2.3 Origin and evolution of stellar magnetic field

Magnetic fields play a fundamental role in the life of all stars: they govern the emergence of stars from proto-stellar clouds, control the in-fall of gas onto the surfaces of young stars and



aid the formation of planetary systems. Measurements of magnetic fields have mostly been confined to A- and B-type stars, so our knowledge of magnetic fields in Sun-like stars, and the low end of the main sequence, is still poor. The upgraded CRIRES will make it possible to measure with greater accuracy magnetic fields in M-dwarfs and brown dwarfs for several reasons:

1) The Zeeman splitting of a spectral line is proportional to λ^2 , so there is a huge leverage in going to the IR; 2) For cool objects most of the flux is in the IR so there is also a gain due to the increased signal-to-noise ratio. 3) In order to disentangle Zeeman broadening from other broadening effects one must compare the broadening of Zeeman sensitive lines to magnetically insensitive lines. The large wavelength coverage of CRIRES will include many more lines of different magnetic sensitivities needed for an accurate determination of the field strength. 4) The capability of CRIRES to take circular and linear polarized spectra will support these measurements.

The spectro-polarimetric mode is not offered in P108.



3. The instrument

The optical layout of CRIRES after the upgrade is shown in Figure 1. Light enters from the direction of the telescope Nasmyth focus, either via the telescope or from the calibration unit after insertion of a calibration mirror in the light-path. A carriage stage (not depicted in Fig. 1) can then insert one of the following elements in the light path: (i) The new polarimetry unit; (ii) a gas-cell either for wavelength calibrations when used with the halogen lamp (which creates an absorption spectrum), or for accurate radial-velocity measurements, similar to the way for the iodine cell technique; (iii) a pinhole used for calibration purposes; (iv) an AO fiber for MACAO calibrations; (v) an Uranium-Neon Lamp for wavelength calibration. This carriage has also a free position, with no optical element (see a detailed description of the Calibration Unit in Section 3.2.3).

Light then goes through a 3 mirror de-rotator which can be used to counteract the telescope field rotation for observations with a slit fixed relative to the sky. On the other hand, for point sources, it can also maintain the slit aligned along the parallactic angle to accommodate the differential atmospheric refraction between the R band used by the adaptive optics system and the IR band used for observations and slit viewer guiding. The light enters the cold dewar through a new dichroic window.

The optical light is reflected and used for the adaptive optics system, the infrared light ($0.95 \mu\text{m} < \lambda < 5.2 \mu\text{m}$) will be transmitted to the cold optics of CRIRES. The AO system concentrates the light on the spectrograph's entrance slit. Further details of the AO system can be found in sec. 3.2.1 of this manual. CRIRES can be used without adaptive optics, in which case the AO module just acts as relay optics and the spatial resolution is given by the natural seeing. Under normal conditions this leads to higher slit losses than when AO is used.

3.1 The Cold Part: Opto-mechanics

After the dichroic window, the infrared light passes through a new entrance slit unit (see Figure 4 A), which comprises a movable mask with two slits: 0.2" (resolving power $\sim 100,000$) 0.4" slit (resolving power $\sim 50,000$) preserving the spectral resolution of CRIRES. The mask can also be positioned so that neither slit is in the optical path and the spectrograph is closed to light from the telescope. The reproducibility and stability are significantly enhanced compared to the old slit mechanism. In addition, the CRIRES entrance slit mechanism includes a decenter for polarimetric observations allowing for the left and right-hand polarised beams at two nodding positions. To cover the additional orders the spatial extent of the two main slits was reduced from 40 to 10 arcseconds, providing a balanced compromise (based on an analysis of the past and future scientific requirements and science cases) between cross-dispersion implementation and the old CRIRES long slit usage. The 10 arcsec long slit will not limit observations of extended sources and allow nodding for precise background subtraction observing methods.

The light reflected by the slit mask is used by the slit viewer camera to assist the adaptive optics system in centring and keeping the targets PSF on the slit as for the oCRIRES. However, the CRIRES slit viewer subsystem has been substantially modified: it is composed of two folding mirrors, a camera to image the entrance slit on a detector and a filter wheel to select the filter for guiding. The SV detector is now a H2RG detector, which will significantly enhance the SV camera performance when compared to oCRIRES.

3.1.1 The new Cross-Dispersion unit

The fore-optics of the upgraded CRIRES is shown in Figure 4. It consists of an off-axis parabola, which creates a collimated beam with a diameter of 50 mm, being followed by two flat mirrors with distances and angles adjusted to match the new fore-optics with the already existing three-mirror anastigmatic (TMA) relay optics and the echelle grating which remained from the original CRIRES instrument.

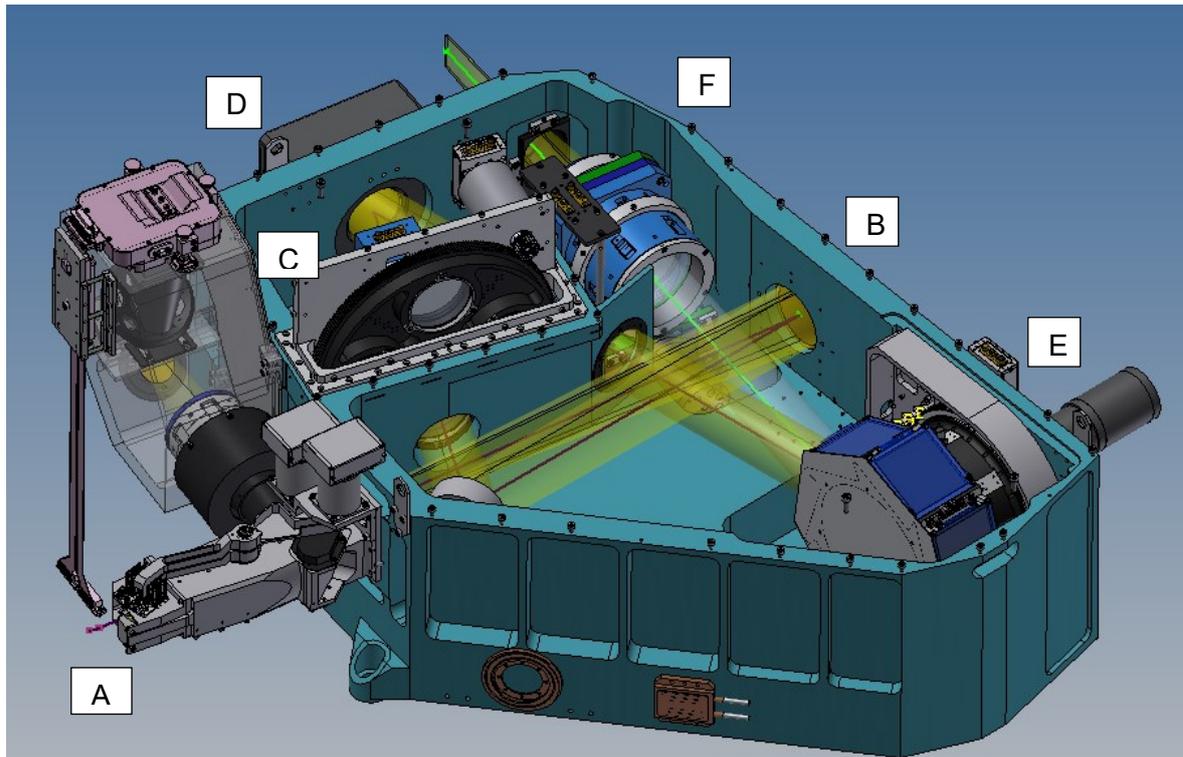


Figure 4: Top view of the new CRIRES fore-optics assembly

Figure 4 shows that the beam from the $f/15$ focus at the new entrance slit (A) is collimated by a parabolic mirror (B) and arrives at the cross-disperser wheel (E) via two flat mirrors and a long pass filter wheel (C) to block the 2nd and higher orders of the cross-disperser gratings. The jitter mirror (D) has two piezo actuators that allow the echellogram to be translated at sub-pixel accuracy on the detectors. The order-sorting filter can be accordingly selected from one of three filters (YJ, KH, LM or an open position) to the chosen cross disperser grating. The cross-disperser wheel contains six reflection gratings, one for each of the wavelength bands Y, J, K, H, L and M. The Metrology system ensures accurate repeatability of the cross-disperser wheel.

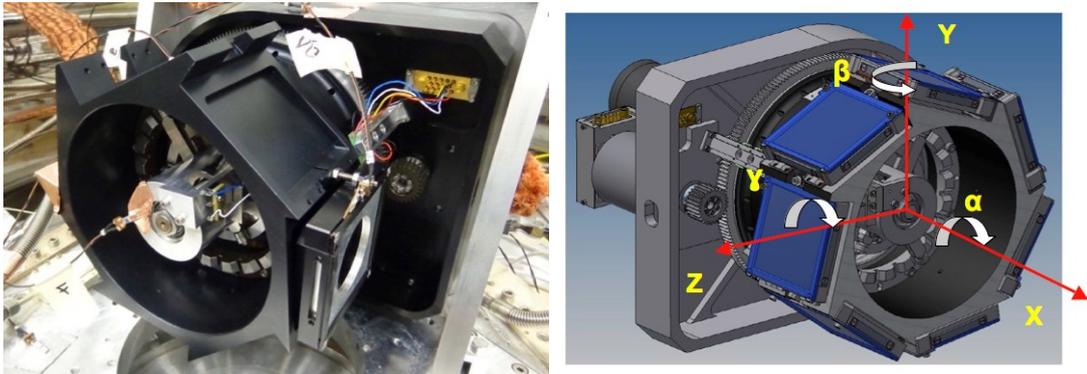


Figure 5: Grating wheel design with locking mechanism and build prototype

Following the cross-disperser grating, an achromatic camera (F) working at a fixed focal length brings the collimated beam to an $f/8$ focus at the field stop. In order to avoid time consuming thermal cycling during the AIT phase the camera is mounted on a small and simple focusing stage. This focusing functionality is only intended for integration and maintenance and not for regular operations.

3.1.2 The spectrograph unit

The echelle grating subsystem is unchanged relative to the oCRIRES. It consists of a 40×20 cm, 31.6 lines/mm, 63,5deg blaze echelle grating plus a TMA (three-mirror anastigmatic) which acts first as a collimator and then as a camera to image the spectrum on the new three Hawaii 2RG detectors effectively forming an 6144×2048 pixels array. More details on the optical and opto-mechanical designs can be found in Lizon et al. (2014) and Oliva et al. (2014), respectively.

3.1.3 The new detectors

Another major part of the upgrade project was to increase the coverage of the focal plane by introducing a set of new detectors. To accommodate the echelle spectral format, a larger field was required to cover the ten orders per band with a slit length of 10 arcseconds. Figure 6 presents a comparison between the oCRIRES focal plane array area and the actual array of CRIRES detectors after the upgrade. The actual detector array, composed by three Hawaii 2RG detectors (the CRIRES H2RG detectors are shown in Figure 7 on the right together with the detector mount on the left), span over 6144×2048 pixels ($111\text{mm} \times 37\text{mm}$) at a pixel size of $18\mu\text{m}$. For comparison, the old Aladdin mosaic spanned only 4096×512 pixels ($111\text{mm} \times 14\text{mm}$) with a pixel size of $27\mu\text{m}$, as described in Dorn et al. (2006).

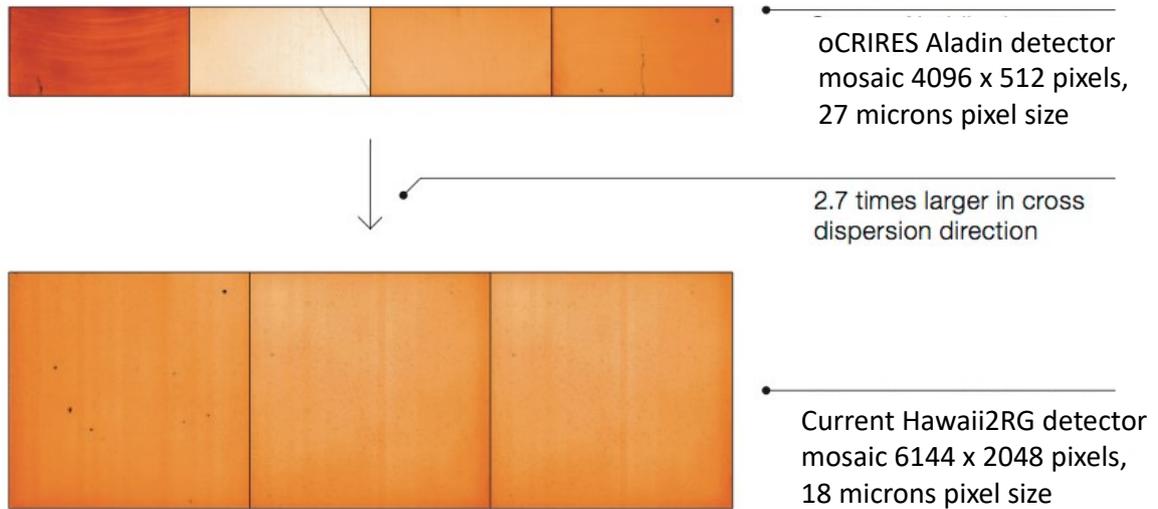


Figure 6: The original CRIRES detector mosaic focal plane array area compared to the new detectors with an increase of a factor of 2.7 in the cross-dispersion direction.

The new detector mosaic does not only provide a larger area but also lower noise, higher quantum efficiency, better cosmetic quality and much lower dark current. Also, the gaps between the detectors in the mosaic are smaller. The detectors operate at 35K with cryogenic preamplifiers located next to the focal plane.



Figure 7: The 3 CRIRES H2RG detectors are shown (right) together with the detector mount (left)

All detector systems, including the slit viewer camera, is upgraded to the current ESO standard New General detector Controller (NGC). This detector upgrade does not only significantly increase the coverage of the focal plane, but the increased spatial homogeneity of the pixel response combined with lower readout noise, dark current and higher QE will result in improved data quality. All detectors have been tested at the ESO detector labs and the full detector system is in operation in the upgraded CRIRES instrument.

3.1.4 The cryogenic vessel

CRIRES is located at the Nasmyth B focus of VLT-UT3. The instrument is mounted in a 3 m-diameter, 1 m high vessel. Including its support structure, the total weight of the



instrument is 6.2 t, spread between 2 t for the warm part or AO system and 4.2 t for the cold part. The optics inside the cryo-vessel is cooled to 65 K. The detectors are stabilized at 35 K within ~5 mK.

3.1.5 The CRIRES

In order to stable exposures with high repeatability, the concept of a metrology system was developed to allow for a 0.1pixel reproducibility. The strategy is to centre a defined set of emission lines of the Kr and Ne pen ray lamps on the science detector by finetuning the positions of the cross-disperser grating and Echelle grating and refining further via the use of a piezo driven tip-tilt mirror that has actuators aligned with the main- and cross-dispersion axes. This is an iterative process which may take a few minutes, the exact duration depends upon the unpredictable behaviour of the cross-disperser grating and Echelle grating functions. The metrology then ensures that these emission lines are indeed located at their fiducial positions on the science FPA before any science exposure (or any calibration exposure when used during daytime) follows. Those science/calibration exposures obtained after a successful application of metrology will have the following metrology keywords written to their headers (values below are examples):

```
HIERARCH ESO OCS MTRLGY DX = 0.002 / [pixels] Final mean x residual relative to
fiducial
HIERARCH ESO OCS MTRLGY DY = 0.039 / [pixels] Final mean y residual relative to
fiducial
HIERARCH ESO OCS MTRLGY ECHCORR = -54 / [Enc] Difference between the nominal echelle
encoder value and the resulting value after metrology
HIERARCH ESO OCS MTRLGY ECHNMOV = 1 / Number of echelle grating moves
HIERARCH ESO OCS MTRLGY NITER = 5 / Total number of iterations performed
HIERARCH ESO OCS MTRLGY PIEZO1 = 4.340 / [V] Cross-dispersion piezo voltage at the
conclusion of metrology
HIERARCH ESO OCS MTRLGY PIEZO2 = 3.990 / [V] Main-dispersion piezo voltage at th e
conclusion of metrology
HIERARCH ESO OCS MTRLGY ST = T / Success or failure of metrology
HIERARCH ESO OCS MTRLGY TIME = 1612768172.0 / [s] Timestamp for the successful
conclusion of metrology
HIERARCH ESO OCS MTRLGY TOTDX = -1.430 / [pixels] Average total applied correction
in the main dispersion direction
HIERARCH ESO OCS MTRLGY TOTDY = 0.194 / [pixels] Average total applied correction
in the cross-dispersion direction
HIERARCH ESO OCS MTRLGY XDGWCORR = 0 / [Enc] Difference between the nominal XDGW
encoder value and the resulting value after metrology
HIERARCH ESO OCS MTRLGY XDGWNMOV = 0 / Number of XDGW moves
```

The metrology can be activated or deactivated in the acquisition and observing templates. When it is enabled during the acquisition the metrology runs in parallel to the telescope preset, therefore no overheads are associated to the metrology (see Table 9).

In Y-, J-, H- and K-bands the metrology converges reliably resulting in residual errors in relative alignment of $\pm 0.1\text{pix}$ in main dispersion and $\pm 0.5\text{pix}$ in cross-dispersion. If the metrology is not used the relative alignment is an order of magnitude larger. In P108 the metrology should not be used for L- and M-band observations, its behaviour has not yet been characterised in these bands (whilst it is known to be more challenging due to the scarcity of suitable emission lines and the significant continuum from the pen-ray lamps).

An important note regarding main-dispersion stability following metrology: During commissioning it was observed that the drift in main-dispersion echellogramme alignment was somewhat higher ($\sim 0.2\text{pix}$ over 30mins) following metrology alignment than it was without metrology (0.05pix over 30mins, consistent with PAE measurements and specifications). This effect is still being investigated and several mitigation strategies are under consideration, but users should keep in mind that during P108 spectral resolution and alignment of data obtained within 30mins of the application of metrology may be degraded due to this effect.

3.2 The Warm Part

The Warm Part of CRIRES consists of different subsystems (see Figure 8 for an overview): the AO Unit, the Calibration Unit which also includes a Fabry-Perot Etalon System and a carriage stage with the new Polarimetry Unit and new sources for wavelength calibration described in detail in Section 3.2.3.

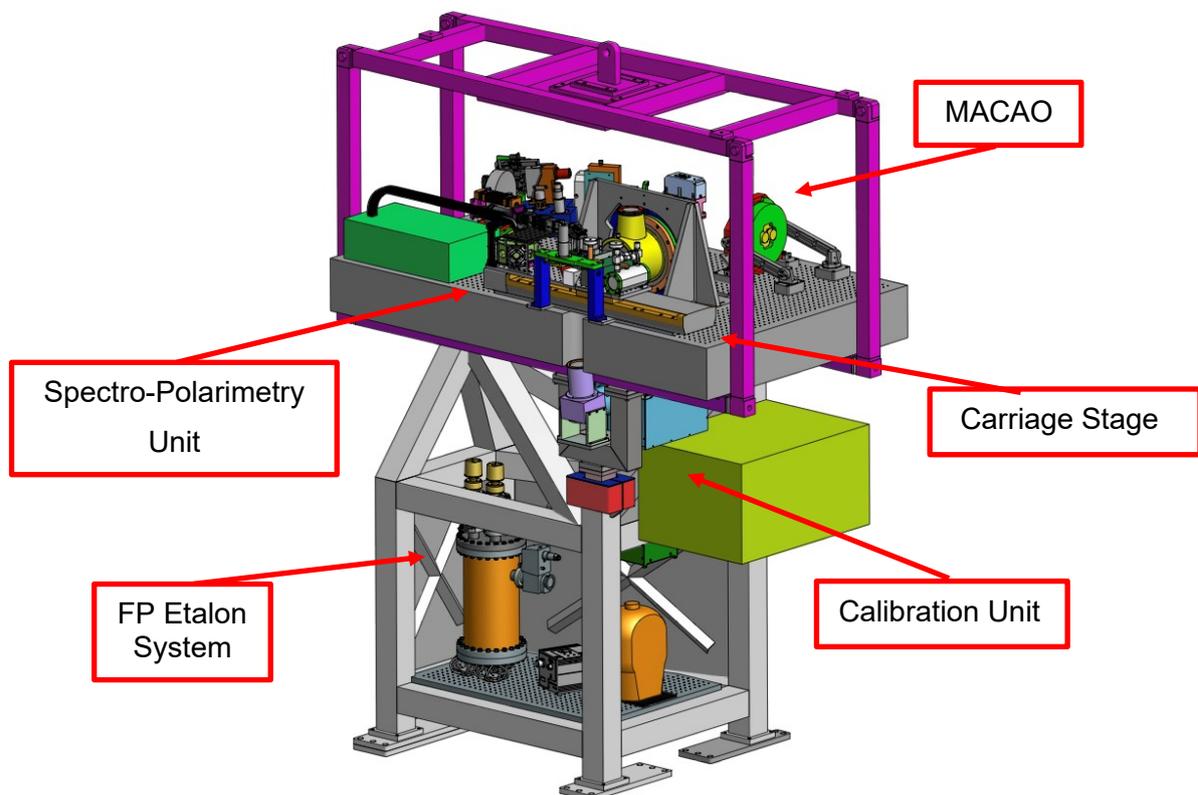


Figure 8: The upgraded CRIRES warm part assembly with etalon system, calibration slide, AO system and de-rotator mechanism

3.2.1 The Adaptive Optic System MACAO

The adaptive optics system of CRIRES is described in Paufiqué et al. (2004, SPIE 5490, 216). The multi-application curvature adaptive optics system (MACAO) for CRIRES corrects a turbulent wavefront and provides diffraction limited images at the focal plane. The overall sensitivity is thereby improved by about a factor two for point-sources. To highlight the advantage of combining MACAO and CRIRES a PSF is shown in Figure 9 in AO open loop (uncorrected) and closed loop, where the PSF is reconstructed from wavefront measurements. The non-circular PSF in open loop is due to the very short integration time used.

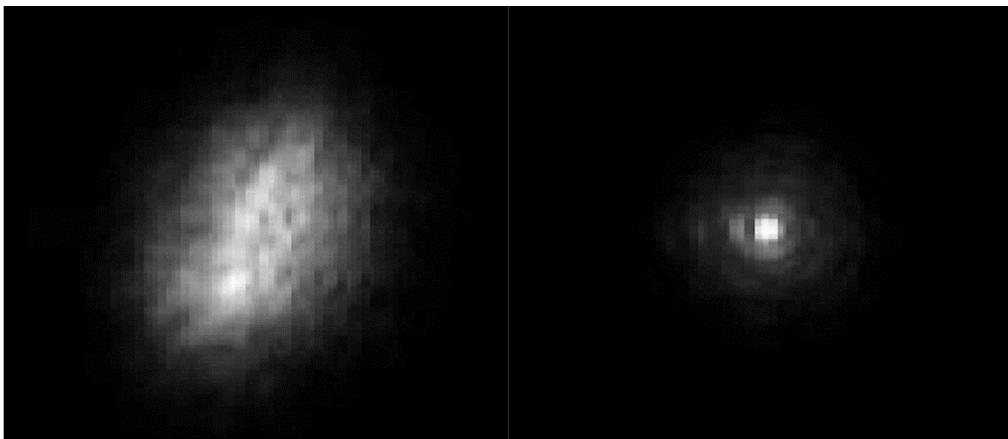


Figure 9: PSF without (left) and with (right) MACAO correction. Images have been taken in lab using a turbulence generator.

The following section provides an introduction to the field of adaptive optics and atmospheric turbulence, and essentially is taken from the NACO user manual. For further reading, see for example: “Adaptive optics in astronomy”, Rodier 1999, Cambridge University Press, or “Introduction to adaptive optics”, Tyson 2000, Bellingham/SPIE.

3.2.1.1 Atmospheric Turbulence

The VLT theoretical diffraction limit is $1.22\lambda/D = 0.07$ arcsec at a wavelength of $2.2 \mu\text{m}$. However, the resolution is severely limited by atmospheric turbulence to $\lambda/r_0 \sim 1$ arcsec, where r_0 is the Fried parameter. r_0 is directly linked to the strength of the turbulence and depends on the wavelength as $\lambda^{6/5}$. For average observing conditions, r_0 is typically 60cm at $2.2\mu\text{m}$.

