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CRIRES User Manual

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Change Record from previous Version

Affected Section(s)	Changes / Reason / Remarks
All	First version after on sky commissioning, to be used for operation
All	Phase 2 for P108; implementation of results from Comm3
Chapters 4-7	Spectro-polarimetry and off-axis templates added; generic offsets, differential tracking and spectro-astrometry; major revision concerning observing limits and overheads; implementation of results from Comm4
4.5, 7.2	Characterization of polarimetry mode, update of wavelength table
4.3.1 4.4.2, 4.6.4, 7.1, 5.2, 6.3.5, 5.6, 6.4.1, 6.4.3 6.6.5	Table 2 - detector gain for detector 1 corrected Guiding on binaries or guide stars with close companions Calibration plan: high S/N flats added Metrology offered in the L-band Update of overheads table DITs in SM; limits for M-band adjusted Clarification of generic offset details New section for polarimetric standard stars (v2021-11-22)
4.3.1 6.4.1	Detector non-linearity section updated Recommendation to use NDIT=1 for long DITs (v2021-12-01)

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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 star (= AO star)
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
S/N	Signal-to-Noise Ratio
SR	Strehl Ratio
SV	Slit Viewer
SVGS	Slit Viewer 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/crires.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 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/crires/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 do not hesitate to contact the ESO User Support Department:

https://support.eso.org

For Visitor Mode related questions before your scheduled run the Paranal Science Operations Team will assist you:

paranal@eso.org

For instrument specific questions please contact:

crires@eso.org

2. Overview

2.1 CRIRES in a nutshell

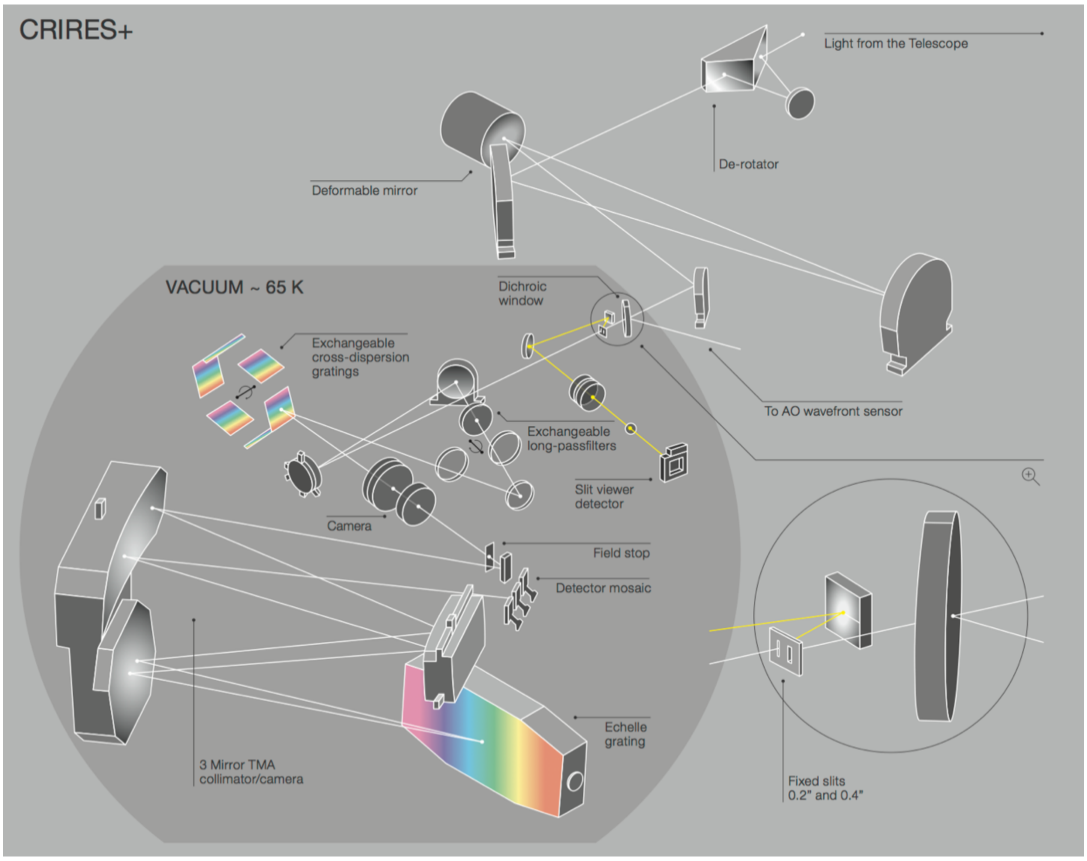

Figure 1: Optical layout of CRIRES

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

Min. spectral resolving power	40,000 and 80,000[1]
Wavelength coverage	0.95 - 5.3 µm (YJHKLM bands)
RV precision	20 m/s by using the Short Gas Cell (SGC)
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 4.6.6 for more details on ongoing analysis

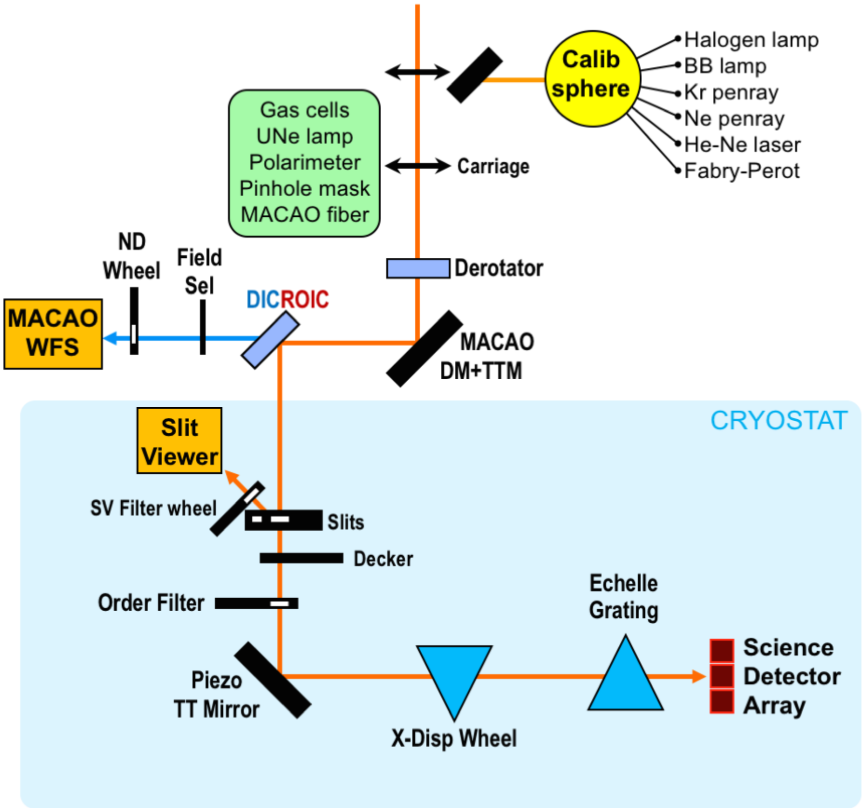

Figure 2: Light path sketch of the upgraded CRIRES.

The CRIRES instrument mounted at UT3 of the Very Large Telescope (VLT) observatory is an upgraded version of the original/old CRIRES (oCRIRES) instrument, which was in operation from 2006 to 2014 at the UT1 of the VLT. 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 in the wavelength regime from 0.95 to 5.2 micron. The setup, however, 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 up to a factor of ten. A new and larger detector focal plane array of three Hawaii 2RG detectors with 5.3µm cut-off wavelength replaced the existing detectors. For advanced wavelength calibration, custom-made absorption gas cells and a Fabry-Perot etalon system have been added. A spectro-polarimetric unit allows 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.

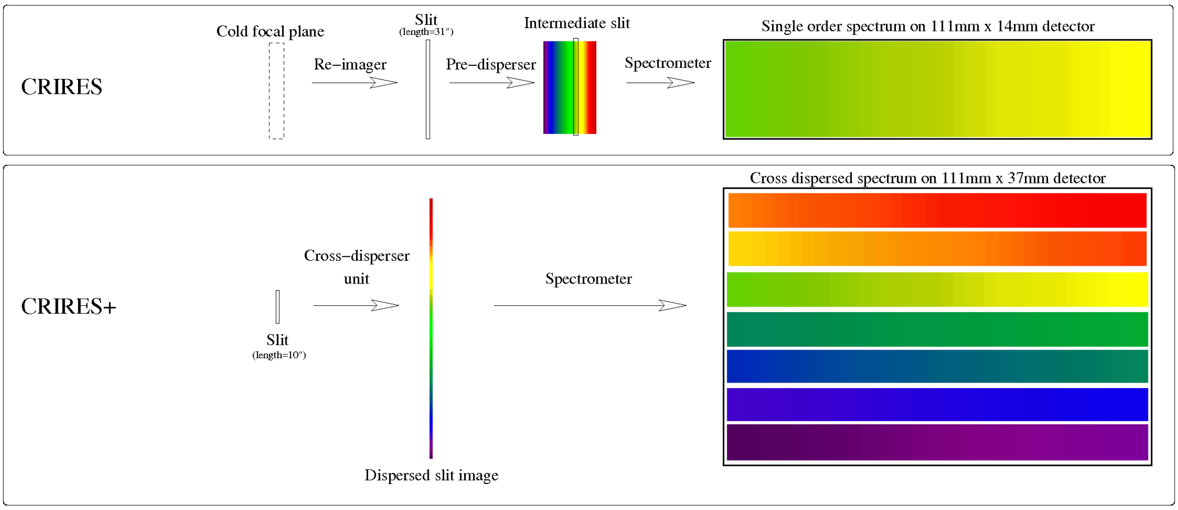

Figure 3: Schematic diagram summarizing the differences between oCRIRES and CRIRES after the upgrade

2.2 Science Drivers

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

2.2.1 Follow-up of terrestrial planets in the habitable zone around 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_{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 their habitable zones are quite close to the star. The reflex motion of an M star (0.15 M_{sun}) with a 1 M_{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 µm), a high-resolution IR spectrograph is therefore ideal for following-up low mass planets around these objects.

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 fields

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 makes 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.

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 into the light-path. A carriage stage (not depicted in Fig.1) can then insert one of the following elements into 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) a Uranium-Neon Lamp for absolute 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 three 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 of the spectrograph through a dichroic window.

The optical light is reflected and used for the adaptive optics system, the infrared light (0.95 µm < λ < 5.3 µm) is 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 Section 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 box "A"), which comprises a movable mask with two slits: 0.2" (minimum resolving power 80,000) 0.4" slit (minimum resolving power 40,000) 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 decker 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 allows 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 significantly enhances 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.

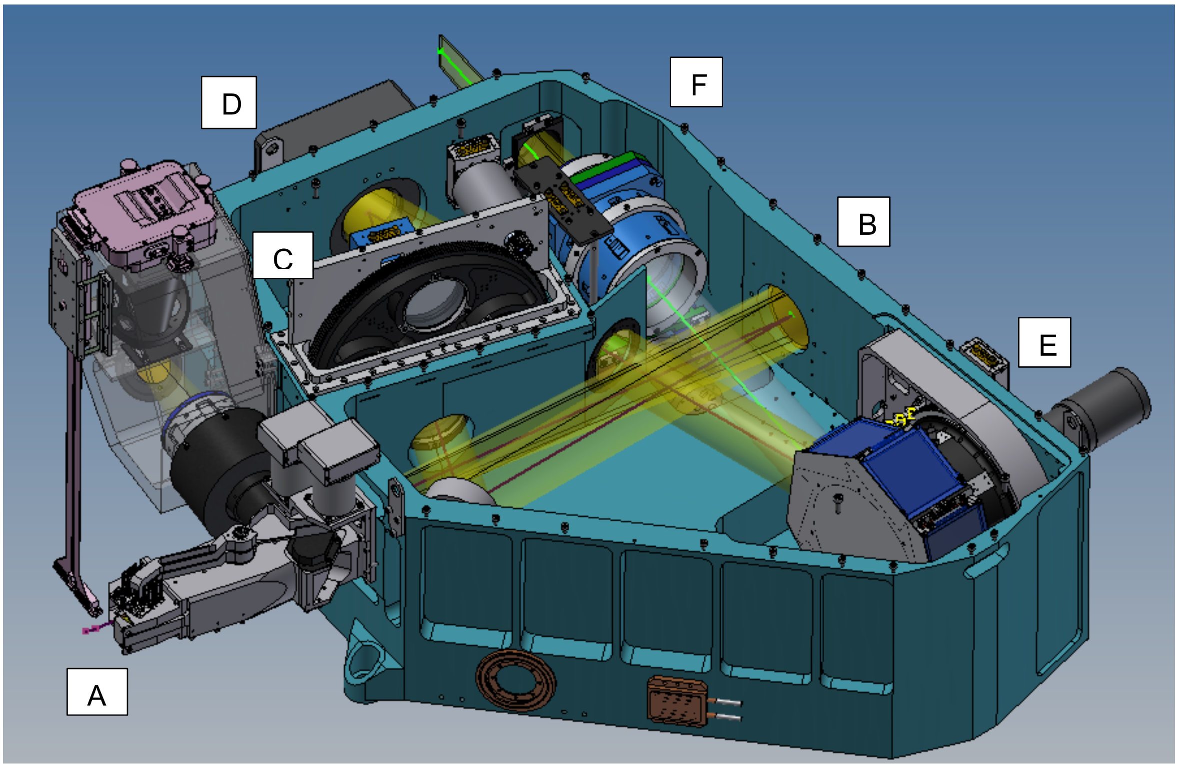

Figure 4: Top view of the new CRIRES fore-optics assembly

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 and echelle grating.

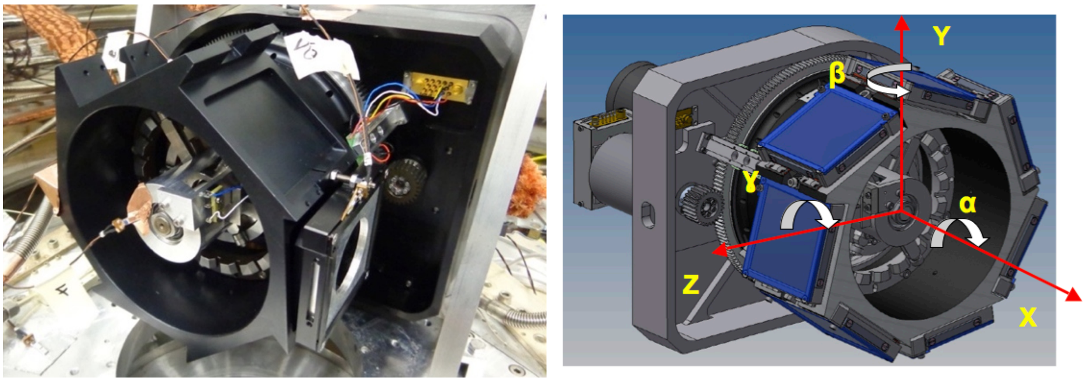

Figure 5: Grating wheel design with locking mechanism and build prototype

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 x 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 6144x2048 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 up to 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 x 2048 pixels (111mm x 37mm) at a pixel size of 18µm. For comparison, the old Aladdin mosaic spanned only 4096 x 512 pixels (111mm x 14mm) with a pixel size of 27µm, as described in Dorn et al. (2006).

The new detector mosaic does not only provide a larger area but also lower noise, higher quantum efficiency and a 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.

All detector systems, including the slit viewer camera, were 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 results 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.

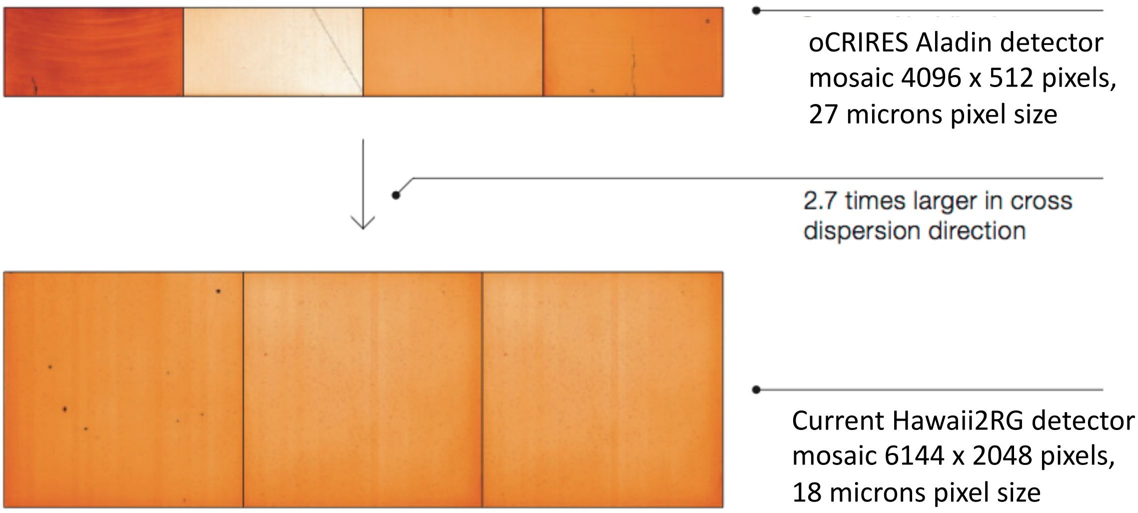

Figure 6: The original CRIRES detector mosaic focal plane array area compared to the new detectors with an increase of a factor of 2.7 in the cross-dispersion direction.