Temperature inhomogeneities in the atmosphere induce temporal and spatial fluctuations in the air refractive index and therefore cause fluctuations in the optical path. This leads to random phase delays that corrugate the wavefront (WF). The path differences are, to a good approximation, achromatic. Only the phase of the WF is chromatic. The coherence time of WF distortions is related to the average wind speed V in the atmosphere and is typically of the order of $r_0/V = 60$ ms at $2.2\mu\text{m}$ for $V = 10$ m/s.

3.2.1.2 Adaptive Optics

A technique to overcome the degrading effects of atmospheric turbulence is real-time compensation of the deformation of the WF by adaptive optics (AO, Figure 10).

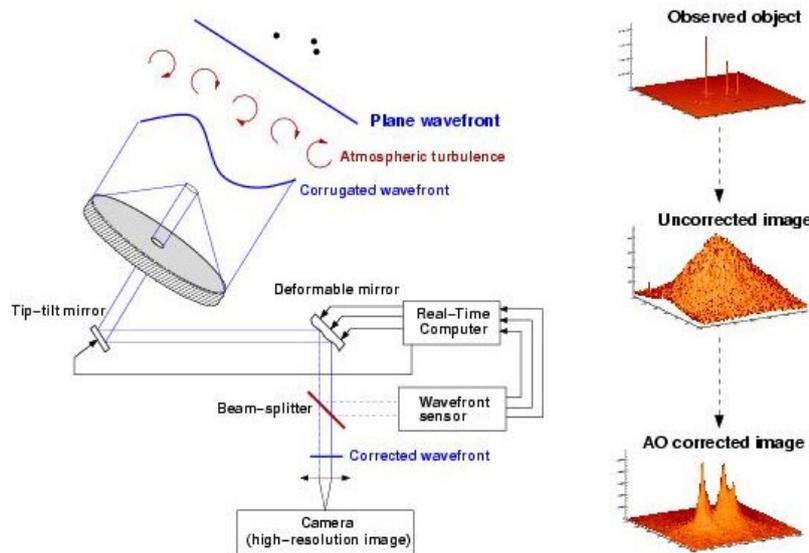


Figure 10: Principle of Adaptive Optics. Note that in practice, and contrary to the this schematic design, CRIRES has not dedicated tip-tilt mirror, but perform low- and high-order correction with a single deformable mirror mounted on a tip-tilt stage (see Figure 12).

The wavefront sensor (WFS) measures WF distortions which are processed by a real-time computer (RTC). The RTC controls a deformable mirror (DM) to compensate the WF distortions. The DM is a continuous thin plate mirror mounted on a set of piezoelectric actuators that push and pull on the back of the mirror. Because of the significant reduction in the WF distortions by continuous AO correction, it is possible to record near diffraction-limited images with exposure times that are significantly longer than the turbulence coherence time. The residual error from the WF compensation (WF error) directly determines the quality of the formed image. One of the main parameters characterizing this image quality is the Strehl ratio (SR), which corresponds to the amount of light contained in the diffraction-limited core relative to the total flux.

An AO system is a servo-loop system working in closed loop. The DM flattens the incoming WF and the WFS measures the residual WF error. A commonly used WFS is the Shack-Hartmann WFS, used for example in NACO. However, CRIRES, as well as other ESO MACAO systems, relies on a curvature WFS: it is designed to measure the WF curvature as opposed to the WF slope. This is achieved by comparing the irradiance distributions of two planes placed behind and in front of the focal plane. In practice, a variable curvature mirror (membrane) is placed in the telescope focus. By vibrating, inside and outside focus blurred pupil images can be imaged on a detector array: in the case of CRIRES, a lenslet array feeds avalanche photo-diodes (APDs). The modulation frequency of the membrane corresponds to the temporal sampling frequency of the WFS. The difference between the inside and outside pupil image measures the local WF curvature.

The performance of an AO system is related to the number of lenslets in the lenslet array, the number of actuators behind the DM, and the rate at which WF errors can be measured, processed and corrected (the server-loop bandwidth).

The performance of an AO system is also linked to the observing conditions. The most important parameters are the seeing, the coherence time, the brightness of the reference source used for WFS and the distance between the reference source and the object of interest. In case of good conditions (i.e., seeing $< 0.8''$ and coherence time $> 3\text{ms}$) and a bright (i.e., $R < 7$), nearby (i.e., within $\sim 5''$) reference source, the correction is good, and the resulting point spread function (PSF) is very close to the diffraction limit. A good correction in the K-band typically corresponds to a SR larger than 30%. At shorter wavelengths (particularly in the J-band) or in the case of poor conditions or a faint, distant reference source, the correction is only partial - the SR may only be a few percent

3.2.2 MACAO Hardware Description

The MACAO system for CRIRES is based on a 60-actuator deformable mirror, inserted in a so-called relay optics. These optics and the wavefront sensor optics are mounted on a bread-board located between the Nasmyth focus and the spectrometer. It is about 1.5m wide and a top view of the warm optics overlaid by the optical path is shown in Figure 11, the assembly of the deformable mirror is displayed in Figure 12 .

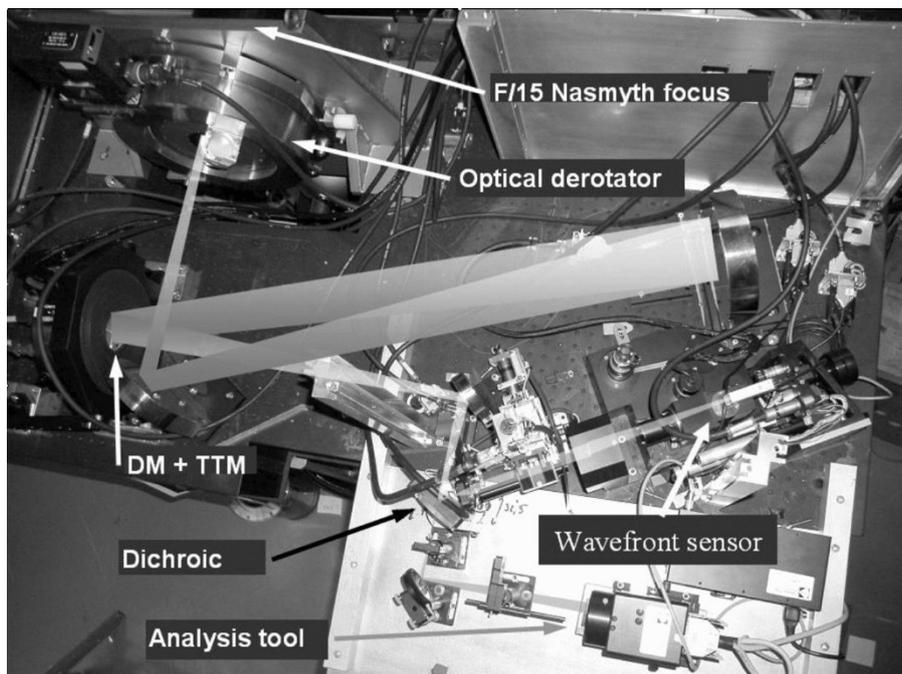


Figure 11: Top view of the warm optics of the MACAO-CRIRES system. From f/15 Nasmyth focus and after the optical derotator, one notices the deformable mirror and the tip-tilt mount assembly. Light enters from the dichroic to the cold and warm part of the instrument. On the right the wavefront sensor and some analysis tools are visible.

3.2.2.1 The corrective optics

The wavefront correction is performed by a 60 electrodes bi-morph mirror developed by CILAS, with a pupil diameter of 60 mm. The 60 electrodes are sandwiched between two thin piezoelectric PZT layers with opposite polarization. The outside surface of the PZT layers is grounded and covered with 0.1mm glass layers, the mirror side being silver coated. Applying a voltage to one electrode produces a constant curvature over its surface. The geometry of the electrodes in the 4 central rings (40 electrodes) matches that of the lenslet array sub-apertures, while the 20 remaining electrodes are located outside the pupil and constrain the edge of the pupil to correct zero-curvature aberrations: tip-tilt, astigmatism, etc. The DM provides a stroke to compensate atmospheric aberrations up to an optical seeing of 1". In order to relax the use of the outer electrodes of the mirror, the tip-tilt error is slowly offloaded to a tip-tilt mount designed and built by LESIA, which provides a $\pm 240''$ mechanical stroke, i.e. $\pm 3.6''$ on the sky, with a 100 Hz -3dB internal closed-loop bandwidth. The assembly of the DM and tip-tilt mount is shown in Figure 12.

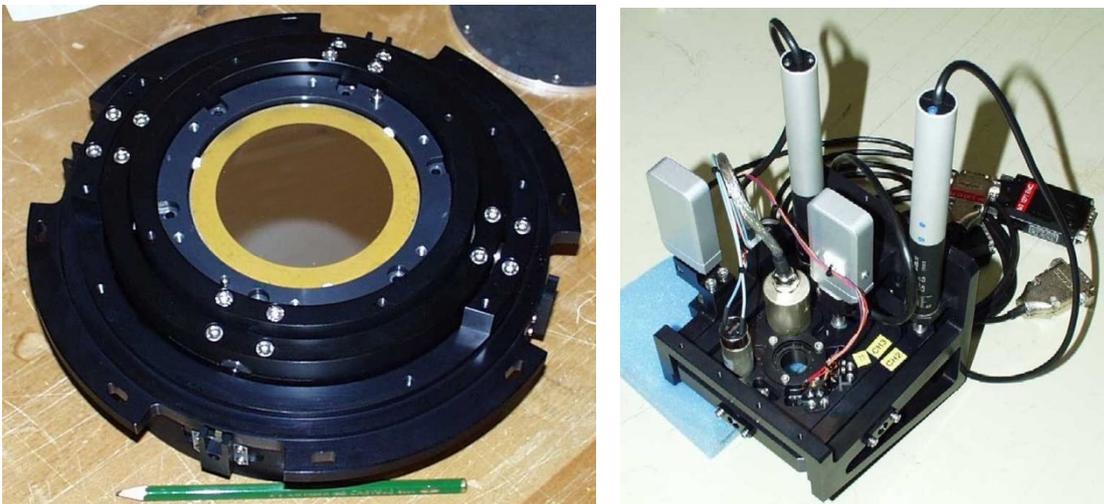


Figure 12: Assembly of the deformable mirror (DM) and tip-tilt mount (TTM)(left) and of the gimbal mount (right).

3.2.2.2 The Wavefront Sensor

The following functions are sequentially implemented in the wavefront analyzer:

- Extraction of the reference star beam (field selector).
- Projection of the reference star image on the membrane mirror (imaging lens).
- Scan of the intra- and extra-pupil regions by modulation of the membrane mirror curvature.
- Creation of a pupil image centred on the lenslet array.
- Reduction of the flux to work within the linear range of the APDs by means of neutral density filters.
- Re-imaging of the 60 sub-pupils on the 60 fiber cores by the lenslet array unit.
- Injection of the collected beams onto the 60 APDs.

The scanning lens of the field selector is mounted on an XYZ table: the XY axes enable the star used for AO correction to be selected in the 22.8"x 33.8" field-of-view, while the Z stage compensates for the VLT field curvature. The position of the field selector defines the reference for the pointing. The imaging lens creates an image of the AO star on the membrane mirror, which is mounted on an acoustic cavity. A voice coil is mounted to the other end of the cavity and driven at 2.1kHz by the APD counter module to force an oscillation of the focus mode of the membrane mirror. The incidence angle of the beam on the membrane mirror depends on the position of the guiding star in the field. In order to keep the pupil image (obtained when the membrane mirror is flat) centred on the lenslet array, the membrane mirror is mounted on a 2-axis gimbal mount, which is coordinated with the field selector. For each (x, y) position of the field selector the gimbal mount is moved so that the light is reflected to the same focus. A diaphragm in front of the membrane enables the field to be adjusted to the observing conditions (seeing and guiding reference size). The assembly of the gimbal mount is shown in Figure 12.

The wavefront sensor box consists of 4 mirrors, which provide parallel beam to image the pupil on the lenslet array. First, the beam is collimated by a spherical mirror. It is then folded by a flat mirror and injected in the beam expander, which adapts its diameter to the lenslet array (14 mm). The optical path of the wavefront sensor box is shown in Figure 13.

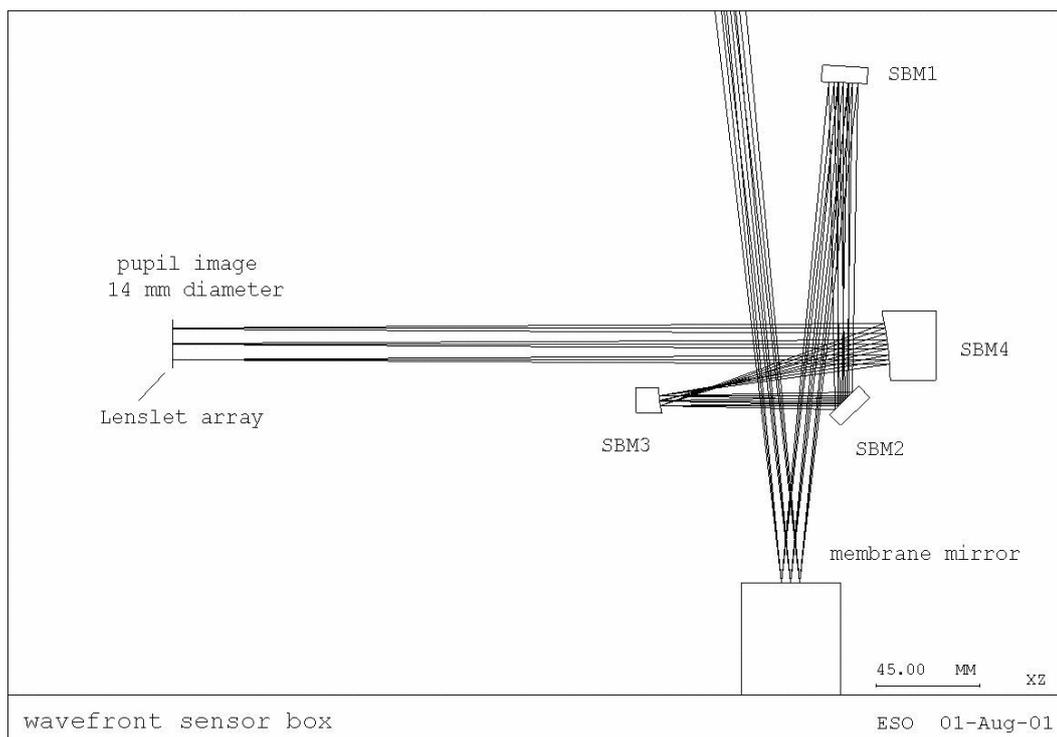


Figure 13: The optical path of the wavefront sensor box.

The lenslet array intercepts the beam and divides the flux in 60 sub-apertures. Each sub-pupil is imaged on a fiber, with a 100 μm core diameter. When the membrane mirror vibrates, the pupil image is projected on both sides of the lenslet array plane. The normalized difference between the intra- and extra-pupil flux collected by each sub-aperture is proportional to the local wavefront curvature, which provides the wavefront error. The fibers drive the signal from the fiber feed module to the APD cabinet, mounted on the

instrument. The APD counts are recorded by the APD counter module, synchronously with the membrane signal. The front-end assembly of the fiber bundle is shown in Figure 14.

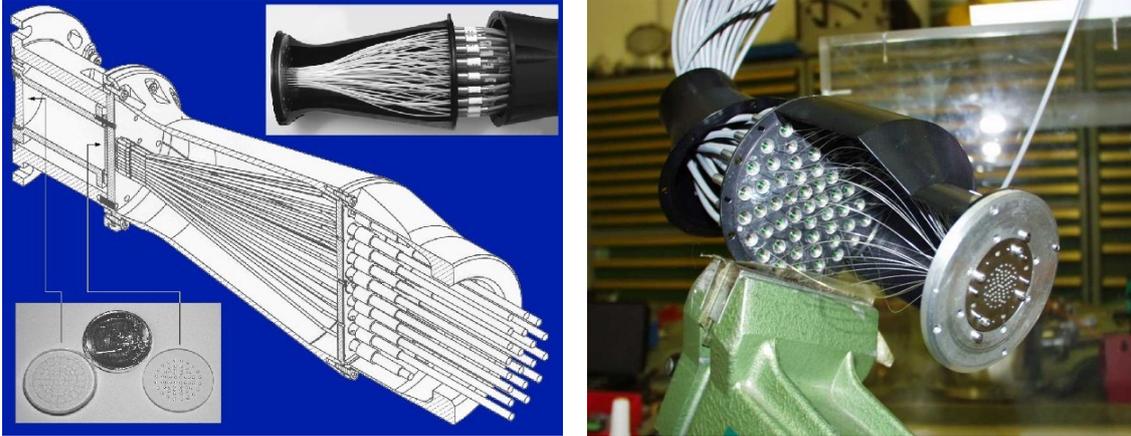


Figure 14: Front-end assembly of the 60 fiber bundle which guide the light to the sensors.

3.2.2.3 The Control Loop

The oscillating membrane produces a signal modulated proportional to the local wavefront curvature. This signal, collected by APDs, is sent to the RTC. The RTC computes this modulation and retrieves the voltages to be applied to the mirror and tip-tilt mount to optimally compensate for the local curvature measured. For this, a precise calibration of the system is required, which includes synchronization of the membrane mirror, determination of the membrane curvature, pupil alignment and interaction matrices.

3.2.2.4 The Membrane Setting

The membrane mirror curvature represents an optical gain for the aberration measurements. A way to increase the performance of the system is therefore to increase the curvature of this mirror. Increasing the curvature, however, requires increasing the field of view of the wavefront sensor optics as well. This and some other non-linear effects can degrade the estimate of the curvature. For the same reason, extended sources will affect the quality of curvature measurement, and lead to a different optimal gain. In some extreme cases, the system can be unable to close the loop (extended 6'' planetary nebula with a faint blue-white dwarf in the middle, or a faint star close to the Moon, for example). A trade-off is needed, and an optimal optical gain has to be determined. This optimal gain mainly depends on the seeing, and marginally on the star magnitude and other factors. It is tabulated in the configuration of the software and is transparent to the user.

3.2.3 The New Calibration Unit

The calibration unit itself consists of an integrating sphere illuminated by a continuum, Halogen lamp for flat-fielding and, together with a gas-cell, for wavelength calibration. An IR-emitter lamp used for technical tests, a Kr/Ne lamps and the Fabry-Perot Etalon System (FPI) fiber are also attached to the integrating sphere (see Figure 15). The integrating sphere provides uniform illumination of the entrance slit of the spectrometer and its flux can be adjusted by a moving baffle.

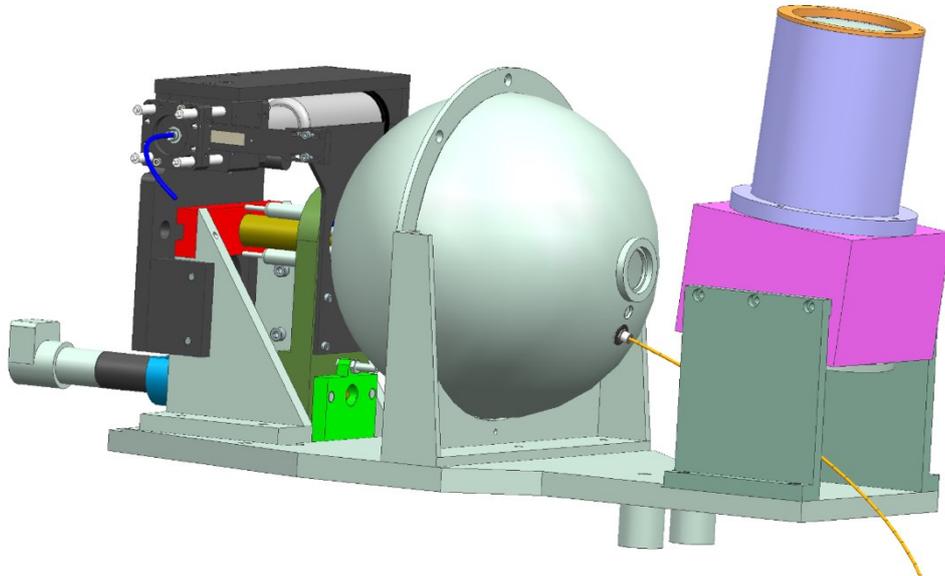


Figure 15: Integrating Sphere assembly. The FPI- fiber is visible on the right.

The following elements are inserted in the light path by a carriage stage place just before the derotator mirror (see Figure 16): (i) The new polarimetry unit; (ii) a gas-cell either for wavelength calibrations when used with the halogen lamp (which creates an absorption spectrum), or for accurate radial-velocity measurements, similar to the way for the iodine cell technique; (ii) a pinhole used for calibration purposes; (iii) an AO fiber for MACAO calibrations; (iv) an Uranium-Neon (UNe) Lamp for wavelength calibration. This carriage has also a free position, with no optical element.

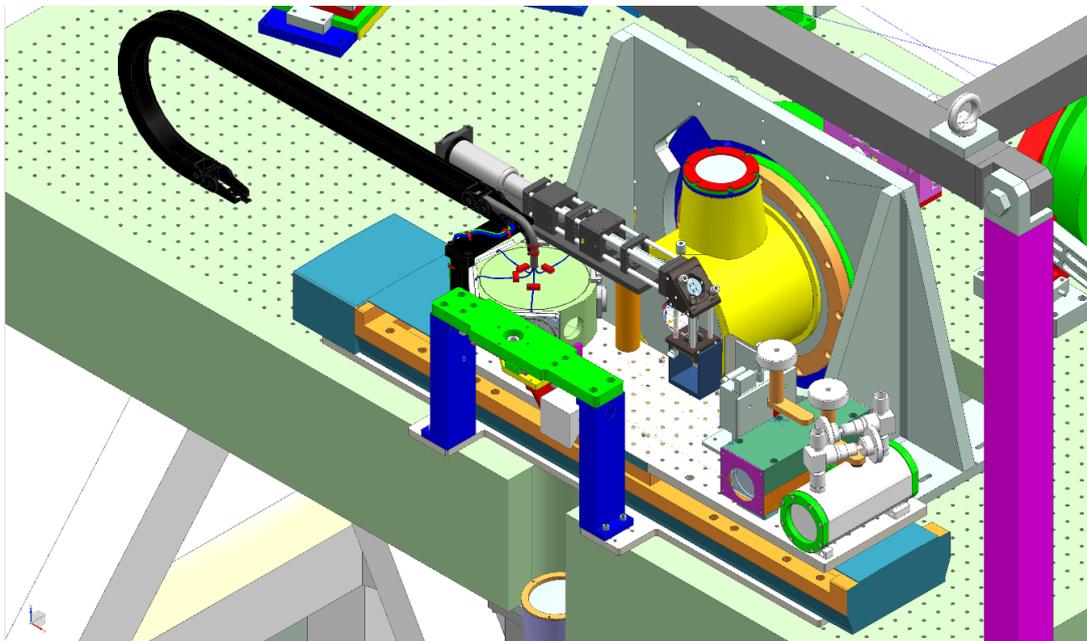


Figure 16: Calibration carriage stage assembly.

3.2.3.1 Gas cells

The CRILES science cases also demand specialized, highly accurate wavelength calibration techniques. Therefore, another part of the upgrade is concerned with the installation of novel IR absorption gas cells with multi-species gas fillings (NH_3 , $^{13}\text{CH}_4$, C_2H_2). These gases will provide a set of densely distributed absorption lines imprinted on the stellar spectra in the *H*- and *K*-bands (see Figure 17). In addition, the existing Thorium Argon hollow cathode lamp is replaced with similar Uranium-Neon lamp that produce a richer wavelength calibration spectrum.

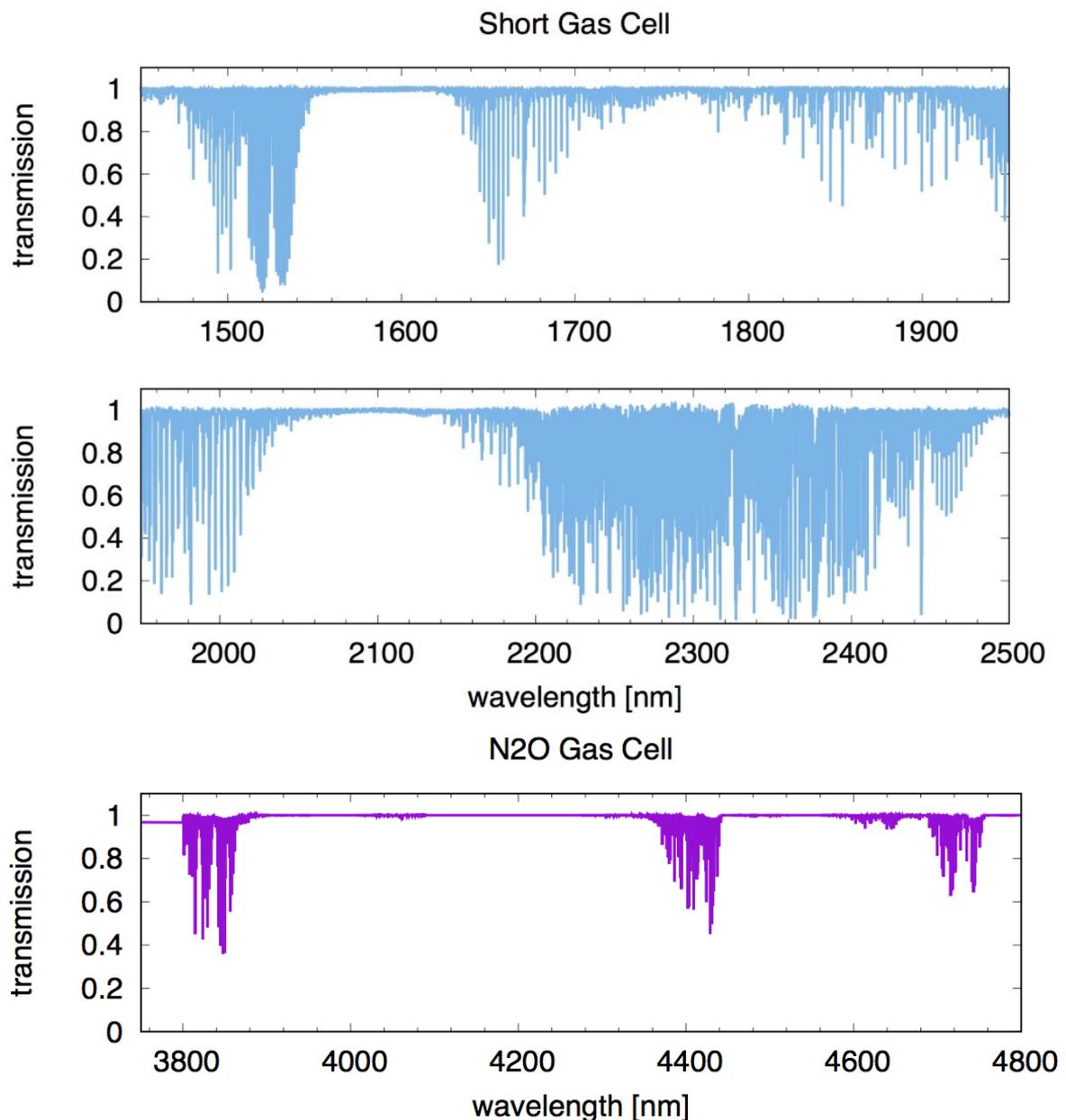


Figure 17: Spectral coverage of the new short gas cell (SGC) in the H and K bands (top) and the N_2O gas cell in the L and M bands (bottom).

3.2.3.2 Fabry Perot Etalon System

An etalon for CRIRES is an addition that was recommended during the design reviews. Such an additional wavelength calibration device mitigates shortcomings of other devices such as the hollow cathode lamp. A Fabry-Perot etalon (or Fabry-Perot interferometer, FPI) can be used to create a periodic signal in frequency space by means of interference. Each of these fringes serves as a reference marker to tackle the wavelength calibration. For this purpose, a continuum light source with a feature free, flat broadband spectrum is coupled to a Fabry-Perot cavity, where interference is produced (see Figure 18). The choice of cavity length and the properties of the cavity's windows/mirrors (finesse, F) determine the peak separation (free spectral range, FSR) and the line strength (sharpness, contrast). The FSR and contrast can thus be tuned and optimized to match the spectrograph's resolving power, sampling, and wavelength range.

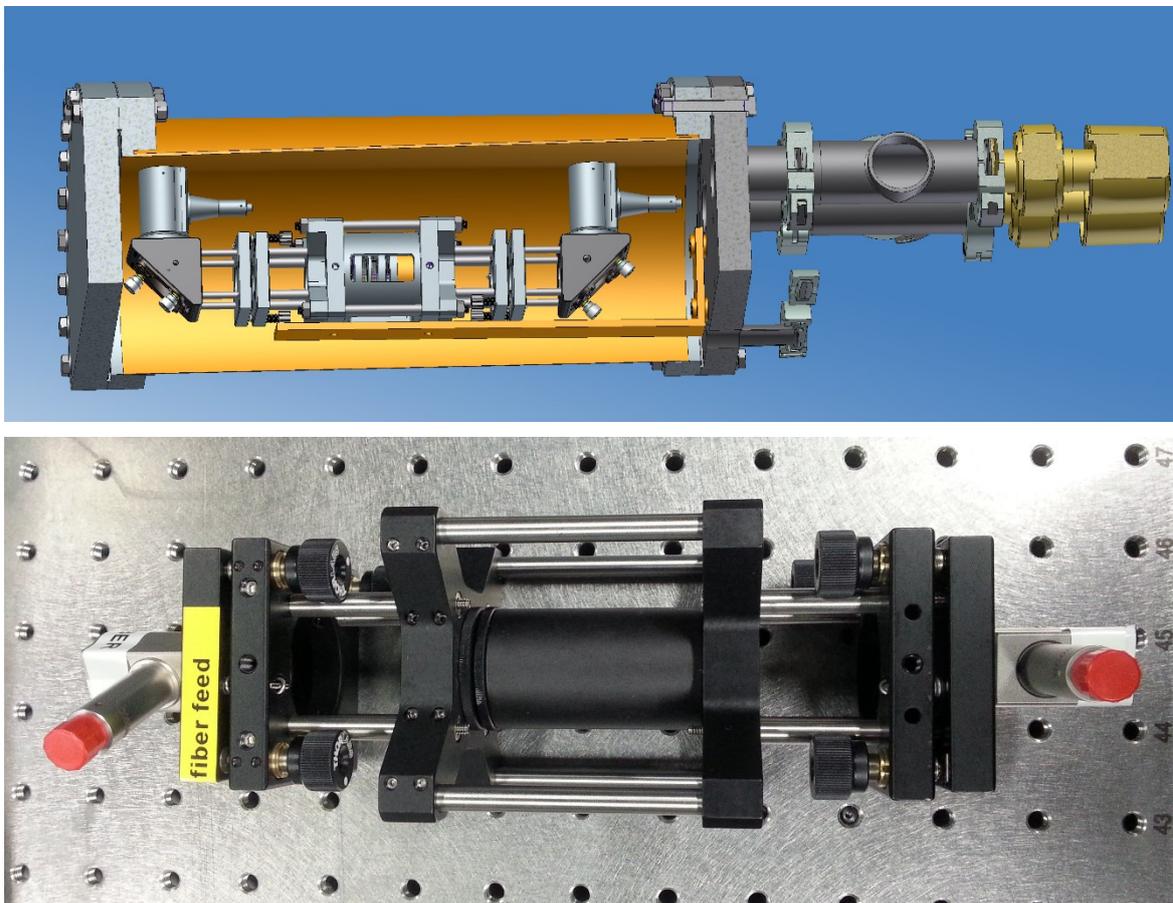


Figure 18: Top: 3D Model of the FPI system in the vacuum chamber (cut view). The vessel layout and gauges are also shown. Bottom: Simplified working proto-type FPI unit.

The major advantages are comb-like, equidistant reference lines over the design range with high homogeneity, equally strong spectral features, thus homogeneous line contrast, broadband coverage with no gaps and a high line density. The FPI subsystem comprises a sealed vacuum vessel, standard ESO vacuum pump and a halogen light source. The vessel is pressure tight. Sub-atmospheric pressure is achieved by daily pumping (duration ~ 30 mins) to $\leq 10^{-3}$ mbar, this pumping process is independent of the main spectrograph cryo-vacuum subsystem. An interlock valve closes the FPI chamber in case of pump failure. All three components are secured on a bench in the base of the warm structure as illustrated



in Figure 8. As can be seen, the base is attached to the warm structure, not directly to the Nasmyth platform. The FPI feeds a fibre which delivers the FPI spectrum to the integrating sphere. The calibration system is described in more detail in articles by Seemann et al. (2014, 2016 and 2018).

3.2.3.3 Summary of the calibration sources

Table 1: Summary of the different calibration sources available for CRIRES

Type	Principal use	Location	Notes
(Atmospheric lines)	Wavelength calibration	Sky	L & M band where the lamps have few lines and continuum
Halogen lamp	Flat Fields (YJHKLM)	Integrating Sphere	Extended spectrum/black body, temperature: 3000-3100K. Can be attenuated with the baffle.
IR black body source	Flat Fields (LM)	Integrating Sphere	Extended spectrum/black body, temperature: 1100-1150K. Can be attenuated with the baffle. Not a part of routine flat field calibration during P108
Krypton & Ne pen-ray lamps	Metrology	Integrating Sphere	Sparse spectral features, which however provide an easily reproducible uniform illumination of the entrance slit for metrology. Can be attenuated with the baffle
He-Ne Laser	Alignment, health checks on resolution	Feeds Integrating Sphere	Dual wavelength 1.1526 μ m and 3.3922 μ m. Coupled to an IR fibre that will transmit both lines that feeds the IS.
U/Ne HCL	Wavelength calibration	On carriage	Dense spectral features up to K-band. Illuminates the entrance slit uniformly.
U/Ar HCL	Alignment tool	Feeds seven "metrology fibres"	Originally intended for use with metrology but no longer part of routine operations. Still a vital alignment tool that bypasses the cross-dispersion.
New Gas-Cells	Wavelength calibration	On carriage	Customised mixture of Ammonia, Acetylene Methane-13. Uniform set of absorption lines in the range of CO band.
Fabry Perot Etalon	Wavelength calibration	Under warm optics table, feeds Integrating Sphere	Frequent, regularly spaced, reference wavelength features with uniform dynamic range from Y- to K-band.

3.2.4 The Spectro-Polarimetry Unit (SPU)

The new polarimetry module (see Figure 19) for CRIRES will use polarizing gratings (PGs) to split the incoming converging beam into left- and right-circularly-polarized beams that continue along parallel optical axes. The choice of PGs as polarizing elements is motivated by their different behaviour at short and long wavelengths, their small thickness, the possibility of producing large and homogeneous samples, and their modest price. The geometry of the periodic pattern that makes up the PGs is chosen such that infrared light (with wavelength longer than 1 μm) is deviated, while optical light is transmitted essentially unaltered. Thus, the PG acts as a polarizing beam splitter for circular polarization without disturbing the operation of the AO system as described by Lockhart et al. (2014). The polarimetric unit is very compact and is installed on CRIRES calibration slide (see Figure 16).

The polarization unit includes two circular polarisation beam-splitters for YJ and HK bands and two beam-splitter for YJ and HK bands combined with an achromatic quarter-wave retarder plate (QWP) for the linear polarization.

Two types of PGs are used for the CRIRES SPU:

- HK PGs with a wavelength limits band from 1480 nm to 2540 nm
- YJ PGs with a wavelength limits band from 960 nm to 1360 nm

The gratings are mounted on a rotating turret capable of carrying the two circular and two linear beam-splitters each pair. Each beam-splitter unit includes two optical elements (polarising gratings) and a rotating stage needed for beam switching. The rotation axis is parallel to the axis of the incoming beam. It allows the positions of the two output beams to be switched enabling calibration of the difference in throughput for the two beams.

NOTE: No Spectro-polarimetric observations are offered in P108

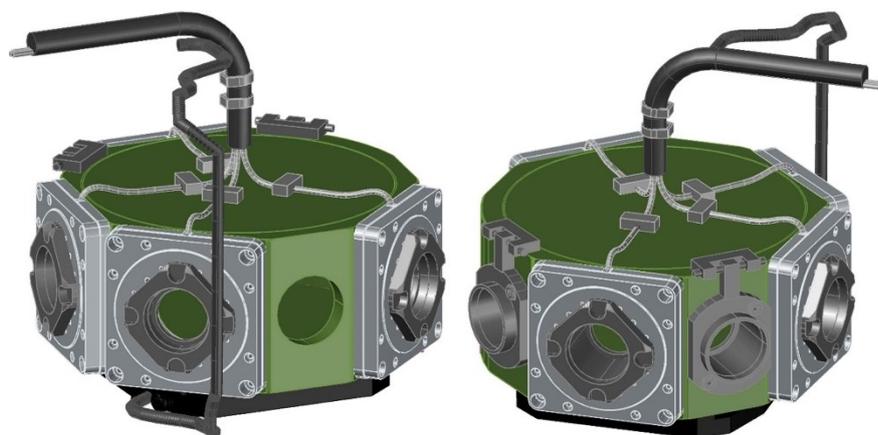


Figure 19: Spectro-Polarimetry Unit (SPU) view from the derotator side (left) and from the telescope side (right). Polarization optics are mounted from the side of rotating turret.



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4. Instrument Performance

4.1 Overview

The sensitivity of the instrument from K up to L and M bands is limited by the thermal background, whereas by the detector performance from Y, J and H bands. In the thermal background regime, observations benefit from the high resolving power of CRIRES as telluric features are better removed compared to spectrographs at lower resolution.

Based on data collected during the first and second on-sky commissioning runs, as well as in the integration hall in Garching:

- Spectral resolution of $\sim 40,000$ and $\sim 80,000$ can be achieved with slit width of $0.4''$ and $0.2''$, respectively.
- The throughput is $\sim 15\%$ higher when compared to the oCRIRES.
- In Y, J, H and K bands, an absolute wavelength repeatability < 5 px (RMS) in the main dispersion is reached without the metrology system, and < 0.3 px when the metrology is enabled. In L and M bands, the absolute wavelength repeatability is of the order of < 10 px.

4.2 AO performance

The performance achieved by the MACAO system of CRIRES has been evaluated by laboratory simulations comparing two cases: *i*) in close loop with guide star of various magnitudes and, *ii*) in open loop (i.e., without AO correction). The optimization was done over the encircled energy on a $0.2''$ slit, representative of the available energy of the spectrograph. Lab results have been confirmed by on-sky measurements and demonstrate some gain in J (i.e., more than 40% for an optical seeing of $0.6''$) and a strong increase (i.e., factor of ~ 2) of the fraction of energy available for the spectrograph in K and M band, respectively (see Figure 20).

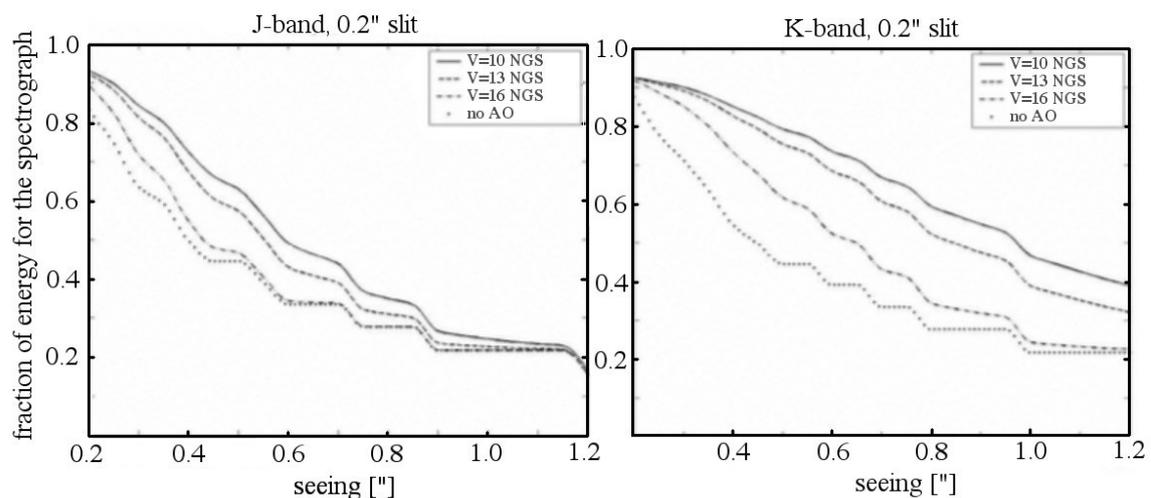


Figure 20: The fraction of energy available for the spectrograph in a $0.2''$ slit as a function of the optical seeing is shown for the J (left) and K (right) band for NGS of $V=10, 12, 16$ mag and without AO correction. For reference, please consult the ETC.

For seeing $>1.4''$, the AO correction becomes very poor and unstable and will not result in any improvement with respect to the No AO mode. Therefore, AO observations are not allowed under Phase 1 Turbulence Category of 100% (see 5.2.1 for more details on the user constraints).

Because the AO correction degrades with airmass, we suggest observing at rather low airmass (≤ 1.4).

Figure 21 illustrates the increased throughput when the AO system is employed. The graph shows the spatial profiles of the spectrophotometric star Pi.02 Ori ($R=4.29$) at a wavelength of 1559.245 nm taken in atmospheric condition corresponding to Turbulence category = 50%, in open and closed loop. In both cases, the exposure times were the same; however, in closed loop a flux level being about 1.8 times higher was attained than in the open loop observations.

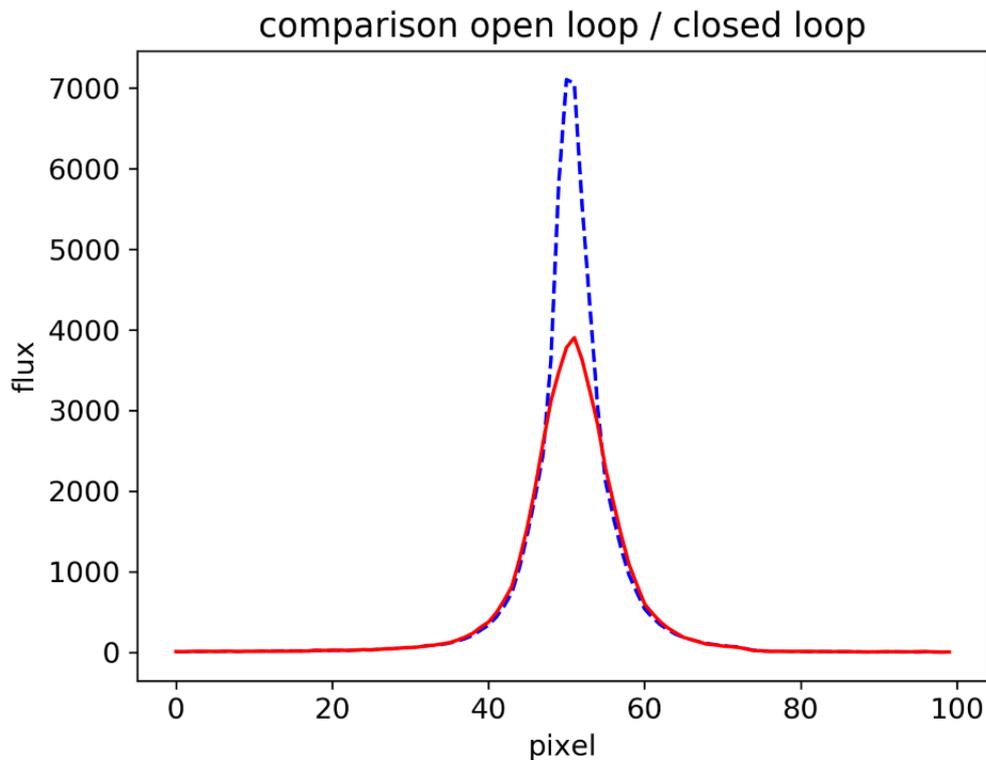


Figure 21: Improved throughput thanks to the use of AO. H-band flux of the star Pi.02 Ori measured along the $0.4''$ slit in open loop (solid red line) and closed loop (dashed blue line).

4.2.1.1 AO guide stars

CRIRES wavefront sensing is done in the R band. The performance of the AO system depends on the distance to the science target and on the brightness of the selected guide star (NGS). The loop may be closed on non-stellar objects such as the surface of Mars or the nucleus of comets, although in these cases NoAO is often used (for example, for a diffuse comet nucleus).



4.2.1.2 The distance of the AO natural guide star

Although nominally the field selector allows the selection of the AO NGS star within 25" from the nominal position of the science target, the AO NGS star should be as close as possible to the scientific target, usually closer than 10": ideally, it is the science target itself. Depending on the atmospheric conditions, in particular, on the isoplanatic angle, θ_0 , mild improvement in the amount of encircled energy can still be obtained if a bright ($R < 11$) AO star is used 20-30" from the scientific target. Targets further away than 20" from the main target will need a waiver. This is for the simple reason that the vignetting of the AO system more than 20 arcseconds from the slit centre is not symmetric.

It is important to recall that the isoplanatic angle decreases with the zenith distance z as $\theta_0 \propto (\sec z)^{-8/5}$ and increases with wavelength as $\theta_0 \propto \lambda^{6/5}$. On the other hand the Strehl Ratio decreases with the angular distance to the AO star θ as $SR \propto \exp(-(\theta/\theta_0)^{5/3})$.

NOTE: during P108 observations in NGS mode are allowed only if the target is also the NGS (i.e., only on-axis AO correction)

4.2.1.3 The brightness of the AO star

The intra- and extra-focal pupil of the AO star is imaged on a lenslet array. Each lenslet feeds an APD that ultimately forwards its signal to the RTC. The flux on an APD is limited to 1 million counts in order not to damage the devices. The optimal brightness of the AO star is $R \sim 11$ mag. Brighter stars up to a bright magnitude limit of $R \sim 0.2$ mag can be dimmed using neutral density filters. Depending on the B-R colour, some stars with slightly brighter R magnitude can be used. Good correction is still obtained with stars as faint as $R \sim 14$ mag under good seeing conditions, while moderate image quality improvement may be seen with stars as faint as $R \sim 15$ mag under very good seeing (0.6") and coherence time (5.2 ms). Stars fainter than $R \sim 15$ mag will not result in any improvement and NoAO should be used, indeed the loop will not close on these targets.

Therefore, the allowed NGS magnitude range is: $0.2 < R < 15$ (see 5.2.1 for more details on the user constraints).

4.2.1.4 The colour of the AO star

The B-R colour is important for precise atmospheric refraction compensation. The AO system takes into account the differential atmospheric refraction between the wavelength used for the AO and the central wavelength of the spectrograph setup in the calculation of the tip-tilt mirror orientation. A correct B-R is crucial for accurate centring of the target in the slit for airmass > 1.2 when guiding with the slit viewer is not possible, as for example, if the AO star is outside the field-of-view of the slit viewer detector.

4.3 Detector characteristic

The focal plane of CRIRES is equipped with three 2048 x 2048 pixels Hawaii 2RG detector arrays (6144 x 2048 in total) and a pixel size of 18 μ m (see Figure 6).

The exposure time is set by the two following parameters: the detector integration time (DIT) and the number of such integrations (NDIT) to be averaged into one single exposure, whose total integration time is therefore $NDIT \times DIT$. The minimum DIT is 1.427s.

The flux level of a pixel always corresponds to an exposure time of one DIT. If $NDIT > 1$, the reading process is repeated NDIT times and the values for a given pixel are averaged. Therefore, the saved value always corresponds to an exposure time of one DIT. If the number of exposures (SEQ.NEXPO) is larger than 1 in the template, each individual exposure is saved independently.

The optimum combination of DIT and NDIT should be determined with help of the Exposure Time Calculator (ETC, see 5.3). Bright objects or observations in the L or M bands (high sky background) require short DITs to avoid saturation; in particular, heavily saturated spectra lead to detector remanence that affects subsequent observations.