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

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 metrology concept

In order to stable exposures with high repeatability, the concept of a metrology system was developed to allow for a 0.1-pixel 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 NITER = 5 / Total number of iterations performed
HIERARCH ESO OCS MTRLGY ST = T / Success or failure 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
```

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 Section 5.6).

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.

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.

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.

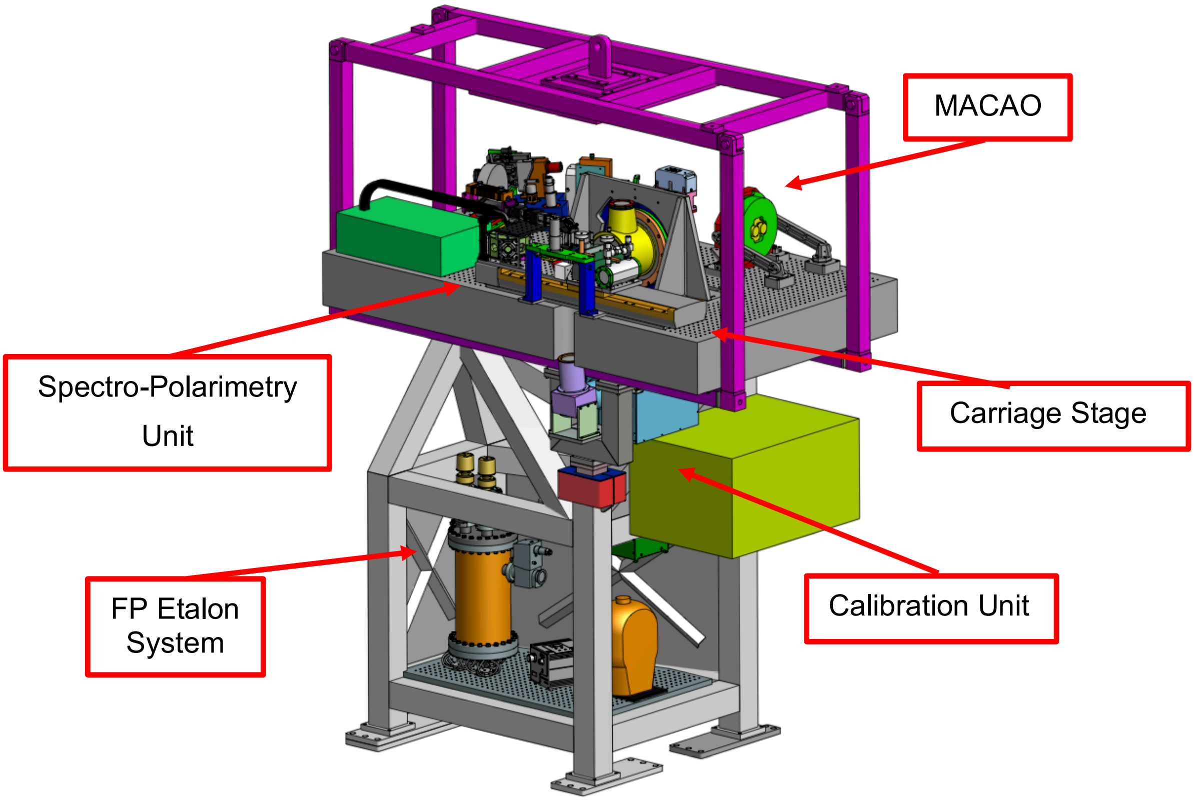

Figure 8: The upgraded CRIRES warm part assembly with etalon system, calibration slide, AO system and de-rotator mechanism

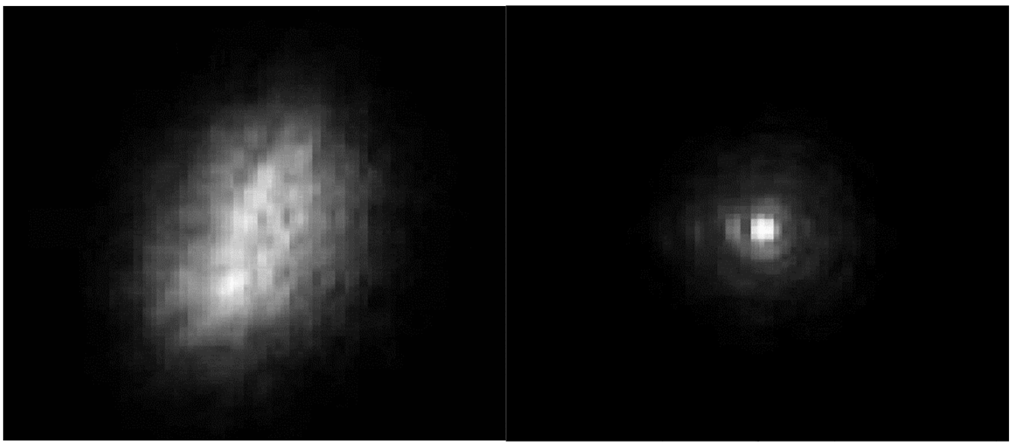

Figure 9: PSF without (left) and with (right) MACAO correction. Images have been taken in lab using a turbulence generator.

3.2.1.1 Atmospheric Turbulence

The VLT theoretical diffraction limit is 1.22×l/D = 0.07 arcsec at a wavelength of 2.2 µm. However, temperature inhomogeneities in the atmosphere induce temporal and spatial fluctuations in the air refractive index and 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 ~60 ms at 2.2µm 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).

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. 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.

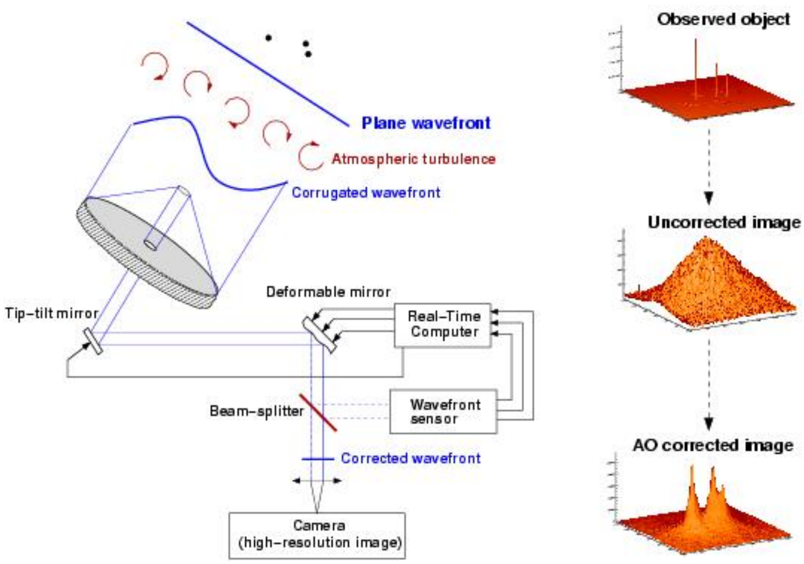

Figure 10: Principle of Adaptive Optics. Note that in practice, and contrary to this schematic design, CRIRES has no dedicated tip-tilt mirror, but performs low- and high-order correction with a single deformable mirror mounted on a tip-tilt stage (see Figure 12).

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 ms) and a bright (i.e., R < 7), nearby (i.e., within ~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.

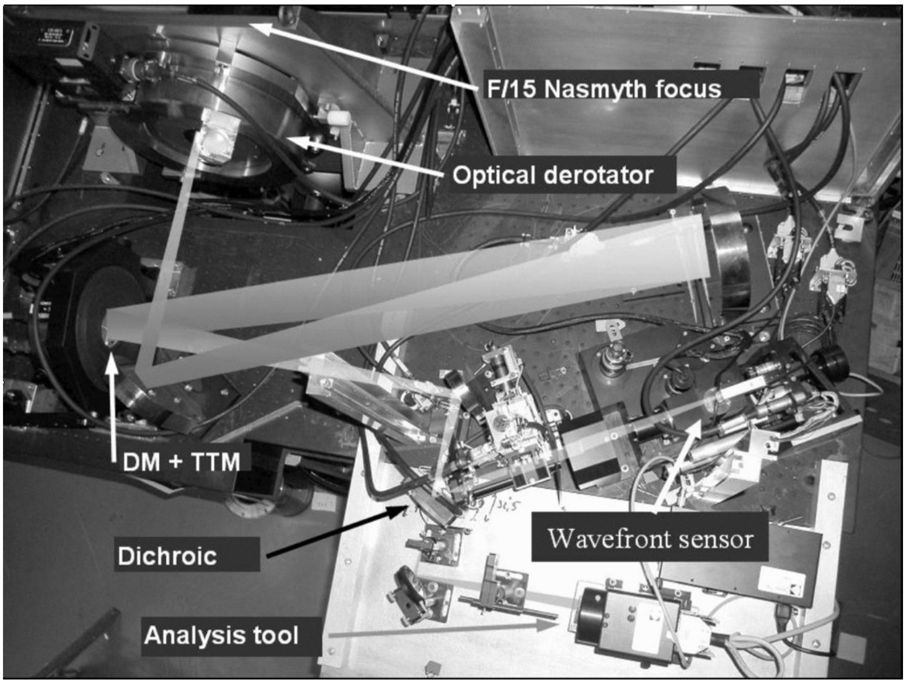

Figure 11: Top view of the warm optics of the MACAO-CRIRES system. From f/15 Nasmyth focus and after the optical derotator, one notices the deformable mirror and the tip-tilt mount assembly. Light enters from the dichroic to the cold and warm part of the instrument. On the right the wavefront sensor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

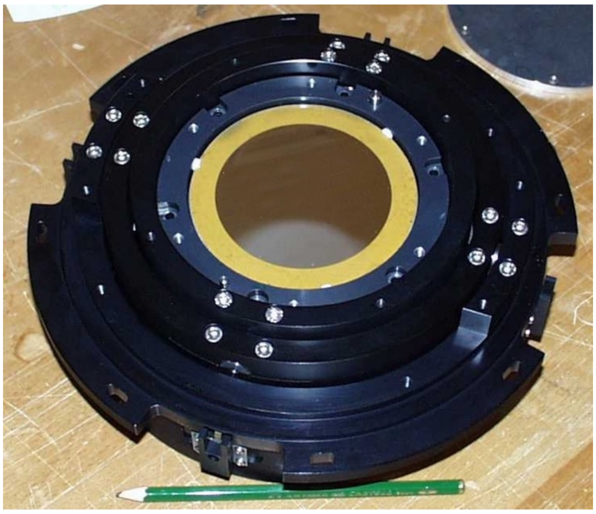

Figure 12: Assembly of the deformable mirror (DM) and tip-tilt mount (TTM)(left) and of the gimbal mount (right).

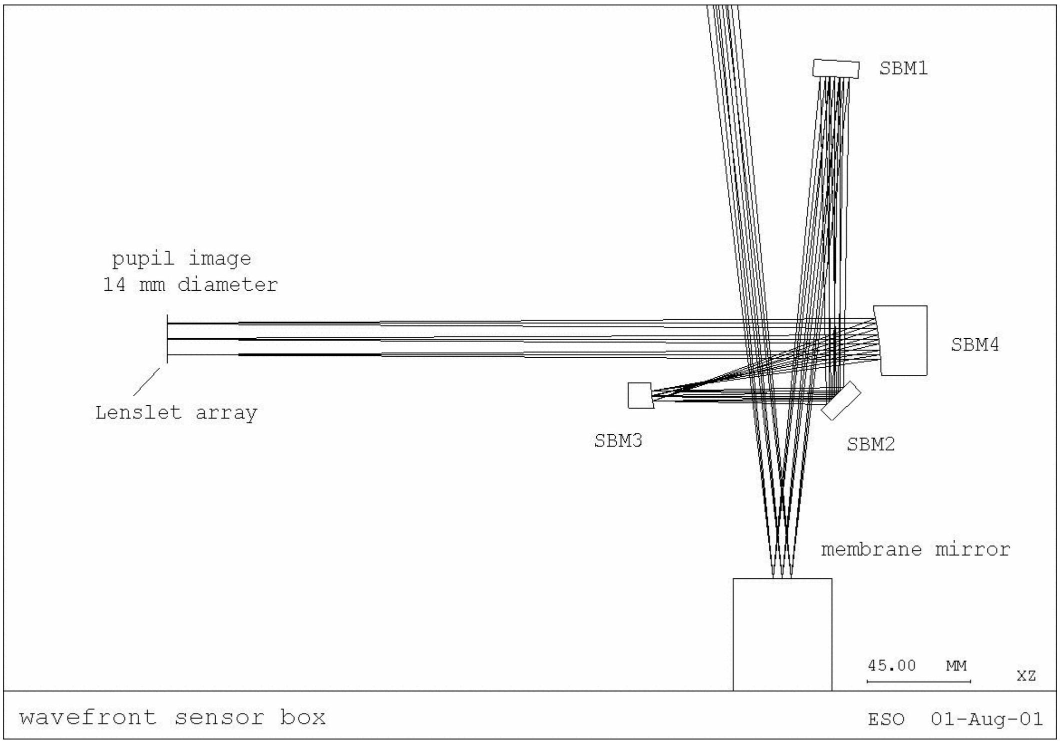

Figure 13: The optical path of the wavefront sensor box.

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 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 .

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 mechanical stroke corresponding to ±3.6'' on the sky. The assembly of the DM and tip-tilt mount is shown in Figure 12.

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 within a 25" circle from the slit center, 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.

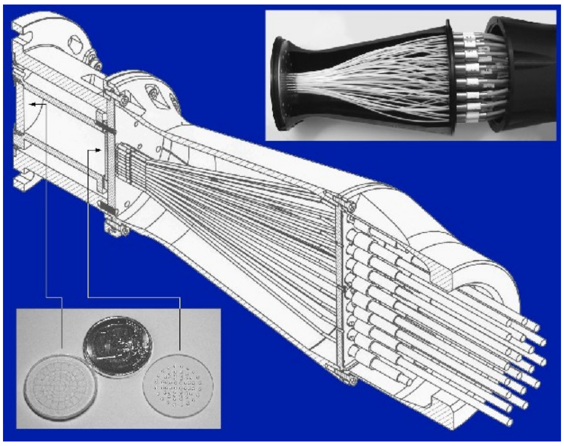


Figure 14: Front-end assembly of the 60 fiber bundle which guide the light to the sensors.

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.

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.

3.2.3 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, Kr/Ne lamps, a He-Ne laser for spectral resolution measurements and the Fabry-Perot Etalon System (FPI) fibre 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.

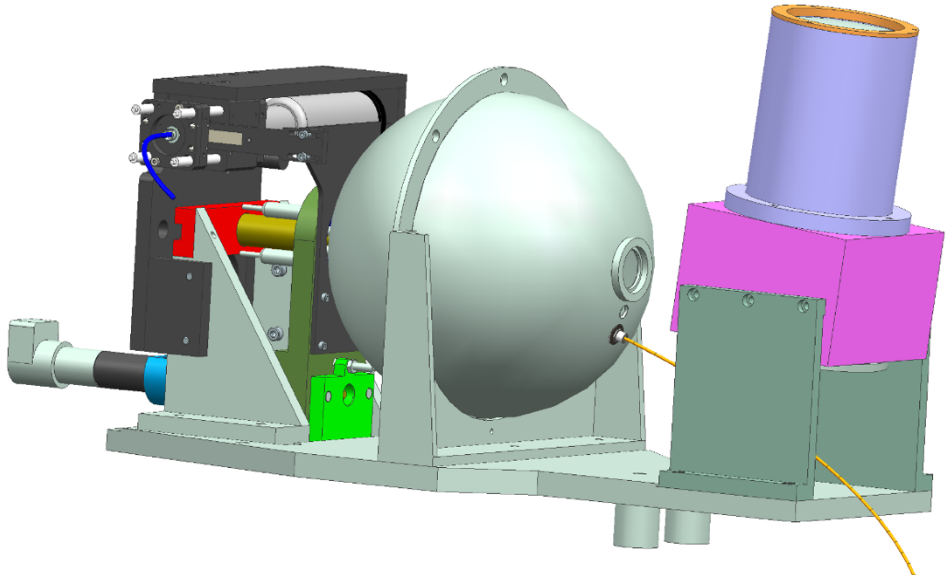

Figure 15: Integrating Sphere assembly. The FPI- fiber is visible on the right.

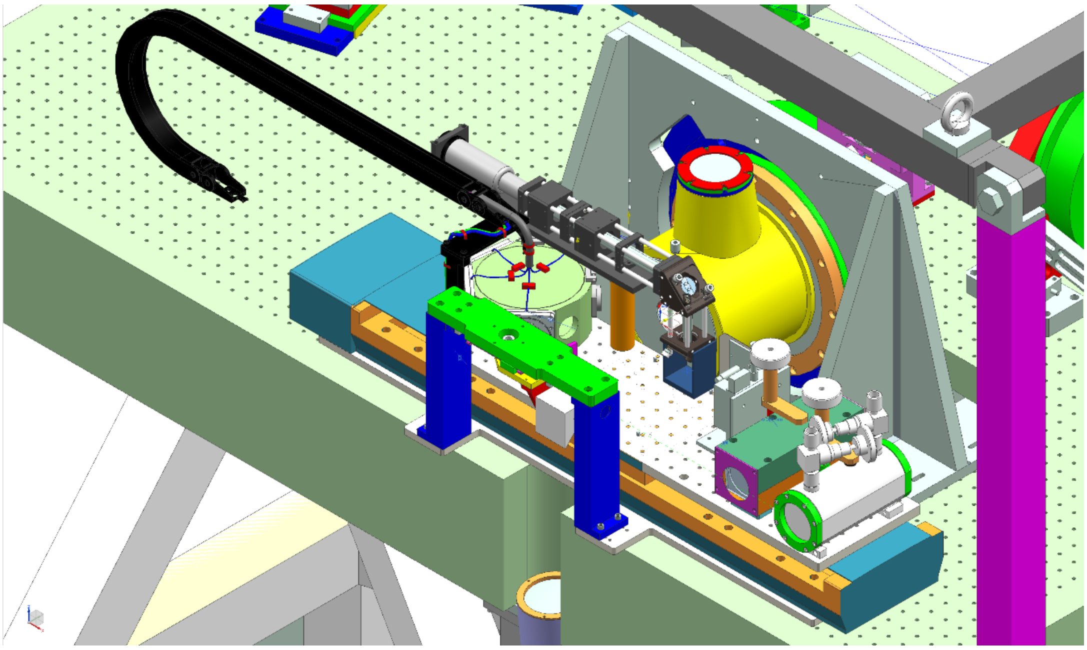

Figure 16: Calibration carriage stage assembly.

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.

3.2.3.1 Gas cells

The CRIRES 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, $^{13}CH_4$, C_2H_2). These gases provide a set of densely distributed absorption lines imprinted on the stellar spectra in the *H*- and *K*-bands (see Figure 17). Note that the pipeline will not calculate the wavelength solution based on the gas cell data; this is left to the experienced user.

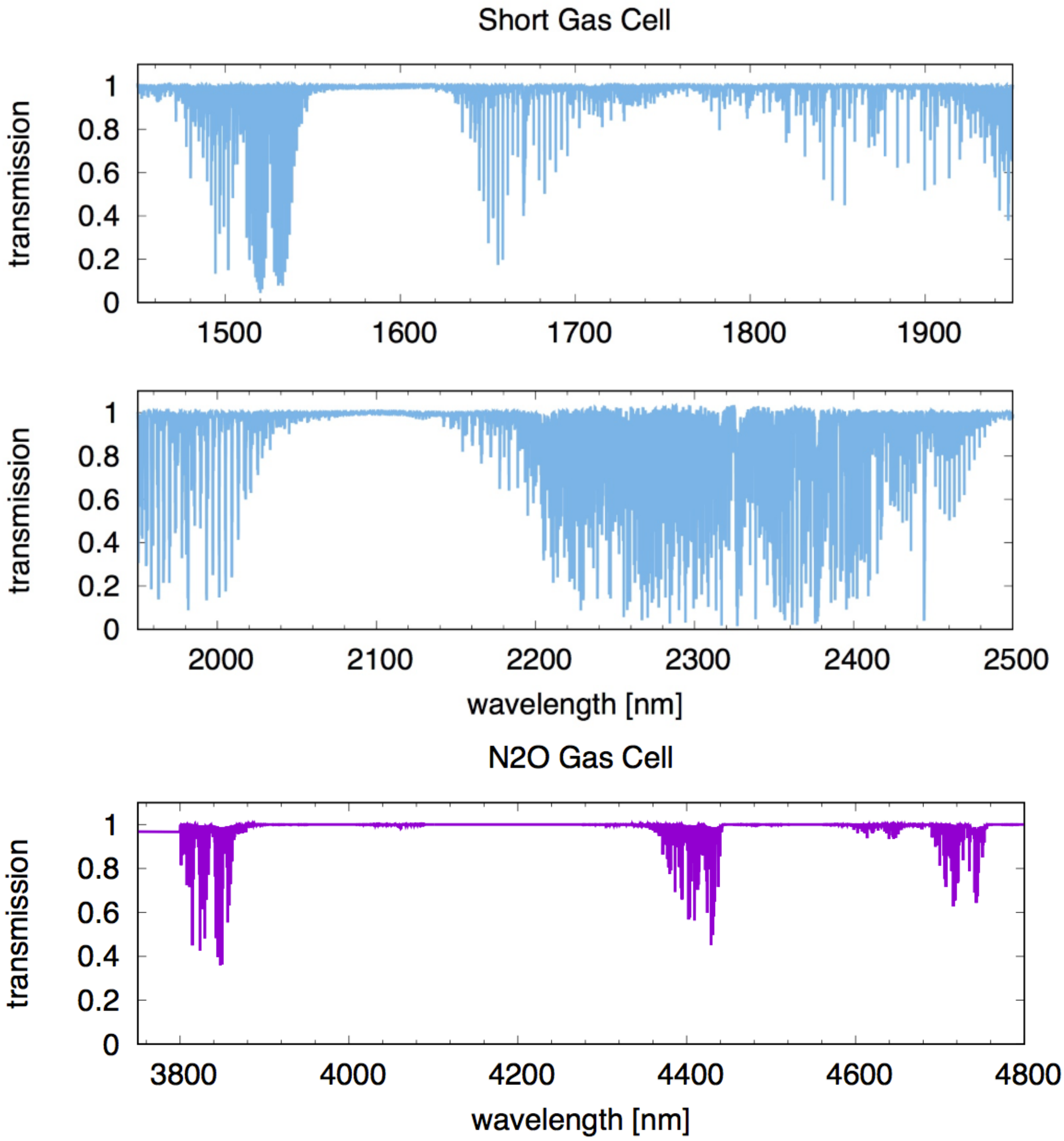