Because the only offered detector read-out mode is the Sample Up The Ramp (DET1.READ.CURNAM = New_RR_UpTheRamp), users must supply only the required DIT, the read mode software then determines the minimum number of read frames that can be fitted into the specified time. As shown in Figure 22, before each integration, the pixels are reset to the initial capacity. During the integration, the detector is non-destructively read (from two readings in case of the minimum DIT up to a maximum of 36 readings for long DITs). These detector readings are equidistantly spaced in time. The flux rate per pixel corresponds to the slope of the flux values of the subsequent readings.

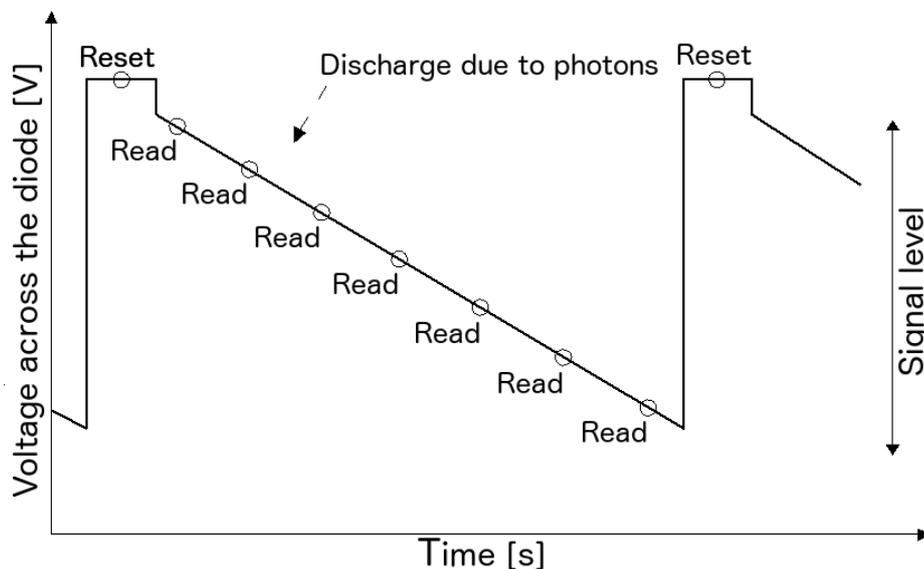


Figure 22: Sample Up The Ramp read-out mode

4.3.1 Dark and gain

The dark current is estimated from the slope of the signal (in ADU or e-) as a function of the integration time (s) for the linear region.



Figure 23 shows the dark current of detector #3 measured in K band. The thermal background is of the order of 0.05 e-/px, making the instrument about 33 times darker than the oCRIRES.

A summary of the science detector characteristics is provided in Table 2.

Table 2: Summary of science detector parameters

Parameter		DETECTOR 1	DETECTOR 2	DETECTOR 3
Serial Number		SN17308	SN17306	SN17310
Dark current [e-/s]		0.03	0.03	0.03
Thermal background [e-/s]		0.05	0.05	0.05
Gain [e-/ADU]		2.28	2.19	2.00
Quantum Efficiency @2000nm [%]		93	98	95
RON [e-RMS]	DIT<40s	11	12	12
	DIT>40s	6	6	6
Saturation [ADU/px]		37000	37000	37000
Non-linearity [ADU/px]	1%	6000	6000	6000
	5%	18000	18000	18000
	10%	29000	29000	29000
Operating Temp [K]		35±0.005	35±0.005	35±0.005

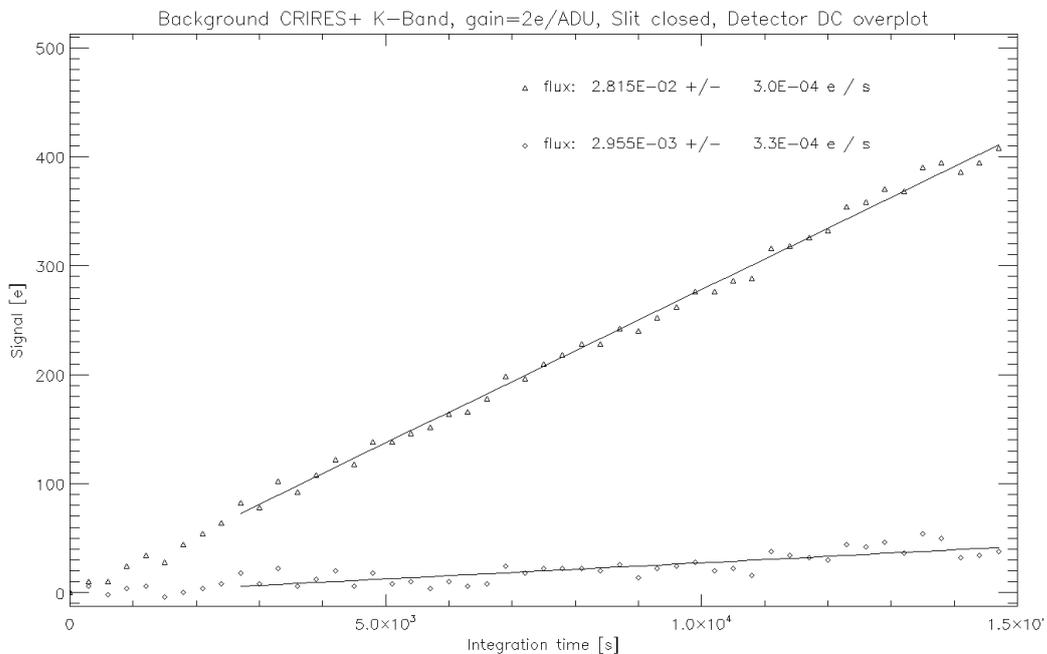


Figure 23: Dark current of detector #3 measured in K band

4.3.2 Correcting for detectors non-linearity

All common IR detectors suffer from non-linearity effects. In the case of CRIRES, deviation from linearity is of the order of 5% of the detected flux at about 18k ADUs and increases with flux. However, the CRIRES pipeline is able to correct for non-linearity effects at low-, medium- and high- count levels (see Figure 24).

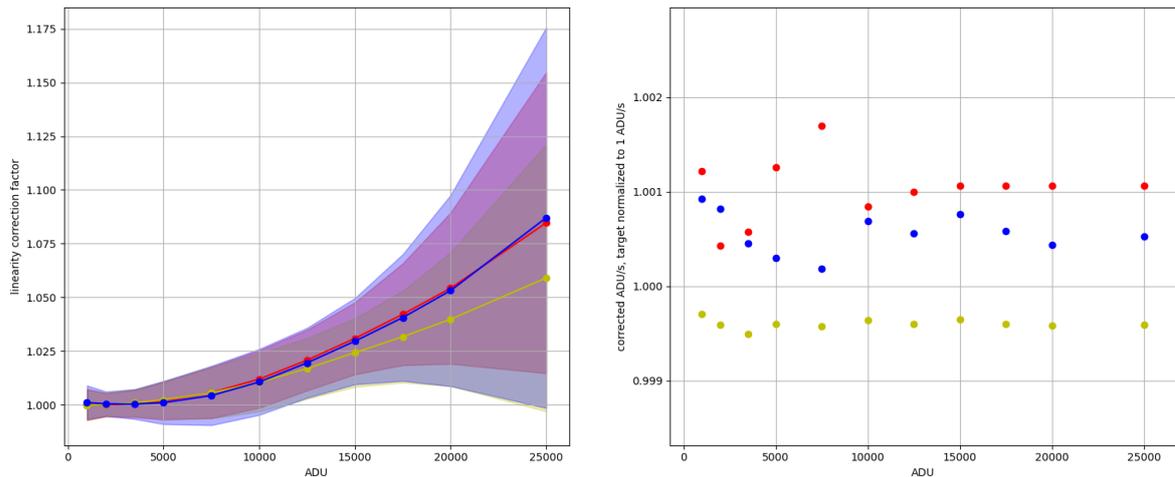


Figure 24: Correction for non-linearity effects implemented by the pipeline. *Left*: correction factor from the polynomial fits (pixel-by-pixel), evaluated at certain ADU-levels and plotted as medians and 1-sigma shaded regions over all pixels. Detectors 1,2,3 in red, yellow, and blue respectively. *Right*: Normalized ADU/s as measured from the frames corrected for non-linearity. For the three detectors, the median over the bins in ADU-level is given.

4.4 Characteristic of the spectrograph

4.4.1 Slit viewer camera field of view

Target centring and NGS acquisition are performed in the NIR via the Slit Viewer camera (SV). Because CRIRES observations require the use of a guide star (SVGS) to ensure that the target is properly kept centred along the slit during the science exposures, the SVGS is also acquired through the SV camera.

With a pixel scale of 37.3 mas, the SV covers a maximum unvignetted sky projected field of view (FoV) of 22.8" x 33.8". 33.8" along the slit and 22.8" perpendicular to the slit, thus making the available FoV slightly smaller than that of the old CRIRES instrument. The position of the slit within this window is off-centred by 3.6" towards West, and 0.2" Northwards, as illustrated in Figure 25, to increase the allowed maximum separation between the target and the SVGS. When the target is also used as SVGS, guiding will be performed using the light reflected off the slit viewer window around the slit. CRIRES also utilises a de-rotator to control the alignment of the slit relative to the sky (namely to compensate for field rotation in the Nasmyth focus) or to align the slit with the parallactic angle so as to reduce slit losses. Finally, it is worth noticing that when the 0.2" slit is used,

the footprint of the 0.4" slit vignettes an area of 0.4"x10" about 8" Eastward with respect to the slit centre (see dark vertical strip in Figure 25).

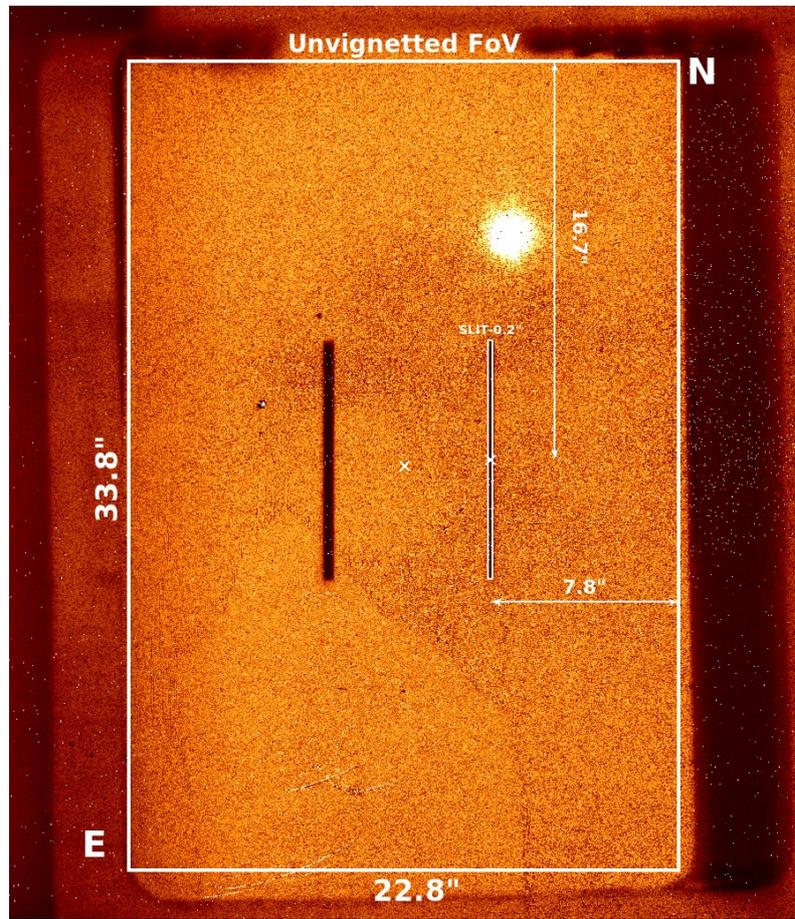


Figure 25: Geometry of the SV detector for PA of 0 deg on sky. North is up and East on the left. The un-vignetted FoV usable for target acquisition and guiding is ~22.8" x 30.8". The centre of the usable FoV and of the slit is marked as white cross. The slit centre (0.2" in this example) does not match the un-vignetted FoV centre, but it's displaced by 3.6" W and 0.2" N. When using the 0.2" slit, the footprint of the 0.4" slit vignettes an area of 0.4"x10" located ~3.6" Eastwards with respect to the FoV centre (see vertical dark stripe). When the 0.4" slit is used, there is no vignetting from the 0.2" slit as its footprint falls at the border of the FoV.

4.4.2 Slit viewer limiting magnitude

The SV is equipped with 5 NIR filters: J, H, K and 2 neutral density H filters.

The SV is sufficiently sensitive that any emitting point source for which one aims to obtain a spectrum should be seen on the SV image. In particular, in AO mode, stars of $H \sim 15$ are easily detected in a 10 s exposure, a typical time scale for guiding. In NoAO mode, $H \sim 15.5$ stars are barely detected (3σ) in a similar 10s integration under 0.9" seeing when located away from the slit.

For guiding on target (TRG=SVGS), the limiting magnitude is much brighter as only a small fraction of the light is reflected by the slit jaws to the slit viewer detector. During the on-sky

commissioning run, under excellent conditions (0.5" seeing) and a slit of 0.2", reasonable guiding was possible with stars of H=14.5 and 13.5 in NoAO and NGS mode, respectively.

NOTE: Observations in P108 are offered only if the target can be used also as SVGS (i.e., no off-target guiding is allowed)

4.4.3 Wavelength settings

The introduction of the cross-disperser increases the single-exposure wavelength coverage of CRIRES by about a factor of 10 compared to oCRIRES, but CRIRES is still incapable of covering a single photometric band in a single exposure without any gaps. By varying the echelle angle and choice of cross-disperser grating, CRIRES is able to fully cover each YJHKLM photometric band (e.g., see Figure 26). The number of exposures depends on the particular band, but fewer exposures are required to cover the shorter wavelength regions. Additional exposures are necessary to cover detector gaps. Similar to the standard settings offered with oCRIRES, the upgraded CRIRES provides a list of fixed wavelength settings to the users. All settings are handled by the Data Reduction Software (DRS). No free settings are offered.

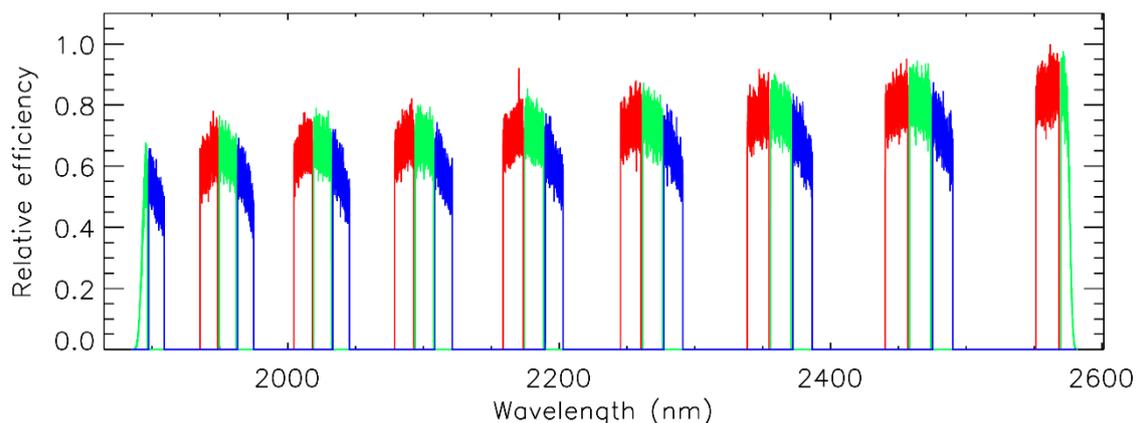


Figure 26: A 1D extraction of the flat-field image indicating the spectral coverage achieved for a single echelle setting, obtained in a single exposure (K-band, echelle angle=65.5). The three different detectors are colour-coded differently.

To reduce the total number of fixed settings offered by CRIRES, the number of settings per photometric band were optimized to provide the best overall throughput per band (in individual and combined images), with the least number of echelle settings needed to provide for gap-free coverage. This strategy reduces the total number of settings that need to be offered to the user, which helps reducing operational overhead and time needed for calibration. In addition, it also removes the need for additional interlaced settings, which were offered with oCRIRES to fill in detector gaps.

One of the goals of the CRIRES upgrade is to achieve a minimum of 80% coverage of the photometric band in the region of operation. In most cases, the expected coverage is much wider. However, as the height of some orders may not be fully covered, the spectral coverage for point sources (at the centre of the slit) differs from the spectral coverage achieved with extended sources that require full slit illumination. Table 3 provides a list of the achieved coverage (using multiple exposures) for each photometric band.



The new adopted naming convention is given by the central wavelength of the corresponding setting (see column 1 of Table 13). Depending on the science template and the observing strategy, observations are carried out before moving to a new fixed setting (e.g., all nodding positions will be done per setting first; a full polarimetric sequence is carried out before moving to a new setting). A total of 29 different settings is required to cover the full operating range of CRIRES. Further details on the offered wavelength settings can be found in §7.2

Some small wavelength gaps cannot be probed with CRIRES due to design decisions to optimise the throughput in the regions of interest. The ranges include the following: 1356-1423nm, 1854-1908nm, and 2527-2725nm (the gaps are larger if full slit illumination is considered). These regions are dominated by telluric lines and are not of general interest for most science cases.

Table 3: Approximate spectral coverage achieved within different photometric bands.

Band	Spectral coverage of photometric band		Spectral coverage of point source (middle of slit)		Spectral coverage for full slit	
	Starting λ (nm)	Ending λ (nm)	Starting λ (nm)	Ending λ (nm)	Starting λ (nm)	Ending λ (nm)
Y	955	1120	948	1120	948	1120
J	1100	1400	1116	1356	1116	1331*
H	1500	1800	1423	1854	1461	1796
K	2000	2400	1908	2527	1946	2472**
L	3200	3700	2810	4150	2840	4100
M	4600	5000	3340	5800***	3360	5600***

*1356nm 85% of slit; **2501nm 75% of slit; *** The detector cut off is 5300nm

4.4.4 Wavelength calibration

The problem of wavelength calibration can be approached by using different methods according to the required accuracy. For an accuracy corresponding to ~3 pixels, the start and end wavelengths and the derived dispersion for each detector is sufficient.

If present in the raw data (i.e., settings below 2500 nm), either emission or absorption sky lines can be used to improve the absolute wavelength calibration. The presence of sky lines in the desired wavelength setting can be checked by using the ETC.

The density of lines provided by arc lamps is usually small in the IR regime, However, Uranium-Neon lamp can provide a large number of lines up to ~2500 nm.

Alternatively, the use of gas cells (i.e., SGC or N₂O, see 3.2.3.1) should be considered for high precision wavelength calibration.

4.4.5 Flat Field

Flats field exposures are taken with the Halogen lamp. Once the user specifies the required NDIT and the maximum flux, the DIT and NDIT is automatically determined by the template.

There is a priori no need to take flat fields at night-time, as the detector characteristics are sufficiently stable in time, and the spectrograph wavelength setting sufficiently accurate. However, flat fields may be important for very accurate radial velocity measurements.

Flat-fields part of the calibration plan (see Section 7.1) have a SNR per pixel larger than 200 at the peak efficiency of a given setting.

Users requiring flat fields with larger SNR should indicate this in the ‘Special Calibration’ section of the proposal form or contact [USD](#) when preparing the observations.

4.4.6 Spectrograph Field-of-View, slit width and seeing

The FoV of the spectrograph is *slit width* x 10". The appearance of a spectrum on the science detectors mosaic is shown in Figure 27. The pixel scale of the science detector is 59 mas.

A slit width of 0.4" offers a close to maximal throughput in most AO observations.

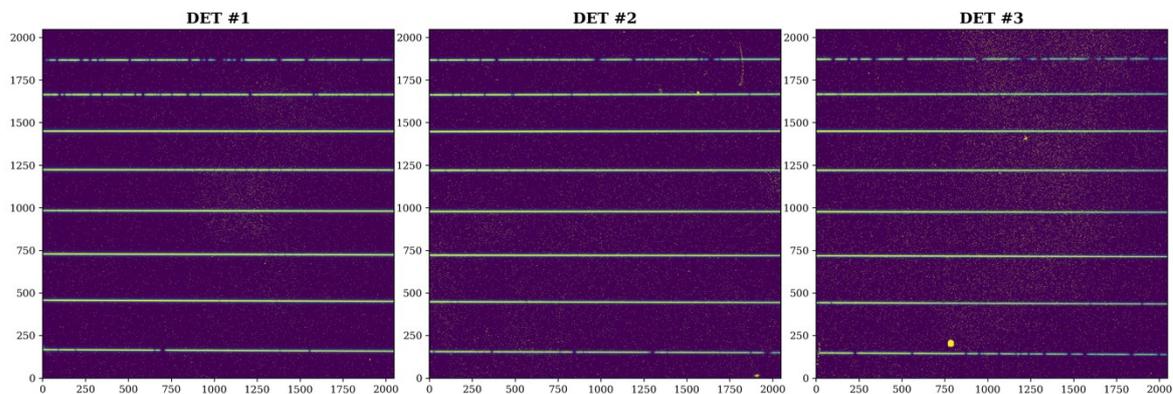


Figure 27: Illustration of the science detectors mosaic (H1582 setting).

4.4.7 Spectral resolving power

Spectral resolving power for the 0.2" slit measured during commissioning was significantly less than the expected $R=100,000$. There is some (expected) variation with echelle grating angle and $R>100,000$ has been measured in some configurations. Nevertheless, for P108 users should not expect $R>80,000$. Full characterisation of the issue is ongoing, and several options exist for recovering the expected spectral resolution.

4.4.8 Radial velocity precision

The short gas cell (SGC) provides a stable long-term wavelength reference in the H and K bands. For a S/N of 150 per spectral pixel in the spectral continuum, an RV precision of 3 m s^{-1} is expected to be attained by employing the short gas cell (SGC) as a simultaneous wavelength calibrator in the K-band with the 0.2" slit (i.e., $R\sim 100,000$). Note that the actual error of the RV measurements will depend on factors like the number of stellar absorption lines observed and broadening due to the stellar rotation.

If a lower RV precision is sufficient, users can make use of the telluric absorption lines of Earth's atmosphere as a simultaneous wavelength reference. In most wavelength settings, these lines will be imprinted on the science data. Figueira et al. (2010; A&A, 515, 106) demonstrated that telluric lines are intrinsically stable down to 10 m/s (rms).

Without a simultaneous wavelength calibrator, the attainable RV precision will be much lower due to a slow drift of the Echelle grating. During commissioning it was observed that

the drift in dispersion was somewhat higher (~ 0.2 px over 30 min; corresponding to a RV drift of 200 m s^{-1}) following metrology alignment than it was without metrology (0.05 px over 30 min; RV drift $\sim 50 \text{ m s}^{-1}$). Users should keep this in mind when planning to obtain RV measurements with attached wavelength calibrations.

4.5 Throughput

The overall throughput of CRIRES has been measured on the spectrophotometric standard Pi2Ori by using the AO modes and the $0.4''$ slit width.

The total throughput was derived by scaling the observed spectrum, expressed in $e^-/s/px$ and corrected for silt loss, by the theoretical. Figure 28 shows the overall efficiency measured on the observed spectrophotometric standard in four different settings (i.e., Y1029, J1228, H1559 and K2148). The throughput over the whole spectral range can be downloaded from the ETC webpage. The observation of spectrophotometric standards is part of the instrument monitoring plan, and as such the results shown in Figure 28 should be regarded as preliminary.

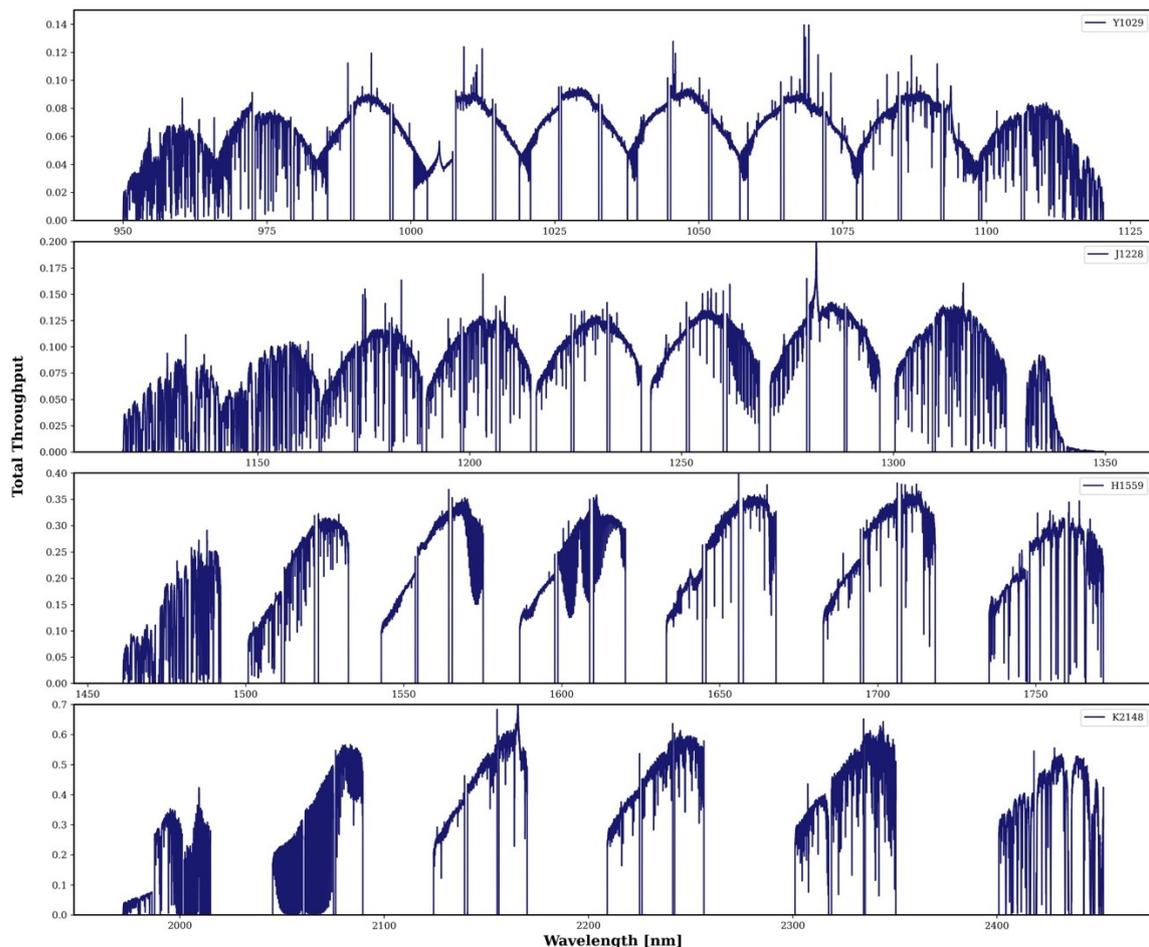


Figure 28: Total observed throughput in 4 different settings. Preliminary results from commissioning run in January 2021



That being said, based on these preliminary results obtained during the commissioning run in January 2021, the throughput is found to be about 10-15% higher than the oCRIRES.



5. PHASE I: Observing Proposal Preparation

5.1 Instrument modes offered in P108

The properties of the CRIRES modes offered in P108 are summarized in Table 4.

Table 4: Summary of the instrument modes

Instrument Mode	Observing Wavelength	Resolution
Spectroscopy (AO and NoAO)	29 settings (950 nm – 5300 nm)	50,000 (0.4" slit) and 100,000 (0.2" slit)

Please note the following restrictions:

- Only on-axis AO observations are offered, i.e., Target = AO Natural Guide Star (NGS)
- AO observations with thick cloud are not allowed
- The NGS star must be in the magnitude range: $0.2 < R < 15$
- Guiding is only allowed on-target, i.e., Target = Slit Viewer Guiding Star (SVGS)
- Observations are offered in stare mode and nodding along the slit
- Observations are offered with sidereal and non-sidereal tracking
- Large and monitoring programmes with CRIRES are not offered

5.2 Phase I: General information and User Constraints

As for all Paranal instruments, there are two Phases (I and II) in the application for time with CRIRES. Phase I starts with the Call for Proposals issued by ESO twice per year. At each call², users must create a proposal with p1, the web-based tool for proposal preparation available at www.eso.org/p1. Using this tool, user is requested to provide both scientific rational and technical details of the proposed observations. In particular, one or more observing runs must be created for any requested instrument and, in some cases, any instrument modes. An observing run is uniquely defined by:

- Requested instrument and telescope
- Type (see §4 of Call for Proposal)
- Telescope time, which includes instrument and telescope overheads (see §5.4)
- Observing constraints set, consisting of Moon phase (see §5.2.3), Turbulence Category (see §5.2.1), atmospheric transmission (see §5.2.2), sky transparency and airmass
- Observing mode: Service or Visitor

² An exception is represented by the DDT proposals, which can be submitted at any time during the observing period (see http://www.eso.org/sci/observing/policies/ddt_policy.html)



- Proprietary time (see <https://archive.eso.org/cms/eso-data-access-policy.html>)
- Time constraint (if applicable)

The selection of the observing constraints set that best matches the scientific goal should be done by using the ETC. Users are strongly encouraged to pay particular attention to the selection of the constraints set at Phase 1 because such request is binding. During Phase II preparation and review only, users are allowed to relax the requested constraints. It is not possible to specify at Phase II constraints more stringent than at Phase I.

Before describing the available features of the CRIRES ETC (see §5.3), we first address some of the most important aspects of near-IR observations that influence the choice of the observing constraints set and the observing strategy, hence consequently the total telescope requested time.

5.2.1 Turbulence Category

As of Period 105, the Phase I seeing constraint (i.e., seeing at the zenith in V-band) has been replaced by the Turbulence Category (TC). For CRIRES NoAO observations, the TCs are defined using the percentiles of the seeing distribution as listed in Table 5.

Table 5: Turbulence categories for CRIRES No AO mode.

Turbulence Category	10%	20%	30%	50%	70%	85%	100%
Seeing (at 500 nm) threshold	0.5"	0.6"	0.7"	0.8"	1.0"	1.3"	all

For CRIRES AO observations, the TCs are defined as combinations of seeing (at zenith in the V-band) and coherence time (see Table 6). AO observations under TC=100% are not possible.

Table 6: Turbulence categories for CRIRES AO observations

Turbulence category	Maximum seeing	Minimum Coherence time
10%	0.6"	5.2 ms
20%	0.7"	4.4 ms
30%	0.8"	4.1 ms
50%	1.0"	3.1 ms
70%	1.15"	2.2 ms
85%	1.40"	1.6 ms

5.2.2 Atmospheric transmission and Precipitable Water Vapour

The transmission of the Earth's atmosphere in the J, H, K, L and M bands is shown in Figure 29.

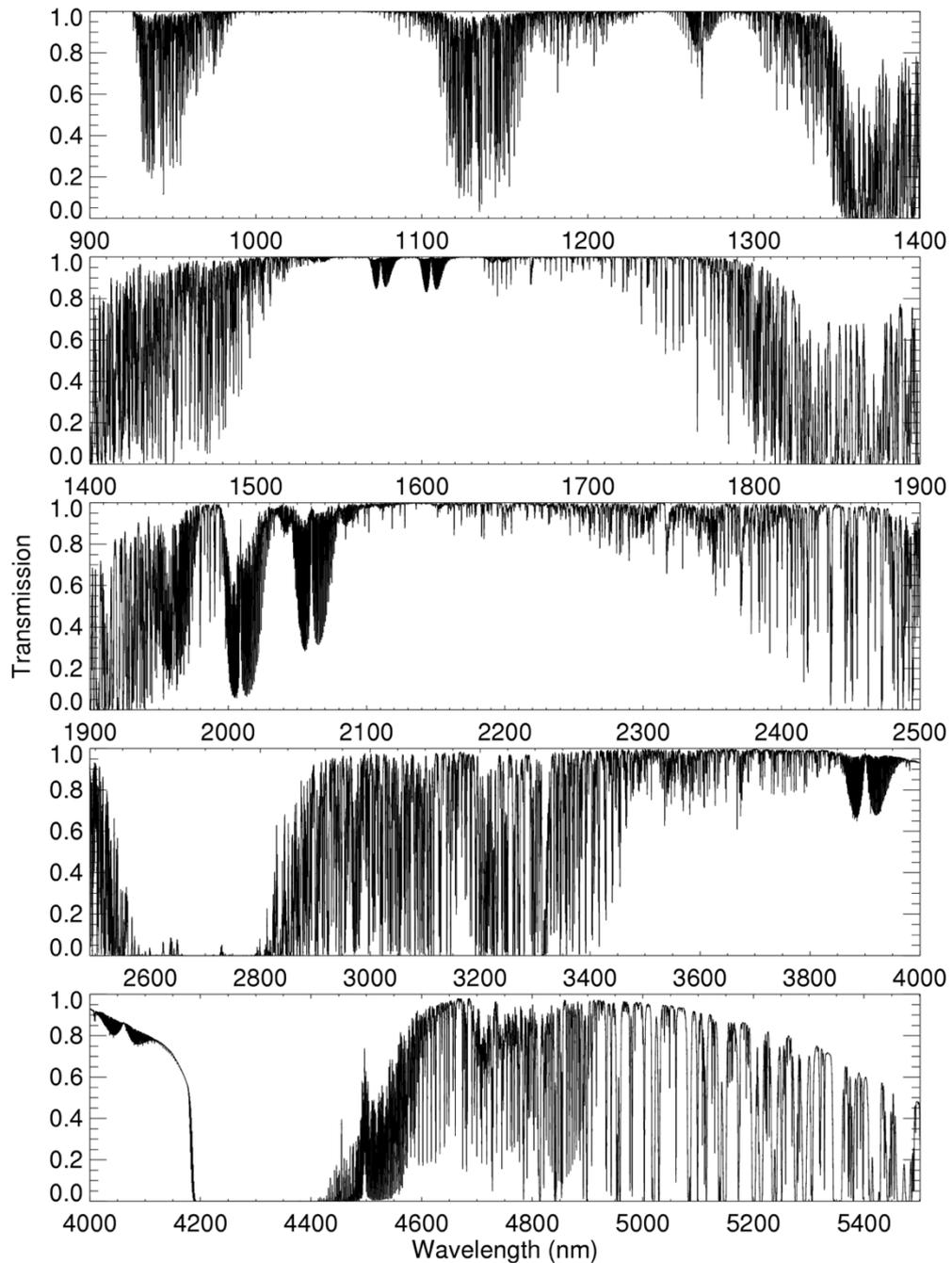


Figure 29: Atmospheric transmission from 900-5500nm computed by PCLnWin/HITRAN for Paranal atmosphere, PWV = 2.5mm, at zenith and smoothed to a resolution of $\lambda/\Delta\lambda = 10^4$.

In order to facilitate the identification of sky regions affected by Precipitable Water Vapour (PWV) lines, Figure 30 shows the atmospheric transmission spectrum only including PWV absorption lines.

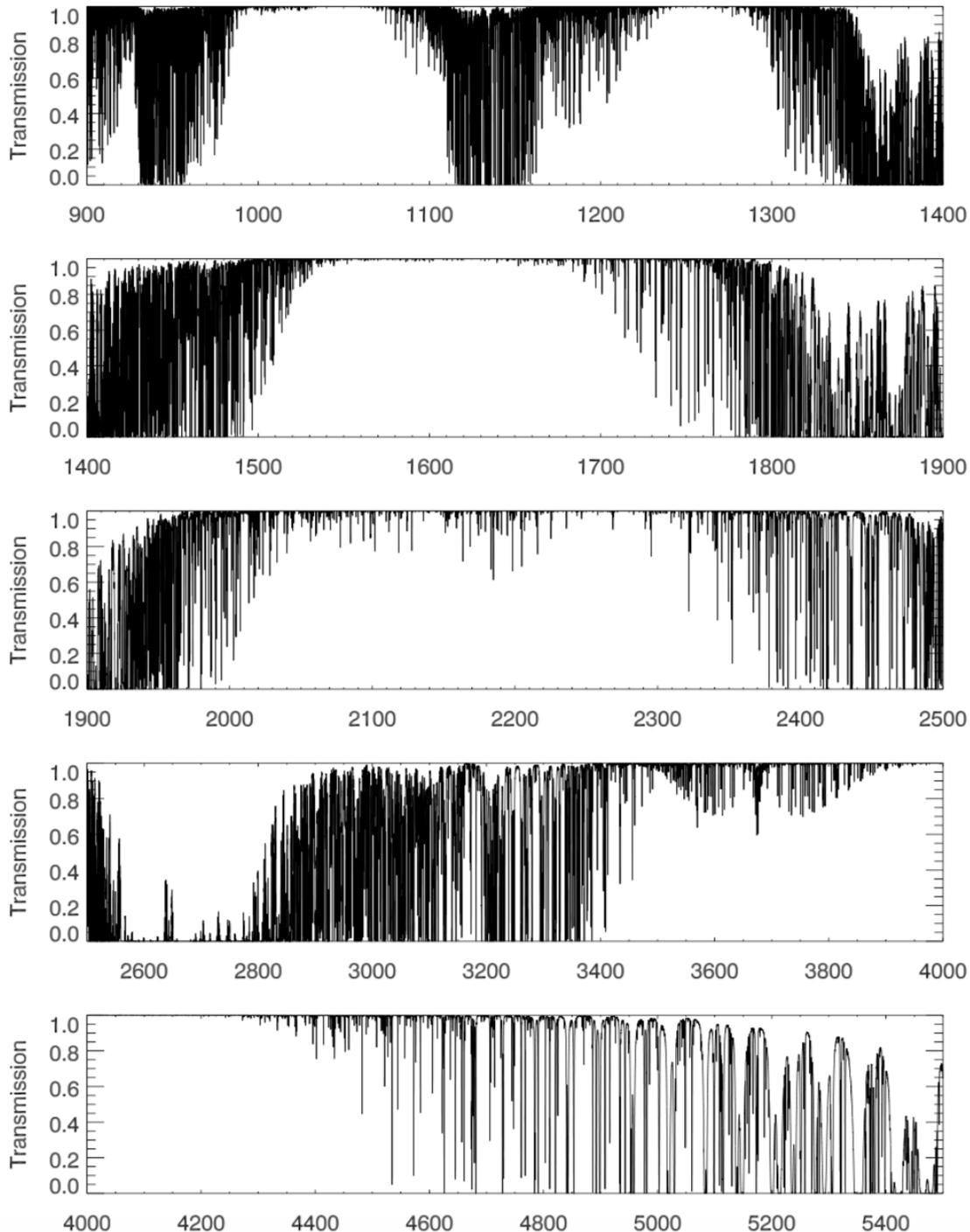


Figure 30: PWV sensitive atmospheric transmission from 900-5500nm computed with RFM/HITRAN for Paranal atmosphere, PWV=2.5 mm at zenith at resolution of $\lambda/\Delta\lambda = 100000$.

It is extremely important that users check if their astronomical lines fall on top of one of these spectral features as their data may be useless if this occurs (see Figure 31).

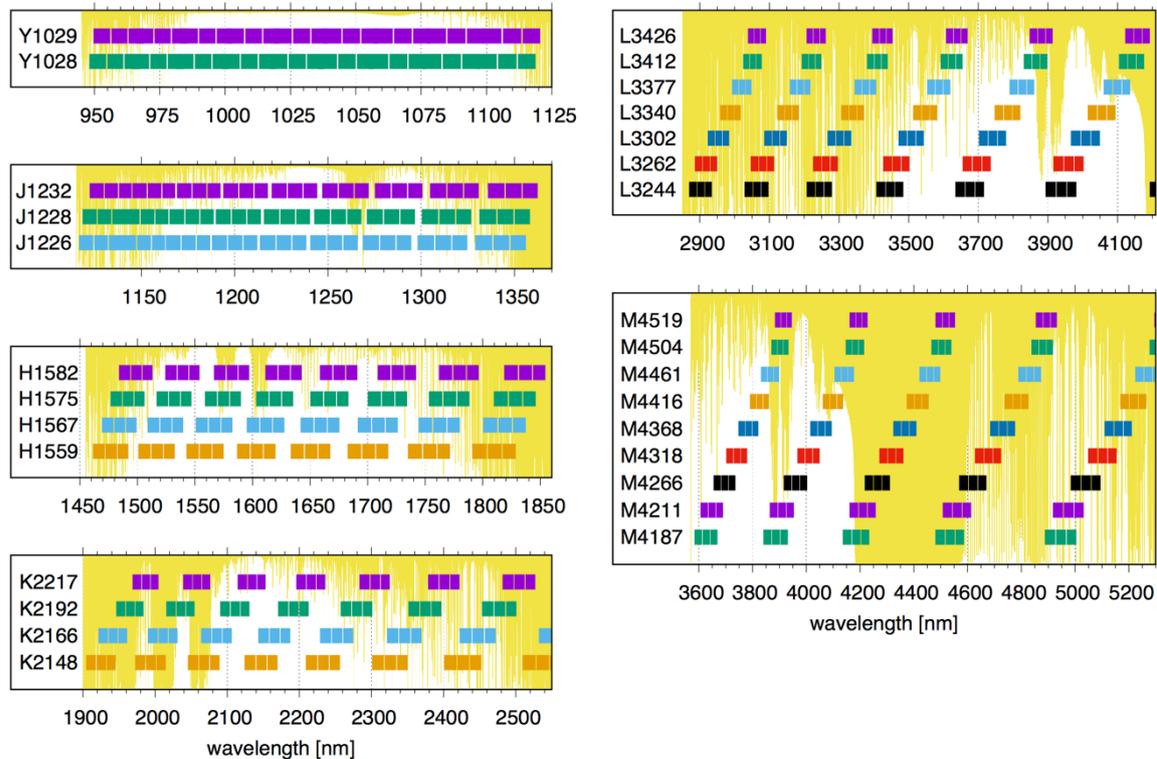


Figure 31: CRIRES wavelength setting coverage compared to the atmospheric transmission. High-resolution version of this figure can be found online (<http://www.eso.org/sci/facilities/paranal/instruments/crises/img/CRIRES-wavelength-settings2021.png>)

The amount of telluric absorption varies non-linearly with zenith distance and PWV (see Figure 32).

The transmission spectrum of the sky for a particular setting is an optional output provided by the ETC, which allows one to select spectra based on different amounts of PWV (i.e., Figure 31). The available values range from a minimum of 0.05 mm to a maximum of 30 mm. The median value of the PWV on Paranal is 2.5 mm.

Note that the PWV is a mandatory user-definable constraint in p1 and p2. For L and M-band observations, we strongly recommend setting the PWV constraint to a value equal or smaller than 2.5.

For any given CRIRES frame, the corresponding PWV is store in the data-fits header keywords TEL AMBI IWV START, while the Phase 2 requested value is available in the keyword HIERARCH ESO OBS WATERVAPOUR.

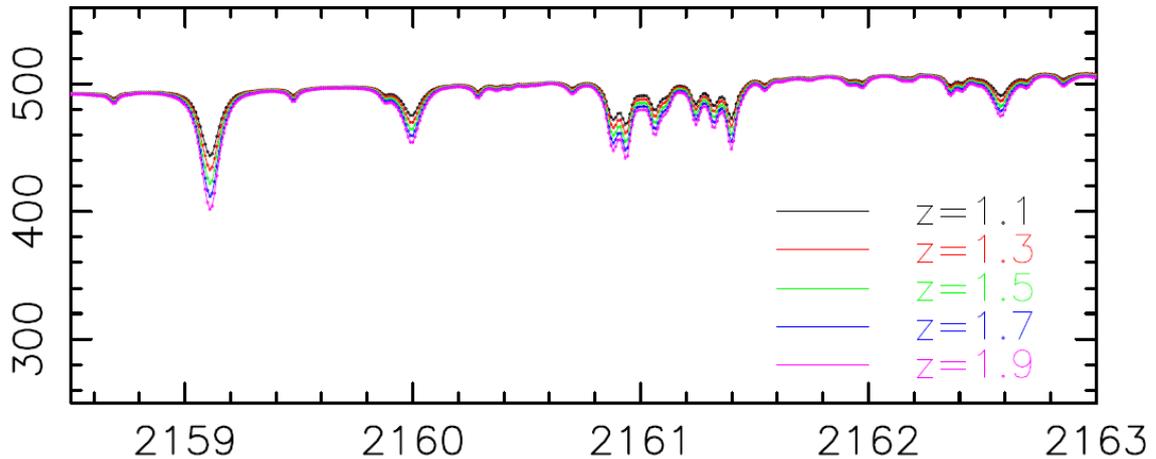


Figure 32: Effect of changes in airmass on PWV absorption produced by the CRIRES ETC.

5.2.3 The influence of the Moon

The Moon illumination (i.e., Fraction of Lunar Illumination, FLI) is defined as the fraction of the lunar disk illuminated at local (Chilean) civil midnight, where 1.0 is fully illuminated. By definition, Moon FLI equals 0 when the Moon is below the horizon on Paranal.

Moonlight does not noticeably increase the background in any of the CRIRES modes, so there is no need to request dark (i.e., $FLI < 0.4$) or grey time (i.e., $0.4 \leq FLI \leq 0.7$). However, it should be avoided to observe targets closer than 30° to the Moon, as this can lead to problems linked with the telescope guiding and active optics correction system.

The Moon, however, may affect the quality of the AO correction if the source used for wavefront sensing is fainter than $R=14$ mag. In this case, reducing the FLI constraint to 0.7 and increasing the distance to the Moon to approximately 50 degrees is recommended.

5.2.4 Sky Transparency

Thin clouds (THN) usually do not hamper CRIRES observations for bright objects. Clear (CLR) conditions are justified for observations requiring stable AO corrections, for example to study the close environment of the target, as clouds could affect the quality of the adaptive optics correction. For the same reason, CLR conditions should be requested for AO observations using AO stars fainter than $R=14$. Please note that AO observations cannot be performed under THK condition. Observations requiring accurate flux calibration of the spectra should be done under PHO conditions.

5.2.5 Background removal

Background removal in NIR spectra consists of dealing with sky emission lines and sky brightness variability, as well as with detector cosmetics and instabilities.

The sky background emission can be divided in two regimes depending on the wavelength. Below 2200 nm, the sky emission is dominated by OH lines, formed at an altitude of 80 km.



Beyond 2200 nm, the thermal background dominates with contributions from both atmospheric and telescope emission.

Detailed sky spectra with OH line identifications are available at:

<http://www.eso.org/sci/facilities/paranal/decommissioned/isaac/tools.html>

To this end, spectroscopic observations in the near-IR regime are performed by using the following techniques, which mostly rely on splitting the total integration on source in multiple sub-exposures taken at different positions.

5.2.5.1 Nodding

The classical technique in spectroscopy consists in observing a given target at two positions along the slit (i.e., nodding along the slit), with the specific purpose of removing the sky emission lines, the detector dark current, glow and eventually some ghosts. Indeed, the sky background is effectively removed by subtracting one frame from the other and vice versa. This process is sometimes called *double subtraction*.

Specifically, the total on-source integration time is split in N pairs of exposures. The exposures pair (i.e., usually referred to as AB pair) are taken always along the slit but at a given separation. The telescope nods between the two positions, A and B. The number of nodding cycles (i.e., number N of AB pair spectra) and the nodding throw (i.e., separation between the A and B positions) are free observing parameters. However, in spectropolarimetry mode the nodding throw is fixed at 2.5". The number of defined AB pair affects the total amount of overheads, therefore already at Phase 1 we strongly encourage the user to carefully plan the observing strategy.

5.2.5.2 Jittering

The purpose of jittering is to correct for bad pixels and decrease systematics originating from the detector. This is particularly important for CRIRES observations, as the detectors suffer from a relatively large number of bad pixels. In addition, the spatial extent of a spectrum is at most a few pixels in nominal conditions with AO. Jittering is obtained by adding a small, random offset to the telescope in addition to the nodding offset. The recommended maximum size of the jitter offset is a free parameter. It must be smaller than half the nodding offset but larger than the spatial extent of the minimum feature that one hopes to detect; for point sources, it should be larger than the width of the spatial profile. The jitter offset is always along the slit.

5.2.5.3 M2 Chopping

No M2 chopping can be done with CRIRES.