Figure 17: Absorption line spectrum of the new short gas cell (SGC) in the H and K bands (top) and the N_2O gas cell in the L and M bands (bottom). The FTS scan of both cells is provided on the CRIRES webpages under 'Tools'.

3.2.3.2 Uranium-Neon Lamp and Fabry Perot Etalon System

The absolute wavelength calibration reference of CRIRES is a Uranium-Neon (UNE) lamp, which produces a richer emission line spectrum in comparison to the Thorium-Argon hollow cathode lamp used in the old CRIRES instrument. In addition, CRIRES now offers a Fabry-Perot etalon, following a recommendation during the design reviews. Such a relative 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.

Any Fabry-Perot etalon produces just relative wavelength values, but not absolute ones. For this reason, the zero point of the Fabry-Perot etalon needs to be determined by taking exposures with the UNE lamp right before or after any Fabry-Perot etalon exposure.

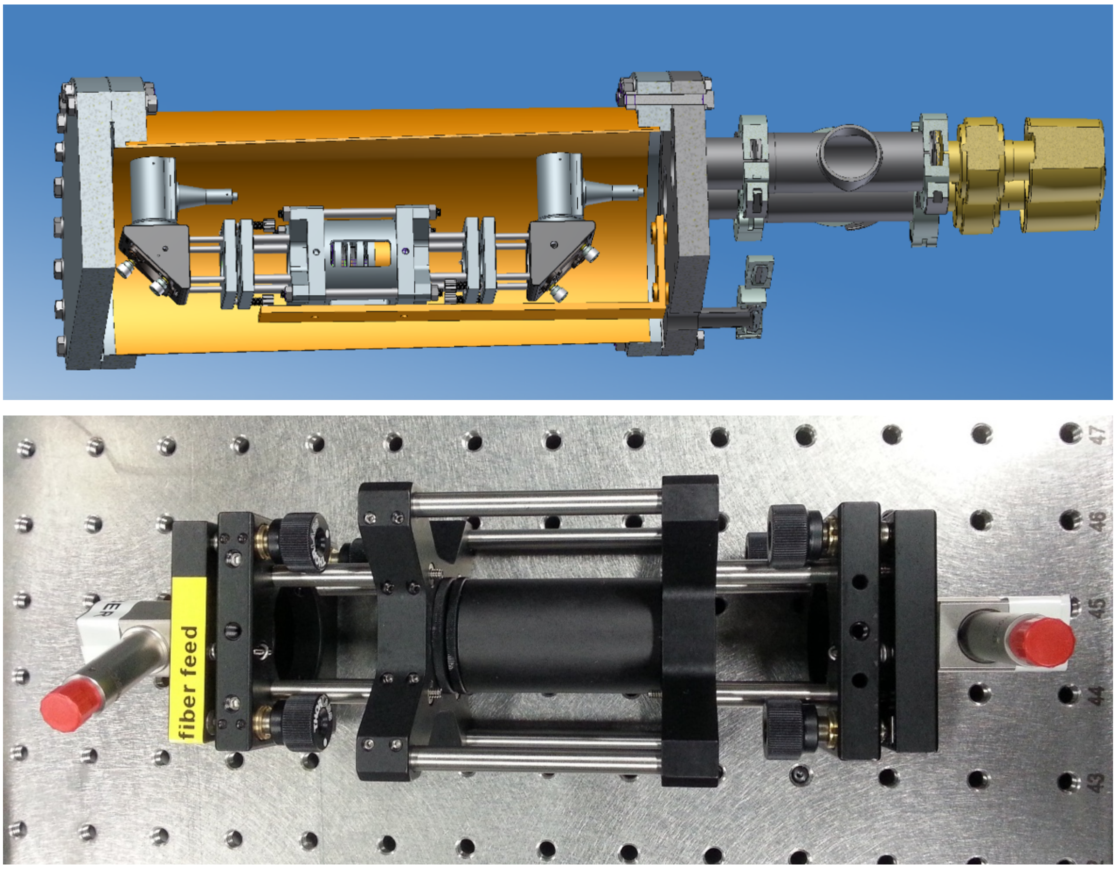

Figure 18: Top: 3D Model of the FPI system in the vacuum chamber (cut view). The vessel layout and gauges are also shown. Bottom: Simplified working proto-type FPI unit.

The major advantages are comb-like, equidistant reference lines over the design range with high homogeneity, equally strong spectral features, 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 min) to ≤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 (Figure 19). The FPI feeds a fibre which delivers the FPI spectrum to the integrating sphere. The calibration system is described in 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.
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 1.1526µm and 3.3922µm. 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. Serves as absolute wavelength reference.
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 20) uses 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 carriage (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.

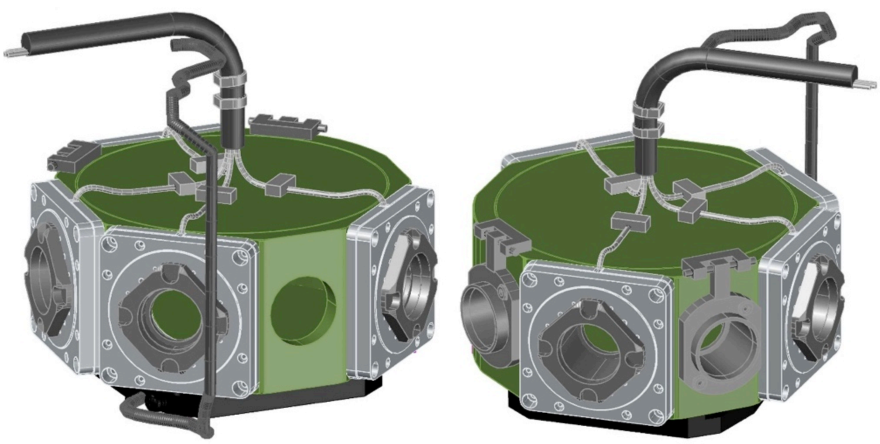

Figure 20: Spectro-Polarimetry Unit (SPU) view from the derotator side (left) and from the telescope side (right). Polarization optics are mounted from the side of rotating turret.

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, while it is limited by the detector performance in the Y, J and H bands. Based on data collected during the first and second on-sky commissioning runs, as well as in the integration hall at ESO Garching:

- Spectral resolution of at least 40,000 and 80,000 can be achieved with slit width of 0.4" and 0.2", respectively.
- The throughput is ~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 <0.2px 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 closed 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 spectrometer in K and M band, respectively (see Figure 21).

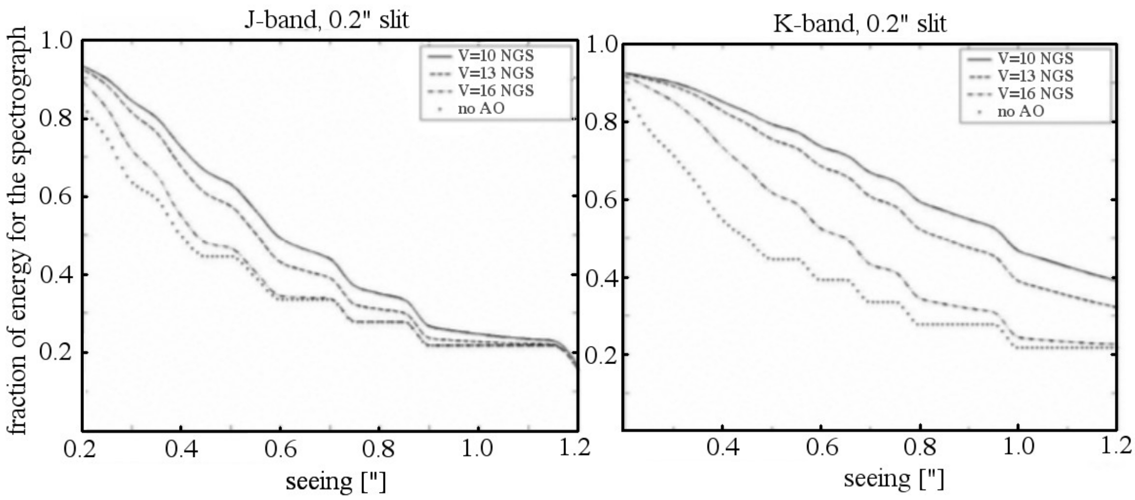

Figure 21: The fraction of energy available for the spectrograph in a 0.2" slit as a function of the optical seeing is shown for the J (left) and K (right) band for NGS of V=10, 12, 16 mag and without AO correction. For reference, please consult the ETC.

For seeing >1.4", the AO correction becomes very poor and unstable and will not result in any improvement with respect to the NoAO mode. Therefore, AO observations are not allowed under Turbulence Category of 100% (see 5.3.1 for more details on the user constraints). **Because the AO correction also strongly degrades with airmass, we strongly recommend observing at low airmass (≤1.4) only.** This is especially important for off-slit NGS, as the AO correction of the target further degrades with increasing distance between the NGS and the slit. In any case, airmass values > 2.0 must be avoided whenever employing AO.

Figure 22 illustrates the increased throughput when the AO system is employed. The graph shows the spatial profiles of the spectro-photometric 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.

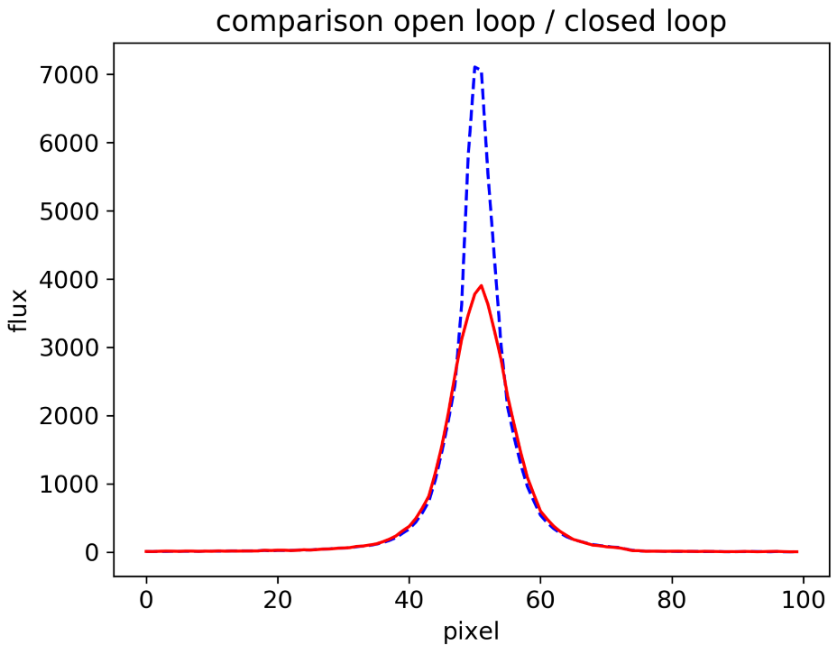

Figure 22: Improved throughput thanks to the use of AO. H-band flux of the star Pi.02 Ori measured along the 0.4” slit in open (solid red line) and closed loop (dashed blue line).

4.2.1.1 AO natural guide stars

CRIRES wavefront sensing is done in the R band (Johnson/Bessell). The performance of the AO system depends on the distance to the science target and on the brightness of the selected natural guide star (NGS) for AO. 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 from the slit centre