5.2.6 Flux calibration and telluric correction

5.2.6.1 General Procedure

Flux calibration and telluric correction are generally carried out in three steps:



1. Removing the telluric absorption features by dividing the wavelength calibrated science spectrum by the one of a telluric standard star, or a suitable synthetic telluric model spectrum.
2. Removing the intrinsic spectral features of the telluric standard imprinted in the science spectra after performing step 1.
3. Setting the absolute flux scale by using a spectrophotometric standard.

The spectrophotometric standard and the telluric standard can be the same star. Note that CRIRES, as spectrometers in general, is not meant to provide high absolute spectrophotometric accuracy due to slit losses. A list of spectrophotometric standards supported by the pipeline is provided in Table 10.

The Observatory does not take observations of telluric or spectrophotometric standard stars as part of the calibration plan. Observers who wish to correct for telluric features or flux calibrate their spectra therefore need to supply a standard star OB. Observing time needed to execute telluric or spectrophotometric standard stars is charged to the observer and must be accounted in the amount of time requested during Phase 1.

5.2.6.2 Telluric correction via Molecfit

Users are encouraged to check the suitability of the tool Molecfit to correct near-IR spectra for telluric features. This tool allows to fit synthetic transmission spectra to the astronomical data and to estimate molecular abundances, especially the water vapour content of the Earth's atmosphere.

<https://www.eso.org/sci/software/pipelines/skytools/molecfit>

This tool is based on the work presented in Seifahrt et al. (2010, A&A, 524, 11); this work discusses the performance and limitations of the technique to synthesize telluric absorption and emission line spectra.

5.2.6.3 Telluric correction via telluric standard stars

In case that users wish to observe a telluric star, then it should be observed within 2 hours in time and with an airmass difference of less than 0.2. Usually either hot stars or solar analogues should be used as telluric standards. The observations of the science and telluric standard star are typically taken consecutively (i.e., as a concatenation)

Hot stars as telluric standards. Spectra of stars hotter than B4 are well fitted by a black body, with the exception of a few lines (for example, neutral hydrogen Brackett lines). So, by knowing its spectral type, the continuum of a star can be fitted by a Planck function with the appropriate temperature. Some hot stars also have emission lines or are in dusty regions and should therefore be avoided. A positive value of the V-I colour of a star can be used as an indicator of reddening due to the presence of dust on its line-of-sight.

Late-type stars or G stars as telluric standards. Although stars cooler than A0 show molecular features, they could be used as telluric standard stars if the region around the hydrogen and helium lines is of interest. Late type stars exhibit only weak hydrogen and helium lines in their spectra.

Solar analogues, for the purpose of removing telluric features, are stars with spectral type G0V to G4V. These stars have many absorption lines in the IR, particularly in the J band.



These features can be removed by dividing the solar analogue spectrum by the solar spectrum at the resolution of the observations.

5.2.6.4 Catalogues

The CRIRES tools web page <http://www.eso.org/instruments/crides/tools> provides a number of catalogues listing suitable telluric and spectrophotometric standards.

5.3 The Exposure Time Calculator

The CRIRES exposure time calculator can be found at:

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

The ETC returns an estimate of the on-source exposure time necessary to achieve the requested Signal-to-Noise Ratio (SNR) given the *Target* properties, the *Instrument* setup and the constraints set, i.e., *Sky*, *Seeing and IQ* (see Figure 33).

A detailed description of all ETC input and output parameters is given on the [web page](#), however below we provide some general guidelines, and advise on the main ETC features.

CRIRES ETC

DIT: 10

NDIRT

S/N per pixel

S/N per pixel: 10

measure: median

Computed NDIRT: 1

λ min [nm]:

λ max [nm]:

Click to activate...

Activate λ range selection for the S/N with the mouse in the plot panels

Total exposure time: NDIRT * DIT = 1 * 10 s = 10 s = 00:00:10 [hh:mm:sss]
Excluding overheads

Figure 33: Screenshot of the CRIRES ETC *Exp. Time* tab. User requests the desired SNR by using a given DIT and the ETC returns the total exposure time (DITxNDIT) needed.

Target tab:

- The target input magnitude can be specified for a point or an extended source. For the latter, the input parameter corresponds to the magnitude per square arcseconds. Also input flux can be specified as surface brightness. If the *Emission line* option is chosen, it corresponds either to the total line flux, for a point source, or to the surface brightness for an extended source.



- If the observing date is known, it may be useful to compute the radial velocity shift due to orbital and rotational movement of the Earth. Alternatively, the tool allows the user to select the best time of the year to observe an object so that the targeted feature avoids a specific telluric line.

Sky tab:

- The sky conditions are defined in terms of airmass, moon phase (range: $0^\circ - 360^\circ$), angular distance between the moon and the target (range: $0^\circ - 180^\circ$) and PWV (see Sec 5.2.2 and Sec 5.2.3).
- By specifying the vertical amount of PWV in the atmosphere, the ETC uses the appropriate emission and transmission spectra for the PWV and airmass chosen. This functionality allows one to determine if the SNR will be or not affected by water vapor. One should note that the effect of water vapor lines also depends on the temperature at the time of observation, as well as the altitude of the layers where the water vapor is concentrated, therefore limiting the accuracy of the SNR determination to a few 10%.
- Because the AO correction degrades with airmass, when the NGS mode is selected, we suggest limiting the airmass to ~ 1.4 .

Seeing and IQ tab:

- For NoAO observations, the desired seeing condition is defined either in terms of requested TC or image quality (IQ) at a given reference wavelength. The ETC provides automatic conversion between the TC (i.e., phase 1 constraint) and IQ (i.e., phase 2 constraint).
- The seeing is given exclusively in term of TC when the AO mode is selected. Hence, in this case, TC is the relevant constraint for phase 1 and 2. AO observations are restricted to TC= 10%, 20%, 30%, 50%, 70% and 85%. SNR calculations for larger values in this mode are not supported by the ETC as AO in those conditions would result in an insignificant correction.
- When the AO mode is selected, the R mag, B-V colour, spectral type and target separation of the NGS must be specified. Suitable NGS can be retrieved from online catalogues available at Simbad/VizieR, or from Gaia-DR2 after having transformed the Gaia magnitudes to the Johnson-Cousins system³.

Instrument tab:

- The instrument setup is defined in terms of setting (i.e., Y1029 see Table 13, column 1), and grating orders.

Exp. Time and S/N tab:

- Requested output can be either the exposure time to achieve a given SNR or the SNR achieved in a given exposure time. In both cases the DIT needs to be specified.
- The SNR corresponds to that obtained by integration over a user-defined aperture (in spatial pixels). The available options for the aperture are in unit of $2 \times \text{FWHM_IQ}$ and diffraction limited PSF core for the NoAO and AO modes, respectively

³ Gaia DR2 Photometric Transformations are available at https://gea.esac.esa.int/archive/documentation/GDR2/Data_processing/chap_cu5pho/sec_cu5pho_calibr/ssec_cu5pho_PhotTransf.html



- For a point source, the SNR is given per pixel in the spectral dispersion and not per resolution element. To compute the SNR for a resolution element the right number of pixels needs to be combined (i.e., typically 2 pixels for the 0.2" slit).
- For an extended source, the calculated SNR corresponds to that obtained by integrating the signal over the area $A = \text{slit width} \times \text{FWHM}$ of the seeing in the spatial direction and is given per pixel in the dispersion direction (and not per resolution element).
- ETC outputs the on-source integration time. Depending on observing technique and accounting for overheads, the total execution time will be longer (see Section 5.4).

Select Plots tab:

- By the default the ETC displays the SNR per spectral pixel, however the user can request a number of different plots related for instance to the sky and/or target signal, and to the throughput efficiencies.
- It is always useful to ask the ETC to show the SNR as a function of wavelength due to the presence of numerous telluric features: a small difference in the requested wavelength may lead to very different SNR for a given total integration time or, alternatively, very different integration time for a requested SNR.
- From the ETC page users can access to a python script that allow to download the output of the requested plots in ascii file

5.4 Instrument overheads

In Phase 1 users are requested to provide the total execution time, which is given by the total exposure time (i.e., open-shutter time) plus the overheads.

Estimated overheads related to both telescope and instrument are listed in Table 7

However, an alternative easy way to calculate the overhead is to create a CRIRES mock OB by using p2demo available at: <https://www.eso.org/p2demo/home>

Under the CRIRES programme ID 60.A-9253(K) user finds a folder named USD-Tutorials containing examples of OBs specifically designed for different observing strategy. By coping one of such OBs into a new folder, user is able to change the on-source integration time, as well as number of exposures, offsets etc. and then to run the time calculator software, which will ultimately deliver the final total integration and execution time.

Table 7: Telescope and Observation overheads. (*) When the metrology is enabled only in the acquisition template, no overheads are associated to.

	Action	Times (s)
Telescope	Preset	360
CRIRES	Acquisition with AO	300
CRIRES	Acquisition without AO	180
CRIRES	Read-out	$2.4 + 1.43 \times (\text{NDIT}-1)$



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CRIRES	Nodding cycle	24
CRIRES	Change of wavelength setting	80
CRIRES	Metrology in YJ*	110
CRIRES	Metrology in HK*	180
CRIRES	Attached wavelength calibration	150
CRIRES	Attached lamp flat	120
CRIRES	Change of derotator position angle	60



6. PHASE II: Preparing the Observations

The Phase II begins with the ESO web letter release, which defines the end of the telescope time allocation process. Service and Visitor mode observations with all ESO instruments are performed by means of Observing Blocks (OBs), which contain all the information necessary for the observations. This includes the target position, the instrument and exposure setup parameters, special scheduling requirements, time and weather constraints, the finding chart, and an ephemeris file for moving targets.

Every OB is made up a unique acquisition template and one or more observing templates, and optionally calibration templates if night-time calibrations are needed. OBs must be prepared by using the web-based Phase II interface p2 available at:

<http://www.eso.org/p2>

A detailed description on the use of p2 is given at:

<https://www.eso.org/sci/observing/phase2/p2intro.html>

We advise users to consult the Phase II general guidelines for service and visitor mode available at:

- Phase II Preparation: <http://www.eso.org/sci/observing/phase2.html>
- CRIRES news: <http://www.eso.org/sci/facilities/paranal/instruments/crides/news.html>
- Service Mode (SM): <http://www.eso.org/sci/observing/phase2/SMGuidelines.html>
- Visitor Mode (VM): <http://www.eso.org/sci/observing/phase2/VMGuidelines.html> and <http://www.eso.org/sci/facilities/paranal/instruments/crides/visitor.html>

Finally, the preparation of CRIRES OBs (spectroscopic modes) can be easily performed with the help of the **ObsPrep**, directly within the p2 environment. ObsPrep provides a new user-friendly GUI that displays the target FoV, enables the selection of suitable VLT-GS, SVGS and NGS. In addition, it allows user to visualize and define the observing offsets pattern. All relevant parameters defined within the p2/ObsPrep tab are automatically propagated within the OBs in the corresponding templates.

CRIRES p2 tutorials have been prepared to guide the user through the preparation of successful OBs (see <http://www.eso.org/sci/observing/phase2/p2intro/p2-tutorials.html>). In addition, after logging into [p2demo](#), under the programme ID 60.A-9253(K), users can find a folder named USD Tutorial containing example of OBs specifically defined for different science case (i.e., observing strategy). Example OBs are not editable but can be exported if needed.

6.1 Service mode observations

Service mode (SM) observers must submit their OBs before the Phase 2 deadline announced in the web-letters.



The execution time of a science OB is typically no longer than 1 hour. OBs longer than 1 hour need a waiver that may or may not be granted (especially if the OB belongs to B- and C-ranked observing programs).

Scheduling containers, for example, concatenations, time-links and groups, can be used to implement a certain observing strategy. For science-telluric OB pairs, it is mandatory to use a concatenation which ensures the execution of OBs back-to-back. In the case of concatenations, a waiver is needed if the total execution time of all the OBs in the concatenation is longer than 1.5 hour.

In case of an OB or a concatenation with a total execution time longer than 1 hour, the Observatory only guarantees the weather conditions during the first hour during execution.

6.2 Visitor mode observations

Observers in visitor mode are encouraged to carefully check their target positions with respect to the Moon at the time of their scheduled observations. Backup targets are recommended whenever possible, and users are encouraged to contact ESO in case of severe conflict, i.e., when the distance to the Moon is closer than 30°. Visitors can use either the 'Target-Visibility' tab within p2, or the tools available at

<http://www.eso.org/sci/observing/tools/calendar/airmass.html>

Visitors should bear in mind that in case of strong wind and subsequent telescope pointing restrictions, it might not be able to observe their main targets. For this reason, it is strongly recommended to prepare backup targets with declinations smaller and larger than -24.6 . Such backup targets need to be approved before the observations. Please read the instructions provided on the following webpage:

https://www.eso.org/sci/facilities/paranal/sciops/vm_backup.html

6.3 OB preparation

In the following sections we provide a detailed description of how to define CRIRES observations through the preparation of OBs. In particular, we describe all the parameters that users are requested to provide in the templates. Every science OB consists of a target acquisition template which is followed by one or more science templates.

When referring to the name of any given parameter as it appears in p2 we use bold typewriter font (i.e., **Right Ascension**), while regular typewriter font (i.e., TEL.TARG.ALPHA) is used for the corresponding keyword in the template signature file (TSF).

6.3.1 Target acquisition template

The first template to be included in the OB is the acquisition, which takes care of: i) pre-setting the telescope to the target position; ii) setting up the instrument; iii) acquiring the NGS and SVGS; and iv) centring the target on the slit.



Depending on the selected instrument mode, the CRIRES acquisition involves up to 3 different sources observed at 3 different wavelengths. These are:

1. The target object (TRG): it can be either an extended object or a point-like source with a relevant wavelength between 950nm and 5300nm
2. The slit viewer guide star (SVGS): it is point-like source used for fine guiding using the SV camera in one of the 3 passbands, J, H or K.
3. The AO natural guide star (NGS): when the AO correction is required, the NGS can be either a point-like source or an extended object. In terms of wavelength, only its R band magnitude and B-R colour difference are relevant. (Note that the spectro-polarimetry mode equipped with AO correction is possible only when the NGS is on-axis, i.e., target must be also the NGS).

NOTE: Observations in P108 are only possible for Target = SVGS = NGS

In general, the sequence of the events taking place during the execution of the acquisition templates can be summarized as follows:

1. Telescope presets to the target position; a guide star in the FoV of the telescope is selected for telescope guiding and to correct the M1 mirror shape (active optics, not to be confused with adaptive optics = AO)
2. In NGS mode, the telescope moves then to the NGS specified by the user. Once the NGS is centred on the MACAO field selector, the AO loop is closed.
3. The telescope moves to the SVGS, which is then acquired and centred before starting the secondary guiding.
4. At this point the AO loop is close (if AO mode) and the guiding is active, therefore the telescope offsets to the target, which is manually centred on the slit.

Depending on the accuracy of the provided NGS and TRG coordinates, as well as the offsets between the target and the SVGS, an interactively re-centring may be required.

It should be noted that the instrument setup (i.e., desired wavelength setting, slit width, polarimetry optical element and metrology system if requested) is performed automatically during the acquisition.

Table 8 summarises the list of available acquisition templates as a function of the instrument modes relevant only for P108 observations.

Table 8: Summary of available CRIRES acquisition templates in P108

INSTRUMENT MODE	TEMPLATE NAME	COMMENT
Spectroscopy	CRIRES_spec_acq_NGS	AO assisted spectroscopy
	CRIRES_spec_acq_NoAO	Seeing limited spectroscopy



In the **p2/Target package**, the user is expected to provide the following TARGET details⁴:

• **Right Ascension/Declination/ Equinox / Epoch** (TSF: TEL.TARG.ALPHA, TEL.TARG.DELTA, TEL.TARG.EQUINOX, TEL.TARG.EPOCH) are the of the science target and the equinox for which these coordinates correspond to. In case of multiple objects in the slit or of extended objects, these coordinates correspond to the telescope preset and acquisition. Target coordinates should be as accurate as possible. VLT absolute pointing accuracy is better than 3" rms.

• **Proper Motion Right Ascension/Declination** (TSF: TEL.TARG.PMA, TEL.TARG.PMD) are the target proper motion values in RA and DEC and specified in units of "/year. If they are different from 0, the **Epoch**, (TSF: TEL.TARG.EPOCH), at which the coordinates were valid should be given.

• **Differential Right Ascension/Declination** (TSF: TEL.TARG.ADDVELALPHA, TEL.TARG.ADDVELDELTA) are the target additional velocities in α, δ and in units of arcsec/second. For solar system objects, the coordinates should be the J2000 ICRF, astrometric coordinates. In particular, the user should not provide the apparent coordinates Note: the differential velocities for moving targets are to be specified directly in the ephemerids PAF file (§ 6.3.5).

In what follow, we describe all parameters present in the **acquisition templates** that the user is requested to define, as well as their relevance in terms of selected instrument mode.

VLT-GuideStar (GS) details:

• **Telescope guide star selection** (TSF: TEL.AG.GUIDESTAR): if set to CATALOGUE, the Telescope Control System semi-automatically searches for a telescope guide star. If the user wishes to provide the coordinates of the telescope guide star (optional), then TEL.AG.GUIDESTAR should be set to SETUPFILE. Otherwise, NONE.

• **RA/DEC of telescope guide star** (TSF: TEL.GS1.ALPHA, TEL.GS1.DELTA) are only relevant if TEL.AG.GUIDESTAR = SETUPFILE. These parameters correspond to the J2000 coordinates, epoch of the observations, of the telescope guide star. Otherwise, both parameters should be kept to their default values (i.e., 00:00:00). Ideally, the VLT-GS should have R-band magnitude in the range 11 to 13, located between 1' and 11' from the target and possibly be isolated. Fainter GS may work in good conditions. However, we generally encourage users to leave the VLT-GS selection to the telescope operator (i.e., TEL.AG.GUIDESTAR=CATALOGUE), who is always in the best position to pick the most suitable stars given the real-time conditions.

⁴ For observations of moving object, the target position and motion are provided through tracking table, see dedicated section (§ 6.3.5)



Slit Viewer (SV) details:

• **Use the last sky measurement for the SV** (TSF: SEQ.SV.USELASTSKY): Generally, one can use the last sky measurement and therefore leaves this parameter untouched from its default value, YES (i.e., SEQ.SV.USELASTSKY=T). However, if one observes a faint target or if the SVGS is not particularly bright (i.e., $H < 12$), a new sky exposure should be obtained. In this case set the flag to NO (i.e., SEQ.SV.USELASTSKY = F).

• **RA/DEC offset to sky** (TSF: TEL.SKY.OFFSETALPHA, TEL.SKY.OFFSETDELTA) are only relevant if SEQ.SV.USELASTSKY = F. By default, the sky exposures are taken 30" in RA and DEC from the science target position. In crowded fields however, the RA/DEC offset might need to be fine-tuned to prevent from acquiring the sky exposure in a region highly contaminated by other sources. These offsets are usually executed after the telescope started the field tracking (i.e., step 1 see above), and right before moving to the NGS (if the AO correction is used) or to the SVGS (for NoAO observations).

The convention for these RA, DEC offsets is:

$$\begin{aligned} \text{TEL.SKY.OFFSETALPHA} &= \alpha_{\text{SKY}} - \alpha(\text{NGS}) \\ \text{TEL.SKY.OFFSETDELTA} &= \delta_{\text{SKY}} - \delta(\text{NGS}) \end{aligned}$$

SVGS details:

• **RA/DEC offset between target and SV guide star** (TSF: TEL.TARG.OFFSETALPHA, TEL.TARG.OFFSETDELTA) correspond to the offsets, in arcsec, necessary to move from the target to the SVGS. If $\alpha(\text{SVGS})$ and $\delta(\text{SVGS})$ are the coordinates of the SVGS, the sign convention is as follows:

$$\begin{aligned} \text{TEL.TARG.ALPHA} + \text{TEL.TARG.OFFSETALPHA} &= \alpha(\text{SVGS}) \\ \text{TEL.TARG.DELTA} + \text{TEL.TARG.OFFSETDELTA} &= \delta(\text{SVGS}) \end{aligned}$$

In other words, TEL.TARG.OFFSETALPHA and TEL.TARG.OFFSETDELTA are positive if the SVGS is located to the East and North of the target. Note that during the OB execution the SVGS must be kept always within the SV field of view (see Figure 25). Note that these parameters must be provided only if no differential tracking is needed.

Metrology details:

• **Run Metrology?** (TSF: SEQ.METROLOGY.ST) CRIRES is sensitive to changes of its opto-mechanical setup with positions of spectral lines typically not being reproducible to better than 1.5 pixels in the dispersion direction. The best mitigation strategy is to not change setups between the calibration and science frames. However, even then, drifts may occur. To ensure the highest accuracy of the position of the slit image on the detector, CRIRES offers a metrology function with the goal to ensure repeatability of both the wavelength zero point and dispersion of a given echelle setting to $< 1/10$ pixel along the dispersion direction. Note that the metrology is only available for wavelength < 2500 nm. Caution should be used when enabling metrology in multiple science templates due to the associated overheads. In general, this should only be enabled (i.e., flag set to yes,



SEQ.METROLOGY.ST=T) if your science requires highly reproducible positioning of the echellogram on the detectors.

NGS details:

• **Target = AO guide star** (TSF: SEQ.NGS.ISTARGET) is a flag to be set to YES (i.e., SEQ.NGS.ISTARGET =T, default value) when star used for the adaptive optics is also the science target of the observations, else the flag must be set to NO (i.e., SEQ.NGS.ISTARGET = F).

• **RA/DEC of AO guide star** (TSF: SEQ.NGS.ALPHA, SEQ.NGS.DELTA) RA and DEC coordinates of the NGS. If the NGS is also the target (i.e., SEQ.NGS.ISTARGET=T) then the user does not need to provide the star coordinates and these two parameters can be left untouched to their default value (i.e., 00:00:00). See §4.2.1.2 for the maximum allowed distance between the target and the NGS.

When the NGS is the target the user needs to provide the NGS coordinates.

Note that for the differential tracking case the NGS coordinates are provided through the tracking table.

• **AO guide star: B-R color value** (TSF: SEQ.NGS.COLOR) gives the B-R colour of the NGS. This parameter is needed for accurate correction of the differential refraction between the wavelength used for the observations and the effective wavelength of the wavefront sensor (see §4.2.1.4).

• **NGS MAG** (TSF: SEQ.NGS.MAG) refers to the magnitude of the NGS in the R passband. See §4.2.1.3 for the allowed range.

• **AO guide stars: FWHM (arcsec)** (TSF: SEQ.NGS.FWHM) gives the FWHM of the NGS in arcsec used to optimize the AO system diaphragm. This diaphragm is set as a function of the seeing, and as such it optimizes the amount of light received from the object with respect to the amount of background light from the sky. If the NGS is a point source, the FWHM is best left to zero, such as only the seeing will be taken into account. Only if the NGS is significantly extended with respect to the seeing then this parameter should be set to equal to the FWHM of the object in arcseconds.

• **AO guide star: Minimum S/N** (TSF: SEQ.NGS.SNR) refers to the required signal-to-noise ratio that MACAO needs on the wavefront sensor to be able to close the loop. The default value (i.e., 1000) is fine for most cases, except for the faintest objects that the MACAO can acquire, in which case a smaller value is to be given.

• **Use the last sky measurement for WFS** (TSF: SEQ.NGS.USELASTSKY) is a flag, which if set to **yes** (i.e., SEQ.NGS.USELASTSKY=T), then MACAO will not repeat the sky measurement for the wavefront sensor. The sky measurement is used to determine the SNR of the wavefront sensor flux. The default value (i.e., YES) is adequate for bright AO stars ($R < 10$). For fainter targets, the parameter should be set to NO. Note that in this case, the parameters SEQ.NGS.SKYALPHA and SEQ.NGS.SKYDELTA should be determined with care if observations take place in crowded fields.



• **WFS Alpha/Delta sky offset (arcsec)** (TSF: SEQ.NGS.SKYALPHA, SEQ.NGS.SKYDELTA) provide the offsets of the location relative to the NGS where MACAO measures the sky.

If SEQ.NGS.SKYALPHA > 0, the sky is measured to the East of the NGS.

If SEQ.NGS.SKYDELTA > 0, the sky is measured to the North of the NGS.

Default values are usually fine, except in crowded fields.

• **SV Guide Star = AO Guide Star** (TSF: SEQ.NGS.ISSVGS) is a flag that must be set to YES if the NGS is also the SVGS, otherwise to NO.

Note that this parameter is only relevant when the differential tracking is not used.

- If target = NGS = SVGS (i.e., SEQ.NGS.ISTARGET=T and SEQ.NGS.ISSVGS=T) the parameters “**RA/DEC offset between the target and SV guide star**” (TEL.TARG.OFFSETALPHA and TEL.TARG.OFFSETDELTA), and “**RA/DEC of AO guide star**” (SEQ.NGS.ALPHA and SEQ.NGS.DELTA) can be ignored and left to their default values.
- If target = NGS ≠ SVGS (i.e., SEQ.NGS.ISTARGET=T and SEQ.NGS.ISSVGS=F) the parameters “**RA/DEC offset between the target and SV guide star**” (TEL.TARG.OFFSETALPHA and TEL.TARG.OFFSETDELTA) must be provided, while the “**RA/DEC of AO guide star**” (SEQ.NGS.ALPHA and SEQ.NGS.DELTA) can be still ignored and left to their default values.

Instrument setup details:

• **Entrance slit width** (TSF: INS.SLIT1.NAME): w_0.2 (i.e., 0.2” slit width for a spectral resolution of $R \sim \lambda/\Delta\lambda \sim 100\,000$) or w_0.4 (i.e., 0.4” slit width for $R \sim 50\,000$).

• **Reference wavelength** (TSF: INS.WLEN.CWLEN) allows the user to select from a pull-down menu the wavelength value that uniquely identify the wavelength setting (i.e., cross-disperser + order sorting filters + echelle grating). The settings and corresponding wavelength ranges are provided in Table 13. The selection of a specific standard setting automatically includes the positioning of the corresponding photometric band of interest for the cross-disperser wheel (YJHKLM) and for the order sorting filter wheel + the setting of the relative echelle grating angle. Specifying the wavelength in the acquisition template allows for (a) differential atmospheric refraction between target and a separate guide star, and (b) parallelisation of target acquisition and instrumental setup.

• **Derotator Mode** (TSF: INS.DROT.MODE): can be set to either ELEV or SKY. In the ELEV mode, the slit is always aligned with the parallactic angle (“pupil stabilized”), while in the SKY mode the field rotation is compensated (“field stabilized”).

The SKY mode is relevant for extended sources or for placing multiple objects simultaneously on the slit. For point sources, however, the ELEV mode should be used as it reduces slit loss introduced by differential refraction. This is particularly important if SV guiding is done in one band (e.g., in K) and the observations in another one (e.g., M).



• **Position angle** (TSF: `INS.DROT.POSANG`) determines the position angle (PA) of the slit when the SKY derotator mode is selected. The PA is counted from North (i.e., PA=0 deg) via East.

• **Gas cell** (TSF: `INS.OPTI1.NAME`) sets the name of the optical gas cell to be used during the science. The default value (FREE) should be set for observations without any gas cell, while `GAS_SGC` or `GAS_N2O` should be set for observations at short (i.e., YJHK) and long (i.e., LM) wavelength, respectively. Gas cells provide for simultaneous wavelength calibration by imprinting the absorption spectrum of the gas onto the spectrum of the target. Note: the option of using the gas cell is only available for spectroscopic mode, but not for polarimetry.

6.3.2 Science templates

The science observation template sets the instrument, if different from the acquisition, as well as the detector integration time (DIT) and the number of individual integrations averaged to create an exposure (NDIT). In addition, it defines the number of exposures to be taken in different positions for background subtraction purpose.

As mentioned in §5.2.5.1, the most common observing technique suited for point-source like targets is the nodding along the slit, where the target is always kept along the slit (i.e., no off-slit exposures are possible) and the sky signal is removed from the object spectrum by subtracting two exposures taken at different slit positions.

On the other hand, when the target is an extended object nodding along the slit is no longer a viable strategy because removing the sky signal from the object spectrum requires necessarily to take exposures off-slit (not yet offered in P108).

In addition, CRIRES offers the possibility of using the spectro-astrometry technique (not yet offered in P108) to obtain very high spatial and spectral resolution line imaging (Beckers, J., 1982, Opt. Acta, 29, 361; Bailey, J., 1998, MNRAS 301, 161 and references therein). First results using this technique with the old CRIRES are described in Pontoppidan et al. 2008. Note that this technique requires the target being also the SVGS, whereas the NGS can be different.

Table 9: Overview of the available CRIRES spectroscopic observing templates. (*)
 Templates not offered in P108

INSTRUMENT MODE	TEMPLATE NAME	COMMENT
Spectroscopy	CRIRES_spec_obs_AutoNodOnSlit	Exposures are taken only by nodding the target along the slit. Off-slit exposures are not possible (i.e., recommended for point sources)
	(CRIRES_spec_obs_GenericOffset*)	Exposures can be taken along and/or off the slit, depending on the user defined offsets (i.e., recommended for extended object)



	<i>(CRIRES_spec_obs_SpectroAstrometry*)</i>	Exposures are taken only by nodding the target along the slit and repeated at any given user-defined position angle.
--	---	--

The science observation templates must match the instrument mode defined in the acquisition template. Table 9 provides a summary of the available observing templates as a function of the instrument modes.

In what follows, we describe the parameters present in the **observing templates** that have not been introduced already in §6.3.1 and that the user is requested to define, as well as their relevance in terms of observing technique.

Exposure Time details:

- **DIT** (TSF: `DET1.DIT`) defines the exposure time of an individual detector integration time, in seconds. For bright target (JHK ~ 8-10 mag) or in L/M bands, only the following DITs are allowed: 1, 1.5, 2, 3, 5, 7, 10, 15, 20, 30, 45 s (optimal flat fielding requires > 2 s). Long exposures **must** select DITs of 60, 90, 120, 180, 300, 600 or 900s in service mode; DITs ≥600s require a waiver because of the high risk of not meeting atmospheric quality requirements. In visitor mode, other DITs can be chosen but at the expense of additional calibrations.

- **NDIT** (TSF: `DET1.NDIT`) determines the number of individual integrations averaged into one exposure; therefore, `DET1.NDIT × DET1.DIT` sets the total integration time of one exposure. Normally, FITS files are only written for the average of NDIT sub-exposures.

Therefore, the integration time spent in a single position is given by:

$$DET1.NDIT \times DET1.DIT$$

Nodding details:

- **Number of exposures per nodding position** (TSF: `SEQ.NEXPO`): is the number of exposures required to carry out the scientific goal in any single offset position.

- **Number of nodding cycles** (TSF: `SEQ.NABCYCLES`): sets the number of AB or BA nodding cycles. Setting this parameter to 0 implies staring at position A only. If set to a value ≥1, positions A and B are each visited `SEQ.NABCYCLES` times, and the total integration time of the (non-polarimetric) templates, is given by:

$$DET1.NDIT \times DET1.DIT \times SEQ.NEXPO \times SEQ.NABCYCLES \times 2.$$

Whereas in staring mode (`SEQ.NABCYCLES = 0`):

$$DET1.NDIT \times DET1.DIT \times SEQ.NEXPO$$

- **Nod throw along the slit** (TSF: `SEQ.NODTHROW`) is the nodding throw, or telescope offset between two nodding positions. It should be large enough so that the spatial profiles



of the target in the two nodding positions do not overlap. The nodding positions are located symmetrically (at $SEQ.NODTHROW/2$) around the centring location. Because of the extended wings of the PSF a nodding throw greater than 4" is recommended, preferably 6".

• **Jitter width** (TSF: $SEQ.JITTER.WIDTH$): refers to the small offset added to each nodding offset (see §5.2.5.2). It helps correct for bad detector pixels. $SEQ.JITTER.WIDTH$ gives the width of the jitter box in arcseconds. The maximum offset from the nodding position is therefore given by half of this value. The successive values of the jitter offset in a given template are drawn from a set of 100 numbers determined from a Poisson random number generator. Jittering is currently not possible if $SEQ.NABCYCLES = 0$ (staring mode). Upper limit for jitter size is half the nod throw, but preferably much smaller so that the PSF from the star never crosses the middle of the slit.

• **List of position angles** (TSF: $INS.DROT.POSANG.LIST$) is the list of position angles at which the nodding sequence is repeated. This parameter is relevant only for spectro-astrometric observations (i.e., for template CRIRES spec_obs_SpectroAstrometry). Note that the values of the position angles are absolute.

• **Reset jitter for each DROT posang** (TSF: $SEQ.JITTER.RESET$). Only relevant for spectro-astrometric observations and when $SEQ.JITTER.WIDTH$ (Jitter width) is not zero. If this parameter is set to **yes** (i.e., $SEQ.JITTER.RESET = T$) the list of jitter positions calculated by the observation software is repeated identically, in detector coordinates, for each value of the slit position angle

Examples for Nodding:

1. If $SEQ.NABCYCLES = 1$, the telescope first points to the A position: it is located to the North (if $INS.DROT.POSANG = 0$) at a distance equal to $SEQ.NODTHROW/2$ (and assuming $SEQ.JITTER.WIDTH = 0$) from the centring position. After $SEQ.NEXPO$ exposures, the telescope nods to the B position: it moves to the South by $SEQ.NODTHROW$, and takes $SEQ.NEXPO$ additional exposures. Then the telescope moves back to its original position. The telescope has then executed one AB nodding cycle.
2. If $SEQ.NABCYCLES = 3$, the telescope first points to the A position, as defined in the previous paragraph, and takes $SEQ.NEXPO$ exposures. It then moves to the B position, takes twice $SEQ.NEXPO$ additional exposures. It then moves back to the A position, when it takes twice $SEQ.NEXPO$ exposures. Then, it moves a last time to the B position for a last sequence of $SEQ.NEXPO$ exposures before returning to the original position. The telescope had therefore executed 3 nodding cycles: AB BA AB.

When the nodding is used, the total exposures time is given by:

$$2 \times SEQ.NABCYCLES \times DET1.NDIT \times DET1.DIT \times SEQ.NEXPO$$

In the spectro-astrometry case, the total exposures time is given by:

$$2 \times SEQ.NABCYCLES \times DET1.NDIT \times DET1.DIT \times SEQ.NEXPO \times n_{posangs}$$



where n_{posangs} is the number of position angle defined in `INS.DROT.POSANG.LIST`

Generic-offset details (not offered in P108):

• **Lists of offsets in RA/DEC or X/Y** (TSF: `SEQ.OFFSET1.LIST`, `SEQ.OFFSET2.LIST`) refer to the list of offsets is in arcseconds. The defined offsets are cumulative.

• **Offset coordinate type selection** (TSF: `SEQ.OFFSET.COORDS`) determines if the list of offsets given in `SEQ.OFFSET1.LIST` and `SEQ.OFFSET2.LIST` are given in SKY or DETECTOR coordinates.

If `SEQ.OFFSET.COORDS` is set to DETECTOR the offsets correspond to the apparent motion of the target on the SV detector, with X increasing from left to right (from E to W if the position angle is 0 deg) and Y increasing from bottom to top (from S to N if the position angle is 0 deg). In other words, in this case, a positive offset in both X and Y would bring the target to larger X and larger Y values as seen on the SV. If the position angle is 0, this corresponds to a motion of the telescope to the East and South (see Figure 34). Subsequent offsets are similarly made relative to the last telescope offset.

If `SEQ.OFFSET.COORDS` is set to SKY, a positive value in `SEQ.OFFSET1.LIST` means that the new pointing of the telescope is to the East relative to the previous location (target moves West on the SV); similarly, a positive value in `SEQ.OFFSET2.LIST` means that the new pointing of the telescope is to the North relative to its previous location (target moves South on the slit viewer). During the first exposure, the telescope points to the location given by `TEL.TARG.ALPHA` and `TEL.TARG.DELTA` plus the first value given in `SEQ.OFFSET1.LIST` and `SEQ.OFFSET2.LIST`. In other words, in this case, the offsets correspond to telescope offsets (see Figure 35).

• **Number of exposures on each position** (TSF: `SEQ.NEXPO`): gives the total number of telescope positions that the telescope will have during the execution of the template. Minimum value is 1. If this value is larger than the number of values listed in `SEQ.OFFSET1.LIST`, or `SEQ.OFFSET2.LIST` then the list is started again.

For example, if `SEQ.NOFF = 5`, `SEQ.OFFSET1.LIST = '0 0 0'` and `SEQ.OFFSET2.LIST = '0 10 -10'`, `SEQ.OFFSET.COORDS = DETECTOR`, the list of offsets will be '0 0 0 0 0' along the X direction, '0 10 -10 0 10' along the Y direction. The telescope goes back to the centring location at the end of the template.

When the generic offsets technique is used, the total exposures time is given by:

$$\text{DET1.NDIT} \times \text{DET1.DIT} \times \text{SEQ.NEXPO} \times N_{\text{off}}$$

Where N_{off} is the number of offsets listed in `SEQ.OFFSET1.LIST/SEQ.OFFSET2.LIST`

* **List of observation types (O or S)** (TSF: SEQ.OBSTYPE.LIST) is a list that determines if the exposure taken once the corresponding offset has been completed is an OBJECT (O) or a SKY (S) measurement.

Therefore, the total integration time of one exposure in an OBJECT location is $DET1.NDIT.OBJECT \times DET1.DIT$. Similarly, the total integration time of one exposure in SKY location is $DET1.NDIT.SKY \times DET1.DIT$. Note that SEQ.NEXPO exposures can be obtained at each location. In the case of NGS observations, OBJECT and SKY correspond to MACAO CLOSE and OPEN loop, respectively.

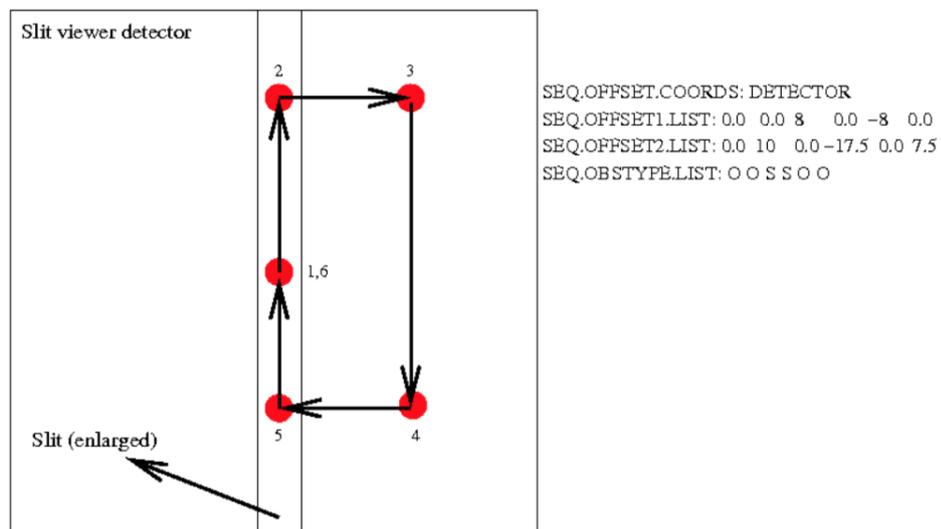


Figure 34: Illustration showing the apparent locations of the target as seen from the SV detector for the given parameters, in the case of DETECTOR coordinate offsets. Although the derotator mode must be set to SKY, the position angle is irrelevant since all motions are made in detector coordinates.

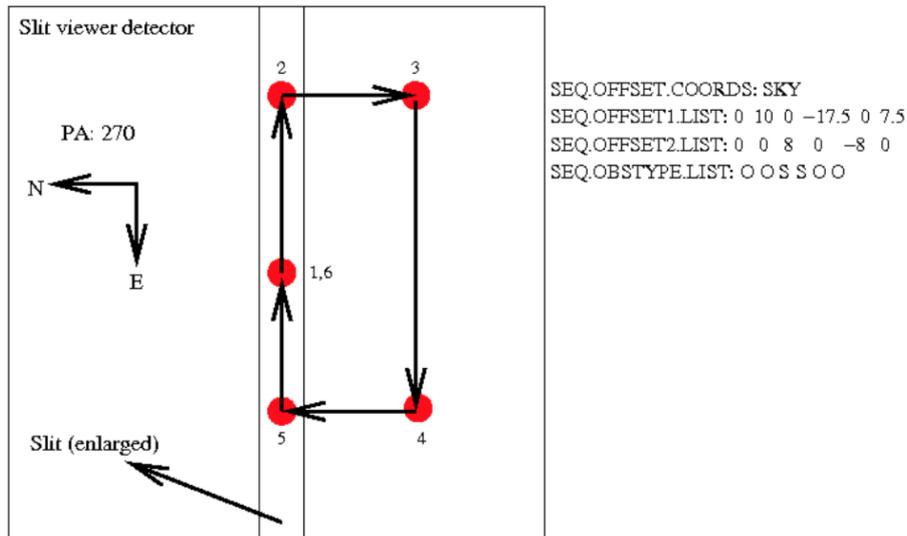


Figure 35: Illustration showing the apparent locations of the targets as seen on the SV detector for the given parameters in the SKY coordinate offsets. If the telescope moves North, the target moves South on the slit viewer

6.3.2.1 Offset conventions and definitions:

CRIRES follows the standard astronomical offset conventions and definitions.

- Position angles (PAs) are measured from 0 to 360 degrees. North corresponds to a PA of 0 degrees, East, to a PA of 90 degrees.
- All offsets are given in arc seconds.
- Proper motions must be given in arcsec per year.
- For solar system objects, additional tracking velocities are given in arcsec per second.
- For a position angle of 0 in SKY mode, the reconstructed SV image shows North up and East left.

6.3.3 Night-time calibrations

Darks, flat fields and wavelength calibrations are taken during daytime as part of the calibrations plan (see §0 for more details). A Halogen lamp is used for flat fields, while UNe lamp or the N₂O or SGC gas cell in front of the halogen lamp are used for wavelength calibration.

However, depending on the science goal, additional calibrations can be requested during the night as well. For instance, dedicated template for wavelength and flats calibrations shall be attached immediately before or after the science template so that the gratings are not moved in between. If the use of Molecfit or synthetic telluric spectra is not a valid option for the correction of the telluric features, then users must supply a telluric standard star OB. If accurate the science requires accurate flux calibration, then the user must provide a spectrophotometric standard OB.



This section describes the use of the templates for night-time calibrations. All calibrations performed during the night-time calibration are charged to the user.

6.3.3.1 Spectrophotometric standard star or telluric observations

OB for either a telluric or a spectrophotometric standard star should consist of an acquisition template (see Table 8) and of the calibration template `CRIRES_spec_cal_AutoNodOnSlit`. The latter is very similar to the observing template `CRIRES_spec_obs_AutoNodOnSlit` described in detail in §6.3.2. The files obtained with this calibration template are automatically recognized by the pipeline as standard star observations.

If the selected star is in the list of spectrophotometric standards supported by the pipeline (see Table 10), then the pipeline outputs also the sensitivity and total throughput (i.e., spectrograph, telescope, Earth atmosphere).

Table 10: Spectrophotometric standards supported by the pipeline

Name	RA	DEC	Rmag	B-R
HR9087	00:01:49.45	-03:01:39.1	5.1	-0.12
HR718	02:28:9.54	08:27:36.2	4.3	-0.05
GD50	03:48:50.2	-00:58:31.2	14.21	-0.42
HZ2	04:12:43.55	11:51:48.8	13.99	-0.2
HR1544	04:50:36.73	08:54:00.5	4.29	-0.07
GD71	05:52:27.62	15:53:13.3	13.17	-0.39
HR3454	08:43:13.48	03:23:55.2	4.37	-0.27
GD108	10:00:47.0	-07:33:31	13.66	-0.31
HR4468	11:36:40.9	-09:48:08	4.64	-0.04
FEIGE67	12:41:52.0	17:31:20	11.97	-0.27
HR4963	13:09:56.99	-05:32:20.4	4.3	-0.09
HR5501	14:45:30.2	00:43:02.2	5.63	-0.02
HR7596	19:54:44.79	00:16:24.8	5.52	-0.18
HIP102497	20:46:20.0	-39:11:57	5.5	-0.12
HR7950	20:47:40.55	-09:29:44.7	3.7	-0.07
HIP104139	21:05:57.0	-17:13:58	4.06	0
G93-48	21:52:25.38	02:23:19.56	12.85	-0.12
HR8634	22:41:27.73	10:49:52.6	3.43	-0.1
NGC7293	22:29:38.55	-20:50:13.6	13.69	-0.53



6.3.3.2 Attached flat field

Flat fields can be obtained with the template `CRIRES_spec_cal_LampFlats`, to be included in the science OB. Because there is no a priori necessity to obtain flat fields during the night, we suggest the use of this template only when observations aim at obtaining very high accuracy radial velocity or for observations of extended targets.

Most of the parameters to be defined in this template are described in §6.3.1. In addition, the user must set the **Decker position** (TSF: `INS.DECKER.POS`) to `OPEN` and define the appropriate value in ADU for the **Maximum Flux** (TSF: `SEQ.MAXFLUX`). The latter is used to calculate the appropriate DIT given the requested NDIT.

6.3.3.3 Attached wavelength calibration

High-precision absolute wavelength calibration can be either obtained with sky emission lines or telluric absorption lines or by employing a spectrum from an artificial calibration source: currently, the reproducibility of the wavelength setting between night-time observations and day-time calibrations is < 5 px. If higher precision is required, then users have the possibility to insert the `CRIRES_spec_cal_Wave` template either before or after any science observing template.

Most of the parameters to be defined in this template are described in §6.3.1 and §6.3.3.2. In addition, the user defines the **Wavelength calibration source** (TSF: `INS.LAMP`). Possible choices are: `UNE` for the Uranium Neon lamp (< 2500 nm), `FPET` for the Fabry-Perot Etalon system (< 2500 nm), `HALOGEN` to be combined with any of the gas cells (`INS.OPT1.NAME=GAS_SGC` or `GAS_N2O`). Note that the `FPET` should be executed together with the `UNE` lamp to establish the zeropoint of the `FPET`.

6.3.3.4 Darks

Darks are obtained during daytime calibrations by the Observatory using the calibration template `CRIRES_spec_cal_Darks`. There is no need to execute dark exposures during the night, particularly when nodding is employed. All parameters to be defined in this template have already been described in § 6.3.1 and §6.3.2.

6.3.3.5 Sky observations

Observed sky lines which can be identified by HITRAN have the advantage that wavelength calibration is done from the science observations themselves. General recommendations on absolute wavelength calibration are given in sec 4.4.4. However, observers are strongly advised to use the ETC with the output options Sky Emission Spectrum and Sky Absorption Spectrum and to check for themselves if enough unsaturated telluric lines are available for a proper wavelength calibration in the spectral range of interest.

In addition, the template `CRIRES_spec_cal_SkyObs` template allows to take a spectrum of the sky at the current telescope location without slit viewer guiding and with the AO loop open. It is unlikely to be needed in any science OB: its main use is for characterizing the atmospheric conditions (amount of water vapour). All parameters to be defined in this template have already been described in § 6.3.1 and §6.3.2.



6.3.4 OB Constraint set

In the *p2/Constraint Set* tab, users are requested to define the suitable observing conditions for the OB execution. These are: i) Airmass; ii) Lunar Illumination; iii) Moon Angular Distance; iv) Twilight; v) Sky Transparency; vi) Image Quality; vii) Turbulence; and viii) Precipitable Water Vapour. As mentioned in §5.2, most of these constraint parameters (i.e., i, ii, v, vii) have been already defined in Phase 1. We remind here that such requirements are binding, and as such users are not allowed to define an OB constraint set more stringent than that requested in the proposal. At Phase 2, observing constraints can be only relaxed.