Although nominally the field selector allows the selection of the AO NGS star up to 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. With excellent atmospheric conditions, mild improvement in the amount of encircled energy can still be obtained if an AO star with an R-band magnitude < 11 is used 20-25” away 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.

Note that any AO NGS being separated by more than 10 arcsec from the target must be at brighter than R=12. This is for the reason that otherwise the AO system would become unstable and the AO performance very poor. Likewise, for any AO NGS that is more than 10 arcsec away from the target, the high airmass limit is 1.4.

Note that for polarimetry as well as for spectro-astrometry, the AO NGS star needs to be the target (i.e., no off-slit AO star possible in these modes).

4.2.1.3 The brightness of the AO star

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 ~ 11 mag. Brighter stars up to a bright magnitude limit of R ~ 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~14 mag under very good seeing conditions, while moderate image quality improvement may be seen with stars as faint as R~15 mag under excellent conditions (0.6”) and coherence time (5.2 ms). Stars fainter than R~15 mag will not result in any improvement and NoAO must be used instead, as the AO loop would not close on these targets.

Therefore, the allowed AO NGS magnitude range is: 0.2 < R < 15 (see 5.3.1 for 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 considers 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 on the slit for airmass > 1.2 when guiding with the slit viewer is not possible, as for example, if an off-slit AO star is outside the field-of-view of the slit viewer detector.

4.3 Science detector characteristics

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 18µm (see Figure 6).

The detector read-out mode is always the “Sample-Up-The-Ramp” mode (Figure *23*). 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 NDITxDIT. **The minimum DIT is 1.427s; it is not possible to integrate shorter than that.**

Example: let us assume that for a given setting the combination of DIT=2 and NDIT=1 yield a flux level of 6000 ADU in a specific detector pixel. If NDIT is changed to 4, then the flux value of the same detector pixel will be still ~6000 ADU, as it is the averaged value of the four integrations. However, the signal-to-noise ratio (S/N) will be about twice as high than as for NDIT=1. Note that for each NDIT, the read-out noise listed in *Table **2*** applies. This means that the larger the number of NDIT, the higher the overall read-out noise per exposure, which will result in a lower signal-to-noise ratio in the observations.

The optimum combination of DIT and NDIT should be determined with help of the Exposure Time Calculator (ETC, see Section 5.5). Bright objects or observations in the L or M bands (high thermal background) will require short DITs to stay below saturation due to the thermal background, as heavily saturated pixel will lead to detector persistence that require a couple of minutes to decay to the extent that it does not affect subsequent exposures anymore.

Note that the parameter NDIT should not be confused with NEXPO, which is the number of subsequent exposures (DIT x NDIT). Any exposure will be saved independently (i.e., NEXPO=2 will produce two FITS files).

For all detectors, at least 2% of the detector pixels are bad, with detector 3 (right) being the most affected one.

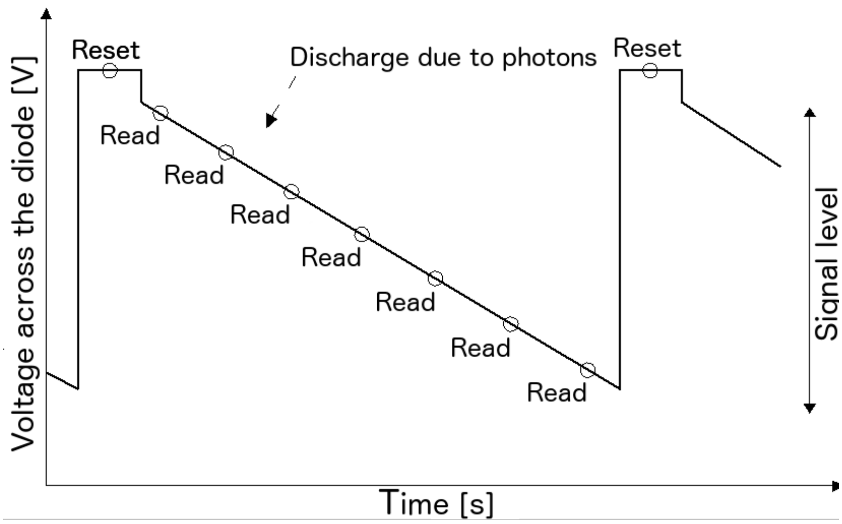

Figure 23: "Sample Up The Ramp" read-out mode. Before each integration, the pixels are reset to the initial capacity. During the integration, the detector is non-destructively read (from two readings in case of the minimum DIT up to a maximum of 36 readings for long DITs). These detector readings are equidistantly spaced in time. The flux rate per pixel corresponds to the slope of the flux values of the subsequent readings.

4.3.1 Dark current 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 24 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]		2.15	2.19	2.00
Quantum Efficiency @2000nm [%]		93	98	95
Read-out noise [e^-RMS]	MinDIT=1.427s	11	12	12
	DIT<50s	*interpolation between the upper and lower value accordingly to selected DIT*		