- I. **AIRMASS** (X): Most efficient AO corrections are obtained at airmass up to $\sim 1.4''$. At higher values of airmass (i.e., $X > 1.4''$) the performance decreases rapidly. In addition, observations (NoAO and AO) with the derotator in SKY mode can be strongly affected by differential refraction. User should adopt the same value requested in the proposal.
- II. **LUNAR ILLUMINATION** (FLI): Most of the observations can be performed under $FLI=1$. However, the Moon may affect AO observations as described in §5.2.3. User should adopt the same value requested in the proposal.
- III. **MOON ANGULAR DISTANCE** (MAD): In general, the Moon does not affect IR observations. Please refer to §5.2.3 for more information.
- IV. **TWILIGHT** (TW): Bright objects may be observed during twilight. In that case, the TW can be used to define the earliest time with respect to the end of the evening astronomical twilight when the execution of the OB can be started. While the relation between the time difference from the evening twilight end and sun elevation varies during the year, for Paranal due to its low latitude this difference is small. Therefore, the constraint is given in minutes as a difference in time with respect to the end of astronomical twilight (i.e., the time when the solar elevation is -18 degrees). The default TW value is -15 (minutes). A negative number means that it is allowed to start the observation before the end of the astronomical evening twilight, a positive number means start the observation at least that many minutes after the end of the astronomical twilight. The twilight constraint can take values between -30 and $+15$ minutes. In particular, K-, L- and M-band observations can already be taken well before the end of the astronomical twilight.
- V. **SKY TRANSPARENCY**: Thin clouds (THN) usually do not hamper CRIRES observations for bright objects. Clear (CLR) conditions are justified for observations requiring stable AO corrections.
- VI. **IMAGE QUALITY** (IQ): Defined as the FWHM of a long exposure stellar image, is a property of the images obtained in the focal plane of an instrument mounted on a telescope observing through the atmosphere. It is therefore a quantity measured at the requested airmass and wavelength of observing. The IQ is relevant only for NoAO observations. User must use the IQ value calculated by the ETC for the requested airmass and wavelength setting.
- VII. **TURBULENCE** (TC): see §5.2.1 for the definition. At Phase 2, the TC constraint is relevant only for OB using the AO mode. User should adopt the same value requested in the proposal.
- VIII. **PRECIPITABLE WATER VAPOUR** (PWV): Observations in the NIR can be severely affected by the presence of PWV in the atmosphere: large amount of PWV can significantly decrease the sky transmission, and, in particular, in the L and M bands increase the sky emission background (see §5.2.2). For L and M-band



observations, we recommend setting the PWV constraint to a value ≤ 3.5 . The ETC offers the possibility to select sky spectra calculated with a set of representative amounts of water vapor in the atmosphere. The allowed values are 0.5, 1.0, 1.5, 2.5, 3.5, 5.0, 7.5, 10.0 and 20.0-mm. User should adopt the same value requested in the proposal.

6.3.5 Ephemeris

To observe moving targets the user must supply ephemeris to be uploaded on p2 and attached to the target science OBs. For SM observations, the provided ephemeris file should cover the whole duration of the ESO Period in question, or for the whole duration of the observability period in case that observations must be executed within a specific time window. On the other hand, in VM the ephemeris should cover the assigned time/night.

The ephemeris files are ASCII files compatible with the VLT parameter file (PAF) format, and can be prepared by using the online tool available at:

<http://www.eso.org/sci/observing/phase2/SMSpecial/MovingTargets.html>

6.3.6 Finding Charts

For SM observations, users are requested to provide finding charts for any given science OB. Finding chart must be compliant with ESO standard and instrument specific requirements. A complete description can be found at:

<http://www.eso.org/sci/observing/phase2/SMGuidelines/FindingCharts.html>

Finding charts for CRIRES observations can be easily and quickly prepared by using the Finding Chart Generator service (p2fc) available directly within the p2 environment (see p2/Finding Charts tab).

6.3.7 README file

For any given SM run, users are requested to provide a README file containing a concise overview of the OBs in terms of observing strategy and scientific goal. Detailed instructions on the README file can be found at:

<http://www.eso.org/sci/observing/phase2/SMGuidelines/ReadmeFile.html>



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7. REFERENCE MATERIAL

7.1 Calibration Plan

The calibration plan defines the default calibrations obtained and archived for the user by the Paranal Science Operations. The CRIRES science calibration plan currently includes the following measurements. Note that ESO reserves the right to decrease the calibration frequency if tests show that this has no effect on the quality of the reduced data.

All standard calibrations will be acquired by the Observatory staff during the day following the night of the observations (or within the validity period indicated in the tables below). "Matching parameters" describes the most critical parameter for generating the automatic calibration. For instance, darks will have the same DIT as the science frames, flats will be taken in the same wavelength setup as the science, etc.; wavelength calibrations and flat field exposures will be taken through the 0.2" or 0.4" slit.

The daily calibrations are taken by employing the metrology system.

Table 11: Standard calibrations

Calibration	Number	Matching parameters	Validity
Darks	3	DIT	1 day
Flats	3	wavelength, slit width	1 day
Wavelength (FP etalon)	1	wavelength, slit width	1 day
Wavelength (UNe lamp)	1	wavelength, slit width	1 day
Wavelength LM (N ₂ O gas cell)	1	wavelength, slit width	1 day
Gas cell spectrum HK (SGC)	1	wavelength, slit width	1 day

In addition to the standard calibrations, we will acquire the following calibrations to monitor the stability of the instrument.

Table 12: Instrument monitoring calibrations

Calibration	Purpose	Frequency
Spectral resolution (day)	Monitoring of the spectral resolving power	1 day
Efficiency monitoring (night)	Throughput monitoring with standards	30 days
RV standard stars (night)	Monitoring of radial velocity stability	90 days
Grating drifts (day)	Monitoring of the wavelength precision	90 days
Distortion map (day)	Monitoring of the spatial resolution along the slit	180 days



Polarimetric calibrations (day)	Monitoring of the polarimeter with the FP etalon	180 days
Polarized standard stars (night)	Monitoring of polarimetric performance	180 days

7.2 Wavelength Settings

The properties of the 29 CRIRES wavelength settings are listed in Table 13, with:

COLUMN [1] = Name of the setting stored in the FITS header keyword `INS.WLEN.ID`

COLUMN [2] = Reference wavelength (in nm) of the setting use in p2 and in the TSF, and stored in the parameter FITS header `INS.WLEN.CWLEN`

COLUMN [3] = Setting minimum wavelength (in nm), stored in the parameter FITS header `INS.EWLEN.MIN`

COLUMN [4] = Setting maximum wavelength (in nm), stored in the parameter FITS header `INS.EWLEN.MAX`

COLUMN [5] = Grating orders range covered by the setting

COLUMN [6] = Minimum grating order providing full-slit spectral coverage

COLUMN [7] = Maximum grating order providing full-slit spectral coverage.

Table 13: Wavelength coverage of CRIRES settings

Name	Ref Wave	LambdaMIN	LambdaMAX	Grating Order range	MIN complete Grating Order	MAX complete Grating Order
Y1029	1029.310	949.649	1120.511	51-59	51	59
Y1028	1027.632	948.026	1118.778	51-59	51	59
J1232	1232.490	1122.298	1330.868	43-50	43	50
J1228	1228.488	1118.476	1326.767	43-50	43	50
J1226	1226.466	1116.546	1356.140	42-50	43	50
H1582	1582.339	1484.075	1854.250	31-39	32	39
H1575	1574.798	1476.653	1845.844	31-39	32	38
H1567	1567.099	1469.084	1837.253	31-39	32	38
H1559	1559.245	1461.369	1828.480	31-39	32	38
K2217	2216.704	1968.714	2527.165	23-29	24	29



K2192	2192.449	1946.077	2500.948	23-29	23	29
K2166	2166.016	1921.468	2472.296	23-29	23	28
K2148	2147.646	1904.398	2452.355	23-29	23	28
L3426	3425.891	2886.255	4193.223	14-20	14	20
L3412	3411.608	2873.573	4176.702	14-20	14	20
L3377	3376.965	2842.872	4136.540	14-20	14	20
L3340	3340.492	2810.627	4094.140	14-20	14	19
L3302	3302.210	2775.889	4049.522	14-20	14	19
L3262	3262.140	2740.603	4002.712	14-20	14	19
L3244	3244.424	2725.025	3981.985	14-20	14	19
M4519	4518.527	3640.452	5918.328	10-16	11	16
M4504	4504.089	3628.157	5900.475	10-16	11	16
M4461	4461.195	3591.705	5847.312	10-16	11	16
M4416	4415.885	3553.308	5791.199	10-16	11	16
M4368	4368.182	3512.986	5731.778	10-16	11	16
M4318	4318.114	3470.761	5669.235	10-16	11	16
M4266	4265.706	3426.660	5603.639	10-16	11	15
M4211	4210.988	3379.981	5535.012	10-16	10	15
M4187	4186.838	3360.014	5504.897	10-16	10	15

7.3 Template Signature Files

7.3.1 Acquisition TSF

The two available acquisition templates are:

- **CRIRES_spec_acq_NGS**: AO assisted spectroscopic observations of sidereal and non-sidereal targets.
- **CRIRES_spec_acq_NoAO**: Seeing limited spectroscopic observations of sidereal and non-sidereal objects.

CRIRES_spec_acq_NGS		
<i>To be specified:</i>		
Parameter	Range (default)	P2 label
SEQ.NGS.ISTARGET	T F (T)	Target = AO Guide Star
SEQ.NGS.ALPHA	(0)	RA of AO guide star



SEQ.NGS.DELTA	(0)	DEC of AO guide star
SEQ.NGS.COLOR	-1..5 (0)	AO guide star: B-R color value
SEQ.NGS.FWHM	0..10 (0.0)	AO guide star FWHM (arcsec)
SEQ.NGS.SNR	0.0..10000.0 (1000)	AO guide star: Minimum S/N
SEQ.NGS.USELASTSKY	T F (F)	Use the last sky measurement for the WFS
SEQ.NGS.SKYALPHA	-30..+30 (4.0)	WFS Alpha sky offset (arcsec)
SEQ.NGS.SKYDELTA	-30..+30 (4.0)	WFS Delta sky offset (arcsec)
SEQ.NGS.ISSVGS	T F (T)	SV Guide Star = AO Guide Star
SEQ.SV.USELASTSKY	T F (T)	Use the last sky measurement for the SV
TEL.SKY.OFFSETALPHA	-120..120 (30.0)	RA offset to sky
TEL.SKY.OFFSETDELTA	-120..120 (30.0)	DEC offset to sky
TEL.AG.GUIDESTAR	NONE SETUPFILE CATALOGUE (CATALOGUE)	Telescope guide star selection
TEL.GS1.ALPHA	(0.0)	RA of telescope guide star
TEL.GS1.DELTA	(0.0)	DEC of telescope guide star
TEL.TARG.OFFSETALPHA	-15..15 (0.0)	RA offset between target and SV guide star
TEL.TARG.OFFSETDELTA	-20..20 (0.0)	DEC offset between target and SV guide star
INS.OPTI1.NAME	FREE GAS_N20 GAS_SGC (FREE)	Optional optical element
INS.DROT.MODE	SKY, ELEV (NODEFAULT)	Derotator: Mode
INS.DROT.POSANG	0.0..360.0 (0.0)	Position angle
INS.SLIT1.NAME	w_0.2, w_0.4 (0.2)	Entrance slit width
INS.WLEN.CWLEN	See Table 13	Standard wavelength setting
TEL.TARG.ALPHA	(NODEFAULT)	Right Ascension
TEL.TARG.DELTA	(NODEFAULT)	Declination
TEL.TARG.EQUINOX	-2000..3000 (2000)	Equinox
TEL.TARG.EPOCH	-2000...3000 (2000)	Epoch
TEL.TARG.PMA	-10..10 (0)	Proper Motion RA
TEL.TARG.PMD	-10..10 (0.0)	Proper Motion DEC
TEL.TARG.ADDVELALPHA	-15..15 (0.0)	Diff RA
TEL.TARG.ADDVELDELTA	-15..15 (0.0)	Diff DEC
Hidden parameters:		
SEQ.PRESET	T F (T)	Preset flag
SEQ.SV.GUIDE	T F (T)	SV guiding



SEQ.FLUX.TOLERANC	0.01..0.10 (0.05)	Flux Tolerance
SEQ.STEPS.EXEC	From PAO CAO AOLP AA0 CA02 PG2 OGS CGS SG PTS OTS CTS ATS (NODEFAULT)	List of template steps to execute
<i>Fixed values:</i>		
DPR.CATG	ACQUISITION	Data product category
DPR.TECH	IMAGE	Data product technique
DPR.TYPE	OBJECT	Data product type

CRIRES_spec_acq_NoAO		
<i>To be specified:</i>		
Parameter	Range (default)	Label
SEQ.SV.USELASTSKY	T F (T)	Use the last sky measurement for the SV
TEL.SKY.OFFSETALPHA	-120..120 (30.0)	RA offset to sky
TEL.SKY.OFFSETDELTA	-120..120 (30.0)	DEC offset to sky
TEL.AG.GUIDESTAR	NONE SETUPFILE CATALOGUE (CATALOGUE)	Telescope guide star selection
TEL.GS1.ALPHA	(0.0)	RA of telescope guide star
TEL.GS1.DELTA	(0.0)	DEC of telescope guide star
TEL.TARG.OFFSETALPHA	-15..15 (0.0)	RA offset between target and SV guide star
TEL.TARG.OFFSETDELTA	-20..20 (0.0)	DEC offset between target and SV guidestar
INS.OPTI1.NAME	FREE GAS_N20 GAS_SGC POL (FREE)	Optional optical element
INS.DROT.MODE	SKY, ELEV (NODEFAULT)	Derotator: Mode
INS.DROT.POSANG	0.0..360.0 (0.0)	Position angle
INS.SLIT1.NAME	w_0.2, w_0.4 (0.2)	Entrance slit width
INS.WLEN.CWLEN	See Table 13	Standard wavelength setting
TEL.TARG.ALPHA	(NODEFAULT)	Right Ascension
TEL.TARG.DELTA	(NODEFAULT)	Declination
TEL.TARG.EQUINOX	-2000..3000 (2000)	Equinox
TEL.TARG.EPOCH	-2000...3000 (2000)	Epoch
TEL.TARG.PMA	-10..10 (0)	Proper Motion RA
TEL.TARG.PMD	-10..10 (0.0)	Proper Motion DEC
TEL.TARG.ADDVELALPHA	-15..15 (0.0)	Diff RA
TEL.TARG.ADDVELDELTA	-15..15 (0.0)	Diff DEC
<i>Hidden Parameters</i>		



SEQ.PRESET	T F (<i>T</i>)	Preset flag
SEQ.FLATTEN_DM	T F (<i>F</i>)	Flatten DM
SEQ.SV.GUIDE	T F (<i>T</i>)	SV guiding
SEQ.FLUX.TOLERANC	0.01..0.10 (<i>0.05</i>)	Flux Tolerance
SEQ.STEPS.EXEC	From PAO CAO AOLP AA0 CA02 PG2 OGS CGS SG PTS OTS CTS ATS (<i>NODEFAULT</i>)	List of template steps to execute
<i>Fixed Values</i>		
DPR.CATG	ACQUISITION	Data product category
DPR.TECH	IMAGE	Data product technique
DPR.TYPE	OBJECT	Data product type

7.3.2 Science observing TSF

Available science observing templates are:

- **CRIRES_spec_obs_AutoNodOnSlit:** AO and NoAO spectroscopic observations performed by nodding along the slit (i.e., recommended for all point source like targets)

The following two science observing templates are not available in observing period 108:

- **CRIRES_spec_obs_GenericOffset:** AO and NoAO spectroscopic observations performed by moving the target along and off slit according to user-defined offsets pattern (i.e., recommended for extended objects).
- **CRIRES_spec_obs_SpectroAstrometry:** AO and NoAO spectroscopic observations performed by nodding along the slit and taken according to user-defined position angles pattern.

CRIRES_spec_obs_AutoNodOnSlit		
<i>To be specified:</i>		
Parameter	Range (<i>default</i>)	Label
DET1.DIT	0..900 (<i>NODEFAULT</i>)	DIT
DET1.NDIT	1..1000 (<i>1</i>)	NDIT
SEQ.NABCYCLES	0..100 (<i>1</i>)	Number of nodding cycles
SEQ.NODTHROW	<i>0.8 (8)</i>	Nod throw along the slit
SEQ.NEXPO	1..100 (<i>10</i>)	Number of exposures per nodding position
SEQ.JITTER.WIDTH	0..8 (<i>0</i>)	Jitter width
INS.OPTI1.NAME	FREE GAS_SGC GAS_N20	Gas cell



INS.SLIT1.NAME	w_0.2, w_0.4 (0.2)	Entrance slit width
INS.WLEN.CWLEN	See Table 13	Standard wavelength setting
INS.METROLOGY	T F (F)	Improve opto-mechanical positioning via metrology function
Hidden parameters:		
SEQ.POISSON	1..100 (100)	Poisson value
SEQ.NO.DELAY	0.0..10.0 (4.0)	Nodding delay in seconds
SEQ.RETURN	T F (T)	Return to origin
SEQ.FLUX.TOLERANC	0.01..0.10 (0.05)	Flux Tolerance
Fixed values:		
DPR.CATG	SCIENCE	Data product category
DPR.TECH	SPECTRUM	Data product technique
DPR.TYPE	OBJECT	Data product type

CRIRES_spec_obs_GenericOffset		
<i>To be specified:</i>		
Parameter	Range (default)	Label
DET1.DIT	0..900 (NODEFAULT)	DIT
DET1.NDIT.OBJECT	1..100 (1)	NDIT for the OBJECT positions
DET1.NDIT.SKY	1..100 (1)	NDIT for the SKY positions
SEQ.NEXPO	1..100 (1)	Number of exposures on each position
SEQ.NOFF	1..100 (1)	Number of offset positions
SEQ.OBSTYPE.LIST	O S (NODEFAULT)	List of observation types (O or S)
SEQ.OFFSET.COORDS	SKY DETECTOR (SKY)	Offset coordinate type selection
SEQ.OFFSET1.LIST	(NODEFAULT)	List of offsets in RA or X
SEQ.OFFSET2.LIST	(NODEFAULT)	List of offsets in DEC or Y
INS.OPTI1.NAME	FREE GAS_N20 GAS_SGC	Gas cell
INS.SLIT1.NAME	w_0.2, w_0.4 (0.2)	Entrance slit width
INS.WLEN.CWLEN	See Table 13	Standard wavelength setting
INS.METROLOGY	T F (F)	Improve opto-mechanical positioning via metrology function
Hidden Parameters		
SEQ.NEXPOSKIP	0	Skip N positions



SEQ.NOD.DELAY	0.0..10.0	Nodding delay in seconds
SEQ.RETURN	T F (T)	Return to origin
SEQ.FLUX.TOLERANC	0.01..0.10 (0.05)	Flux Tolerance
Fixed values:		
DPR.CATG	SCIENCE	Data product category
DPR.TECH	SPECTRUM, GENERIC	Data product technique
DPR.TYPE	OBJECT	Data product type

CRIRES_spec_obs_SpectroAstrometry		
To be specified:		
Parameter	Range (default)	Label
DET1.DIT	0..900 (NODEFAULT)	DIT
DET1.NDIT	1..1000 (1)	NDIT
INS.DROT.POSANGLIST	0.0..360.0 ()	List of position angles
SEQ.NABCYCLES	0..100 (1)	Number of nodding cycles
SEQ.NODTHROW	0.8 (8)	Nod throw along the slit
SEQ.NEXPO	1..100 (10)	Number of exposures per nodding position
SEQ.JITTER.WIDTH	0.8 (0)	Jitter width
SEQ.JITTER.RESET	T F (T)	Reset jitter for each DROT posang
INS.DROT.POSANG.LIST	0.0..360.0	List of position angles in degrees (cumulative values)
INS.OPTI1.NAME	FREE GAS_N20 GAS_SGC (FREE)	Gas cell
INS.SLIT1.NAME	w_0.2, w_0.4 (0.2)	Entrance slit width
INS.WLEN.CWLEN	See Table 13	
INS.METROLOGY	T F (F)	Improve opto-mechanical positioning via metrology function
Hidden parameters:		
SEQ.POISSON	1..100 (100)	Poisson value
SEQ.NOD.DELAY	0.0..10.0	Nodding delay in seconds
SEQ.RETURN	T F (T)	Return to origin
SEQ.FLUX.TOLERANC	0.01..0.10 (0.05)	Flux Tolerance
Fixed values:		
DPR.CATG	SCIENCE	Data product category
DPR.TECH	SPECTRUM	Data product technique
DPR.TYPE	OBJECT	Data product type



7.3.3 Calibration TSF

Available night-time calibrations templates are:

- **CRIRES_spec_cal_AutoNodOnSlit**: AO and NoAO spectroscopic observations performed by nodding along the slit (i.e., recommended for telluric and spectrophotometric standards)
- **CRIRES_spec_cal_LampFlats**: attached flat fields
- **CRIRES_spec_cal_Wave**: attached wave lamp
- **CRIRES_spec_cal_Darks**: attached darks

CRIRES_spec_cal_AutoNodOnSlit		
<i>To be specified:</i>		
Parameter	Range (default)	Label
DET1.DIT	0..900 (NODEFAULT)	DIT
DET1.NDIT	1..1000 (1)	NDIT
SEQ.NABCYCLES	0..100 (1)	Number of nodding cycles
SEQ.NODTHROW	0..8 (8)	Nod throw along the slit
SEQ.NEXPO	1..100 (10)	Number of exposures per nodding position
SEQ.JITTER.WIDTH	0..8 (0)	Jitter width
INS.SLIT1.NAME	w_0.2, w_0.4 (0.2)	Entrance slit width
INS.OPTI1.NAME	FREE GAS_SGC GAS_N20	Gas cell
INS.WLEN.CWLEN	See Table 13	Standard wavelength setting
INS.METROLOGY	T F (F)	Improve opto-mechanical positioning via metrology function
<i>Hidden parameters:</i>		
SEQ.POISSON	1..100 (100)	Poisson value
SEQ.NO.DELAY	0.0..10.0 (4.0)	Nodding delay in seconds
SEQ.RETURN	T F (T)	Return to origin
SEQ.FLUX.TOLERANC	0.01..0.10 (0.05)	Flux Tolerance
<i>Fixed values:</i>		
DPR.CATG	SCIENCE	Data product category
DPR.TECH	SPECTRUM	Data product technique
DPR.TYPE	OBJECT	Data product type



7.4 Data format and reduction

7.4.1 Format

The SV image and the spectra recorded on the three science detectors are saved in extended FITS files. Each of the 3 extensions of the science images has a size of 2048 x 2048 pixels (see Figure 6).

7.4.2 Selection of CRIRES FITS header keywords

FITS header keyword	Parameter
OBJECT	Object name
MJD-OBS	Modified Julian Date at start of exposure
HIERARCH ESO DET SEQ1 DIT	Length of sub exposure (DIT) in seconds
HIERARCH ESO DET NDIT	Number of sub exposures (NDIT)
HIERARCH ESO INS WLEN ID	Name of the selected wavelength setting
HIERARCH ESO INS SLIT1 WID	Slit width in arcsec
HIERARCH ESO INS OPTI8 NAME	Decker position for polarimetry
HIERARCH ESO INS1 OPTI1 NAME	Optical element (polarimeter, gas cell, ...) from the carriage in the light path.
HIERARCH ESO SEQ NODPOS	Nodding position (A or B)
HIERARCH ESO SEQ NODTHROW	Nodding throw along the slit (in arcsec)
HIERARCH ESO AOS RTC LOOP STATE	AO loop state: open or closed
HIERARCH ESO OCS MTRLGY ST	“T” if metrology converged. Keyword only present if metrology was used.

7.4.3 Pipeline

CRIRES+ comes with a new Data Reduction System (DRS) package that is incompatible with data from the oCRIRES. The DRS follows ESO standards for data reduction pipelines and uses the usual tools for execution. It calibrates the detector properties and characterizes the location of the spectral orders on the three detectors for each wavelength-setting. It further measures the orientation and shape of the spectrograph slit and uses this information to optimally extract spectra into 1D. Lastly, it calibrates the wavelength scale and applies the calibrations to the science observations before treating them in the appropriate way, e.g. combining and pair-wise subtracting nodding observations.

The naming scheme of DRL recipes indicates their respective role, like this:



- *cr2res_cal_** indicates calibration recipes that create master calibrations. These are usually triggered by calibration templates.
- *cr2res_obs_** are comprehensive recipes that get master calibrations and science data as input and perform all necessary reductions steps until the final products.

*cr2res_util_** are recipes with smaller scope, typically executing a single reduction step each. These are both useful for testing and for manual step-by-step reductions.

All offered observing modes are supported and data products are deemed to be science ready. The pipeline and corresponding User Manual can be downloaded at:

<http://www.eso.org/sci/software/pipelines/>

--- End of document ---