	DIT≥50s	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

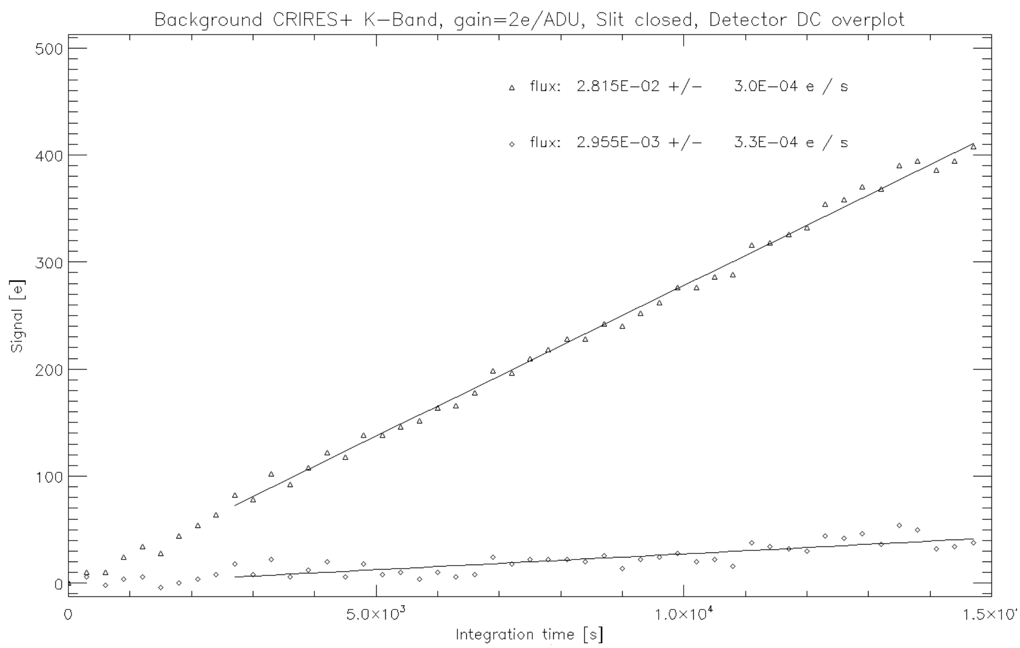

Figure 24: Dark current of detector #3 measured in K band

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 **25*** and *Figure **26***).

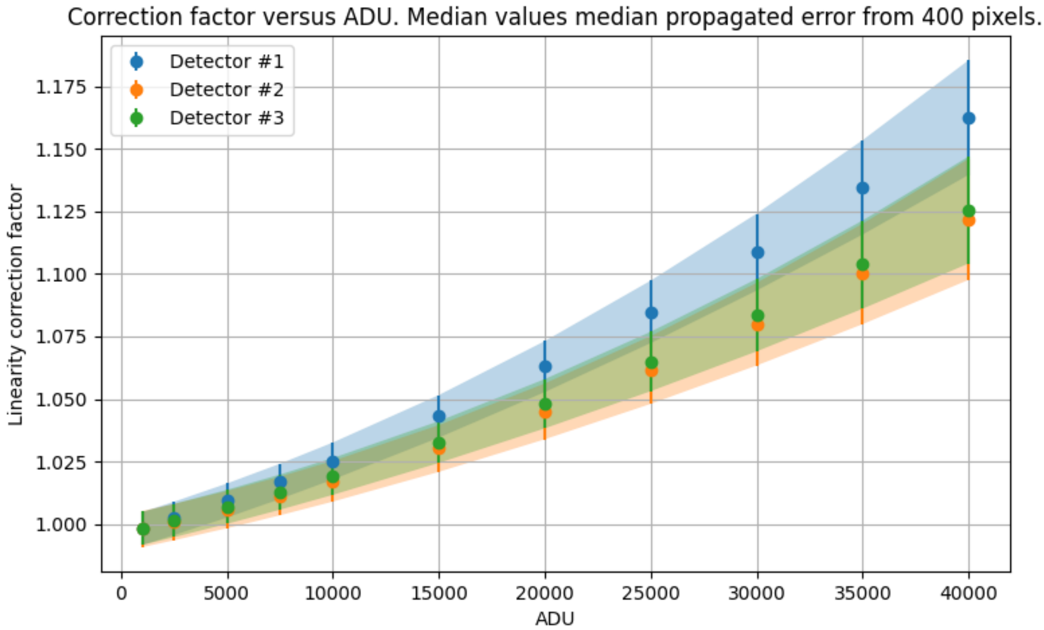

Figure 25: Correction for non-linearity effects implemented by the pipeline. The correction factor from the polynomial fits (pixel-by-pixel), evaluated at certain ADU-levels and plotted as medians and 1-sigma shaded regions over all pixels is shown.

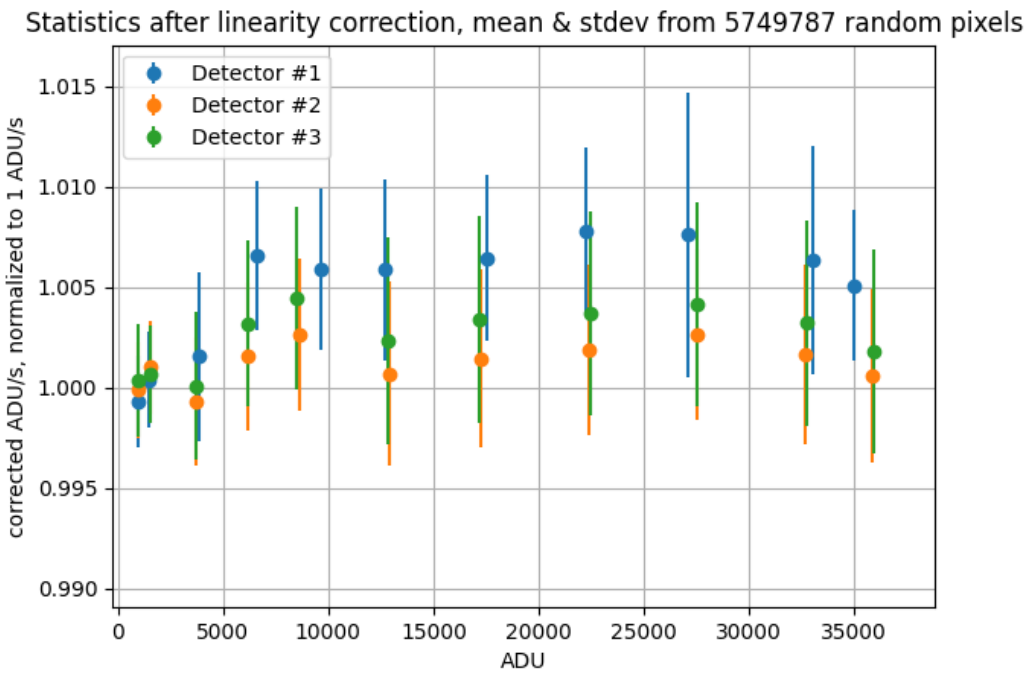

Figure 26: Normalized ADU/s as measured from the frames corrected for non-linearity. For the three detectors, the median over the bins in ADU-level is given. A value of 1.005 on the y-axis corresponds to 0.5% inaccuracy.

4.4 Slit viewer camera

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 slit viewer 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.

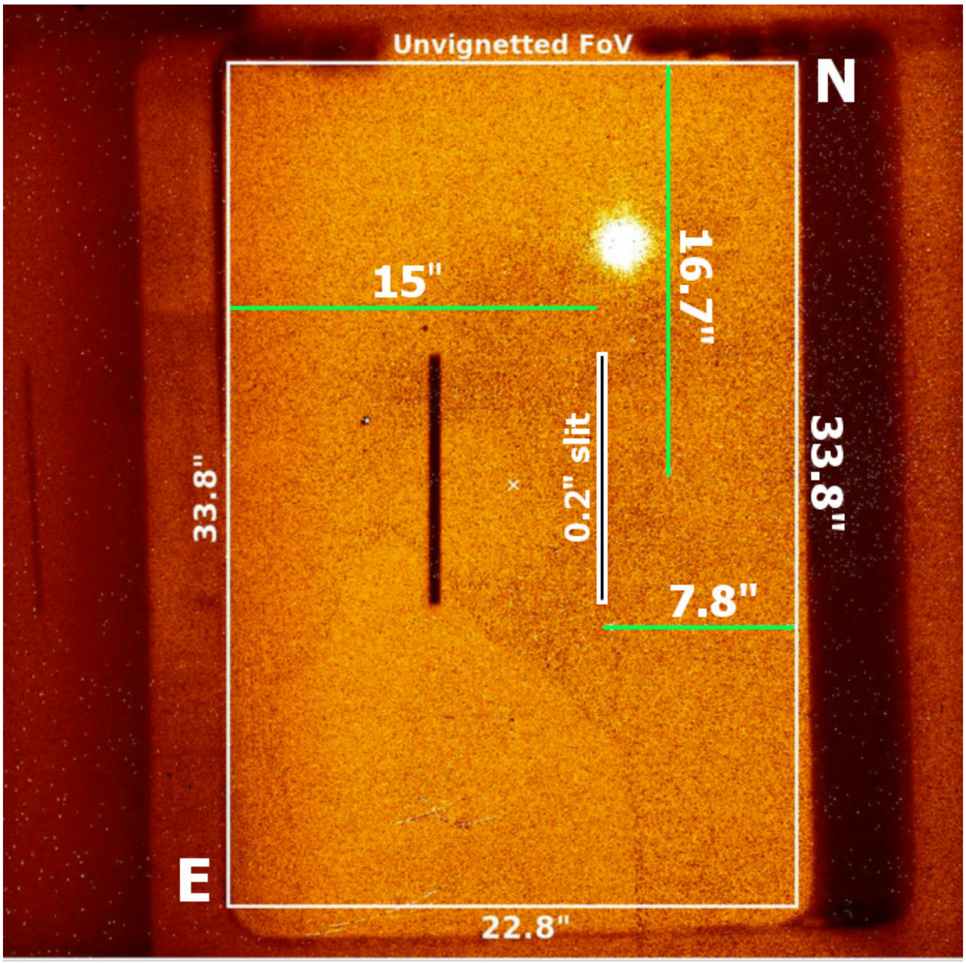

Figure 27: Geometry of the SV detector for PA of 0 degrees in the SKY derotator mode. North is up and East towards the left. The un-vignetted FoV usable for target acquisition and guiding is ~22.8" x 30.8". The centre of the usable FoV and of the slit is marked as white cross. When using the 0.2" slit, the footprint of the 0.4" slit vignettes an area of 0.4"x10" located ~3.6" to the East 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 western border of the FoV.

With a **pixel scale of 37.3±0.2 milli-arcsec** (mas), the SV covers a maximum unvignetted sky projected field of view (FoV) of 22.8" x 33.8", with 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.

Figure 27 shows the FoV of the SV for the derotator in SKY mode, with a position angle of 0 degrees. In this setting, the position of the slit with respect to the centre of the FoV is offset by 3.6” to the West and 0.2” to the North, thereby increasing the allowed maximum separation between the target and the SVGS. Note that when the 0.2” slit is used, the footprint of the 0.4” slit covers an area of 0.4”x10” about 8” to the East with respect to the 0.2” slit (see dark vertical strip in Figure 27).

For obvious reasons, **it is crucial to make sure that the SVGS is within the FoV of the SV at all times** during the observations. This is especially important when applying nodding, jittering or generic offsets. The maximum possible distance between SVGS and target is 20 arcsec, and this only for the case that no nodding and jitter are applied.

When the target is used as SVGS, guiding will be performed using the light reflected by the jaws of the slit. Note that for polarimetry and spectro-astrometry, the SVGS needs to be the target (i.e., no off-slit guiding is possible).

4.4.2 Slit viewer guide star - limiting magnitudes

The SV is equipped with 6 NIR filters: J, H, K, two neutral density H filters and one neutral density filter in K.

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 AO mode, stars of H ~15 are easily detected in a 10 s exposure when located well away from the slit. In NoAO mode, H ~15.5 stars are barely detected (3σ) in a similar 10s integration under 0.9” seeing when located well 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 good conditions (0.8” seeing) and a slit of 0.2”, reasonable guiding was possible with stars of H=14.5 and 14.0 in NoAO and NGS mode, respectively. *Table **3*** lists the SV guide star magnitude limits for different observing modes.

For off-slit guiding, the SVGS must be sufficiently separated from the target, as otherwise the quality of the observations could be severely affected; we recommend a minimum angular distance of 2 arcsec. Guiding with an angular distance smaller than 2" works fine for targets that are at least 3 magnitudes (H-band) fainter than the SVGS, i.e., with target that are (almost) invisible on the SV detector.

Table 3: Slit viewer guide star magnitude limits

	on-slit (SVGS=TRG)	**off-slit (SVGS≠TRG)***
NGS mode with 0.2" slit	$0 \leq H \leq 15$	$0 \leq H \leq 16$
NGS mode with 0.4" slit	$0 \leq H \leq 14.5$	$0 \leq H \leq 16$
NoAO mode	$-2 \leq H \leq 15$	$-2 \leq H \leq 16$

**For off-slit SVGS, we recommend a minimum angular distance of 2" between SVGS and the target unless the H-band magnitude difference target - SVGS is larger than 3.*

4.5 Characteristics of the Spectro-Polarimetry Unit (SPU)

*Figure **28*** shows the throughput of the SPU, respectively for circular and linear polarimetry.

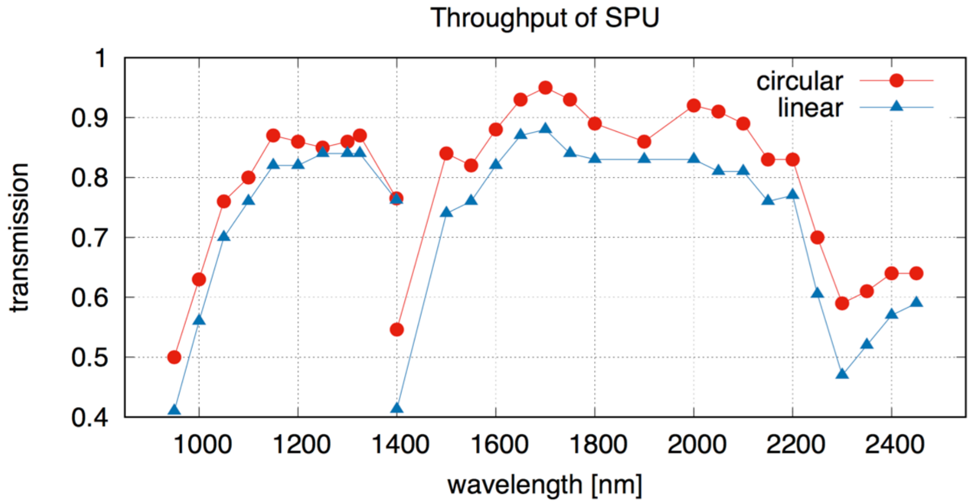

Figure 28: Measurements of the throughput of the Spectro-Polarimetry Unit (SPU).

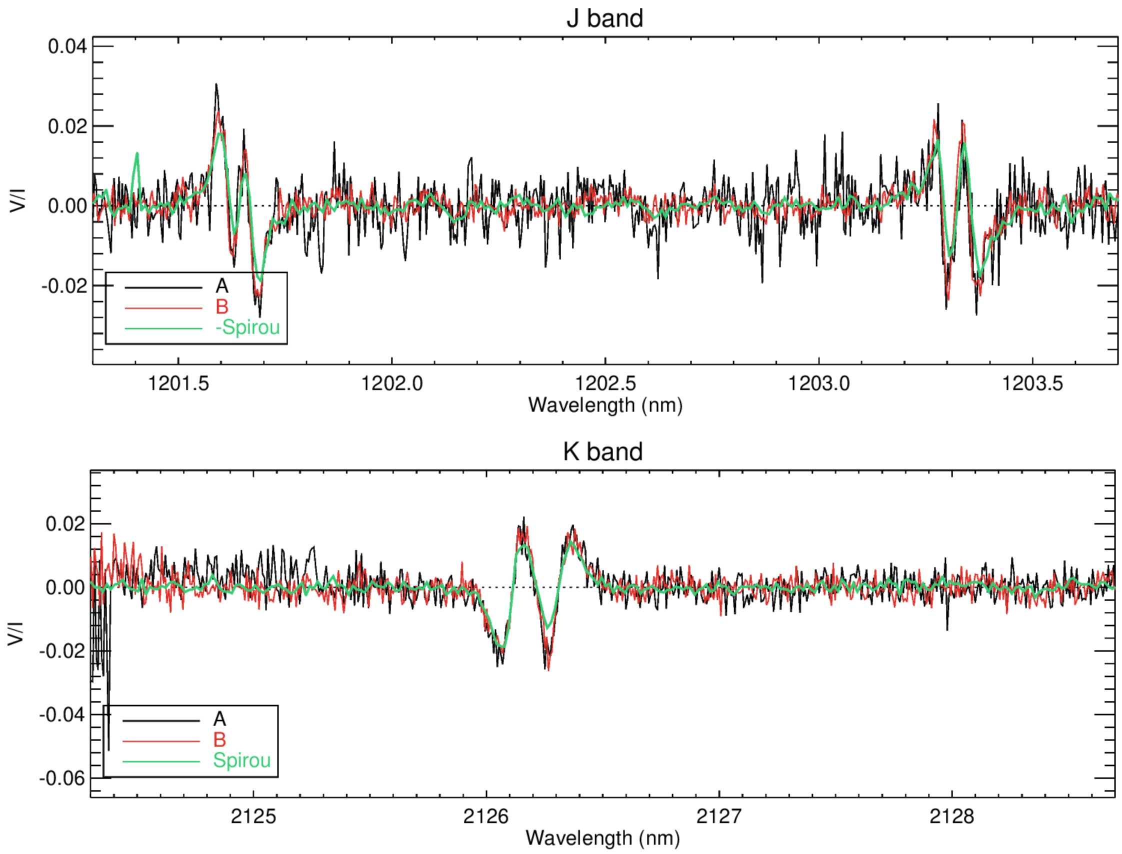

Figure 29. The Stokes V polarization is shown for the star Gamma Equ (H=4.18) at both nodding positions A and B, taken with the 0.2" wide slit; for comparison, we show the performance of the Spirou spectrograph. The upper panel depicts a wavelength chunk in the J-band, while the lower panel one in the K-band. The exposure time of one exposure

was DIT x NDIT = 20s x 1. Note that a total of four exposures were taken at each nodding position, with the polarimeter position angles at 0, 180, 180 and 0 degrees (see §6.3.7).

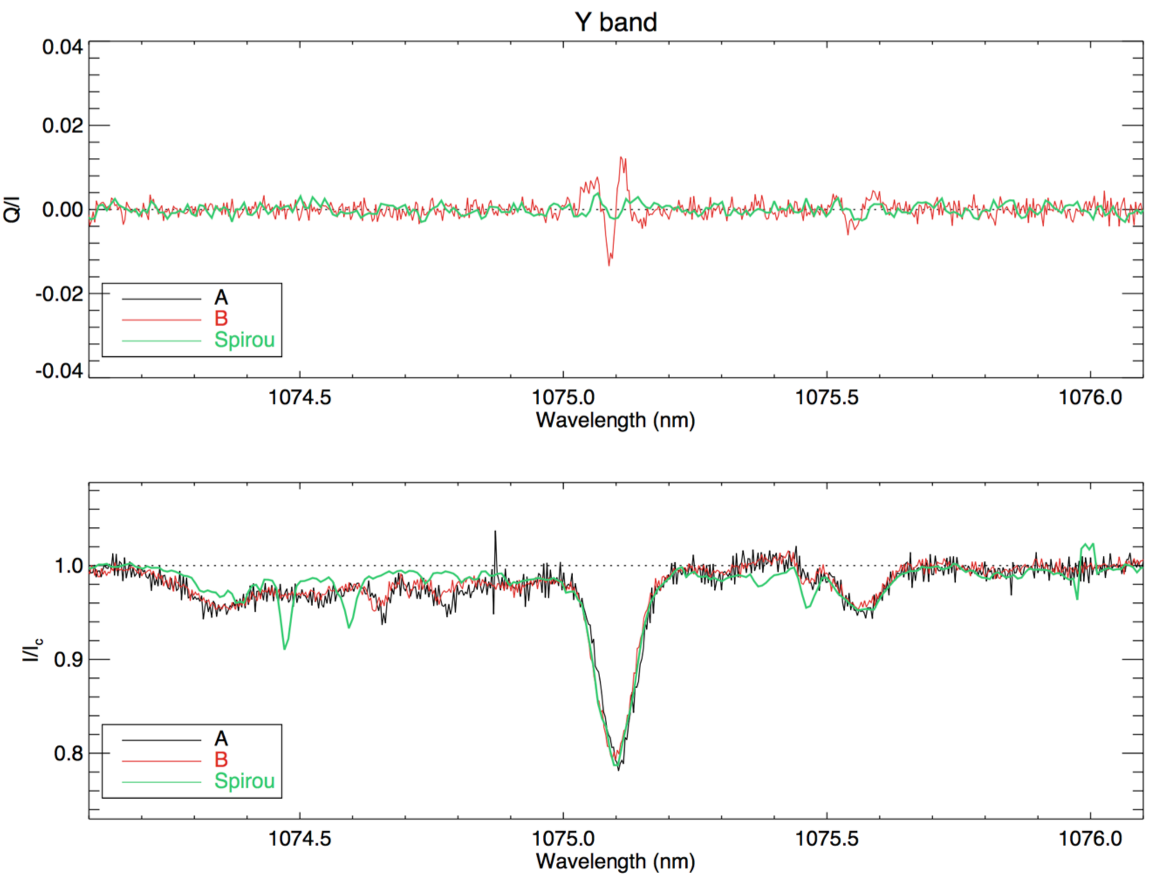

Figure 30: The Stokes Q polarization is shown for the star Gamma Equ (H=4.18) at both nodding positions A and B, taken with the 0.2" wide slit; for comparison, we show the performance of the Spirou spectrograph (green line). The exposure time of one exposure was DIT x NDIT = 20s x 4. Note that a total of four exposures were taken at each nodding position, with the polarimeter position angles at 0, 90, 180 and 270 degrees (see §6.3.7).

<u>Performance:</u> A comparison with another IR spectrometer SPIROU working in the same spectral region and equipped with an SPU unit was done using the spectro-polarimetric standard star Gamma Equ. The polarisation signal was compared in Y to K bands for selected lines with strong Zeeman effect. We find good match for Stokes V and Q profiles. Using the intensity profiles it was possible to confirm that the residual differences are due to higher spectral resolution of CRIRES. *Figure 29* and *Figure **30*** show the standard star Gamma Equ, respectively for circular and linear polarization.

<u>Limitations and systematics:</u> Given that the observing conditions during commissioning were bad, it was only possible to collect S/N of 200-400 on non-polarised test stars and that is what is seen in the intensity, Stokes and Null spectrum. It can be said that the detection limit and the systematics of the SPU/CRIRES are well below 0.01. Technical requirements specify 10^{-4}, but there was no way to check this without collecting spectra of non-polarised

target (preferably for a late-type star) with co-added S/N of 20'000. Only the performance observations of Gamma Equ reached 10'000 counts. For this reason, the limitations and systematics turn out to be inconclusive, and more measurements are required for the Limitations and Systematics assessment of the SPU.

4.6 Characteristics of the spectrograph

4.6.1 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 31*). 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.

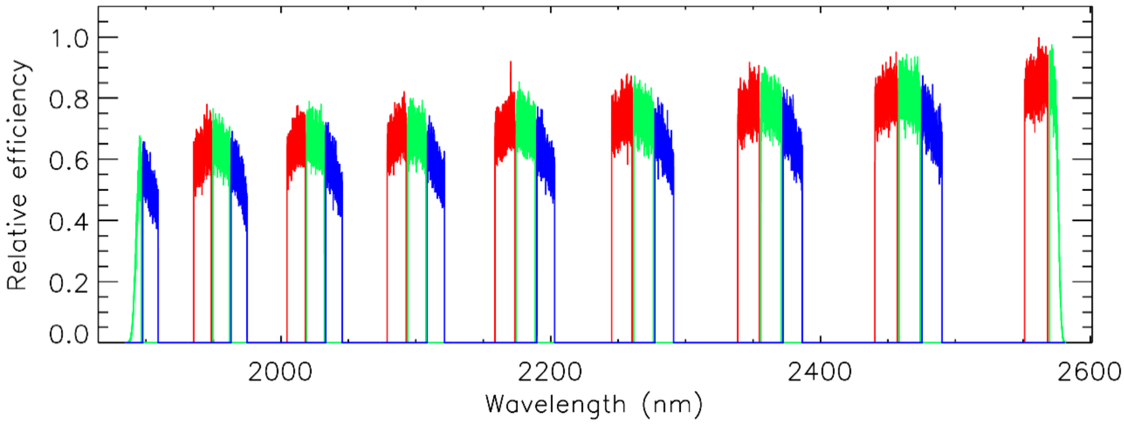

Figure 31: A 1D-extraction of the flat-field image indicating the spectral coverage achieved for a single echelle setting, obtained in a single exposure (K-band, echelle angle=65.5). The three different detectors are colour-coded differently.

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 4 provides a list of the achieved coverage (using multiple exposures) for each photometric band.

The naming convention is given by the central wavelength of the corresponding setting (see column 1 of *Table* ***19***). 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 4: Approximate spectral coverage achieved within different photometric bands.

	Spectral coverage of photometric band		Spectral coverage of point source (middle of slit)		Spectral coverage for full slit	
Band	**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 at 5300nm**

4.6.1.1 Optical ghosts in the Y and J bands

An optical ghost is mainly visible due to internal reflections in the Y and J band wavelength settings (*Figure* ***32***), and to much less extent in the H-band. *Table* ***5*** provides a list of the affected wavelength regions. Check if your lines of interest fall in these wavelength regions and, if necessary, select a different wavelength setting.

Table 5: Wavelength regions affected by the optical ghost in the YJH bands

Wavelength setting	Affected wavelength regions (nm)		
Y1029	955.51 - 956.59 972.36 - 973.46 990.18 - 990.81	1008.18 - 1008.82 1026.81 - 1027.47 1046.15 - 1046.90	1066.29 - 1067.05 1087.15 - 1087.93 1108.83 - 1109.63

Y1028	954.09 - 955.14 970.93 - 971.99 988.67 - 989.29	1006.66 - 1007.31 1025.27 - 1025.92 1044.57 - 1045.25	1064.64 - 1065.35 1085.51 - 1086.17 1107.16 - 1107.86
J1226	1119.44 - 1020.33 1142.78 - 1143.76 1167.12 - 1168.08	1192.52 - 1193.49 1219.01 - 1220.04 1246.71 - 1247.76	1275.70 - 1276.80 1306.05 - 1307.15 1337.98 - 1338.94
J1228	1121.21 - 1122.12 1144.57 - 1145.53 1168.98 - 1169.91	1194.37 - 1195.38 1220.92 - 1221.95 1248.68 - 1249.72	1277.71 - 1278.83 1308.12 - 1309.17 1339.95 - 1341.03
J1232	1124.71 - 1125.60 1148.15 - 1149.46 1172.62 - 1173.55	1198.13 - 1199.08 1224.77 - 1225.74 1252.56 - 1253.59	1281.74 - 1282.74 1312.19 - 1313.26 1344.15 - 1345.23
H1559	1682.63 - 1682.97	1735.50 - 1737.42	
H1567	1744.20 - 1745.84		
H1575	1753.20 - 1754.28		

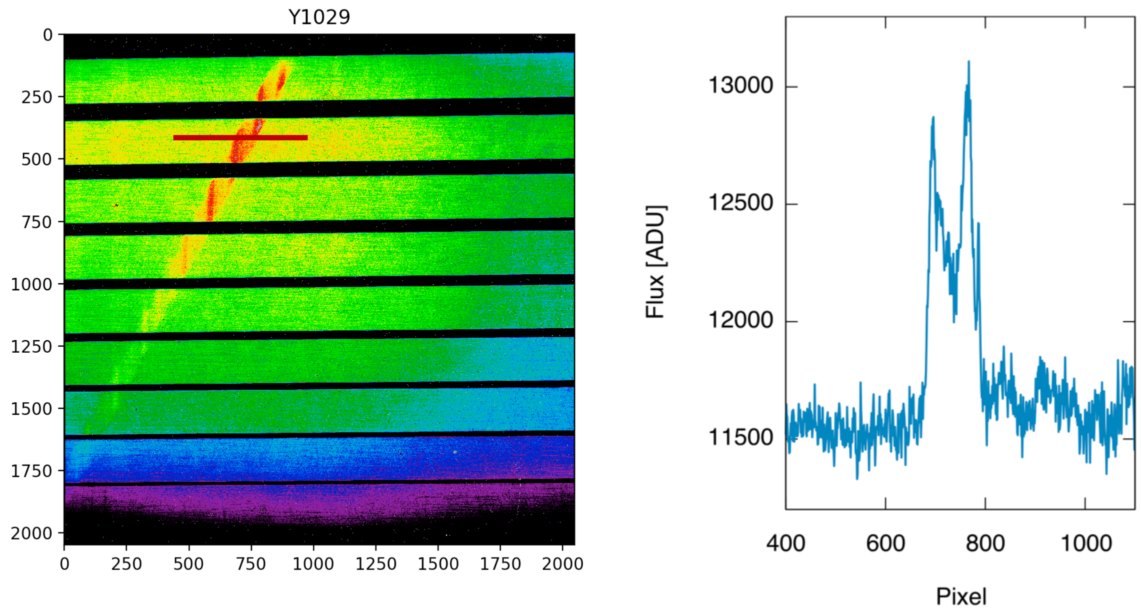

Figure 32. Left: Flat-field exposure exhibiting the optical ghost on Detector 2 in the Y1029 wavelength setting. Note that the ticks correspond to detector pixel. The brown horizontal line depicts the area of the flux distribution shown in the right panel.

4.6.2 Metrology

In YJHKL-bands the metrology converges reliably resulting in residual errors in relative alignment of ±0.1pixel in main dispersion and ± 0.5 pixel in cross-dispersion. If the metrology is not used, the relative alignment can be shifted by 5-10 pixel.

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 (~0.2 pixel over 30 min) following metrology alignment than it was without metrology (0.05 pixel over 30 min); see *Figure **33***. This effect is still being investigated and several mitigation strategies are under consideration, but users should keep in mind that and alignment of data obtained within 15 min of the application of metrology may be degraded due to this effect.

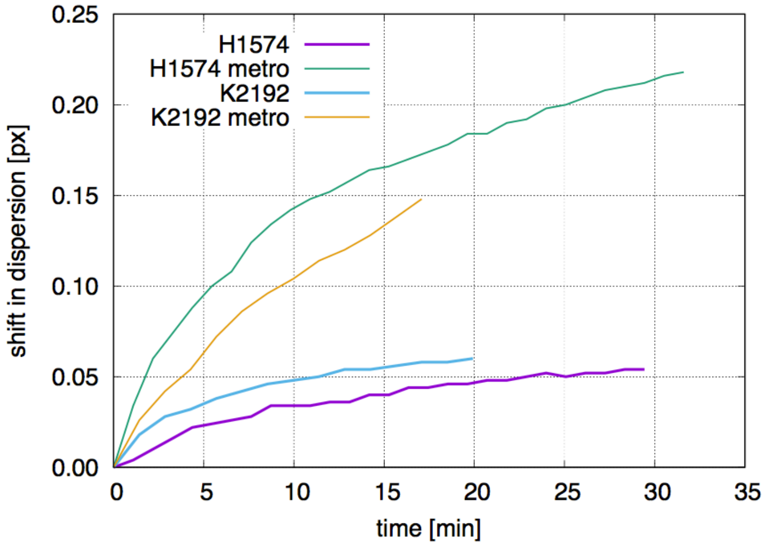

Figure 33: The pixel shift in dispersion vs. time after the change of the wavelength setting and/or application of metrology (labelled as "metro") is shown for two wavelength settings. The effect is being investigated and characterized.

4.6.3 Wavelength calibration

According to the required precision, the wavelength calibration can be done by using different methods. For an accuracy corresponding to ~5 pixels, the start and end wavelengths and the derived dispersion for each detector is sufficient.

In most wavelength settings, both emission and absorption sky lines can be used for absolute wavelength calibration. The presence of sky lines in the desired wavelength setting can be checked by using the ETC.

The pipeline produces absolute wavelength solutions based on the Uranium-Neon (UNE) lamp up to ~2500 nm; **the wavelengths are for vacuum.** Given the lack of suitable emission lines of the Uranium-Neon lamp in the L- and M-band (>2500 nm), the pipeline will not produce any wavelength solution there.

The use of gas cells (i.e., SGC or N_2O, see 3.2.3.1) can be considered for high precision wavelength calibration. The pipeline, however, does not calculate any wavelength solution derived from gas cell data; this is left to the user.

4.6.4 Flat Fielding

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 during night-time, as the detector characteristics are sufficiently stable in time, and the spectrograph wavelength setting sufficiently accurate. Flat-fields taken as part of the calibration plan (see Section 7.1) have a S/N ratio per pixel larger than 200 at the peak efficiency of a given setting.

As part of the calibration plan, we regularly take deep flats with a S/N ratio larger than 600 per detector pixel. We take these flats in the YJHKL-bands settings with NDIT=25 and MAXFLUX = 20'000 as well as NDIT=50 and MAXFLUX=10'000 ADU. These flats can be searched in the CRIRES specific raw data archive[2] by selecting `DPR TYPE` = 'FLAT' and `NDIT` = 25 and 50, respectively.

4.6.5 Spectrograph Field-of-View and slit width

The FoV of the spectrograph is *slit width* x 10", with *slit width* being either 0.2 or 0.4 arcsec. The appearance of a spectrum on the science detectors mosaic is shown in Figure 34. The pixel scale of the science detector is 59 milli-arcsec.

A slit width of 0.4" offers a close to maximal throughput in most AO observations, however, at the cost of spectral resolving power.

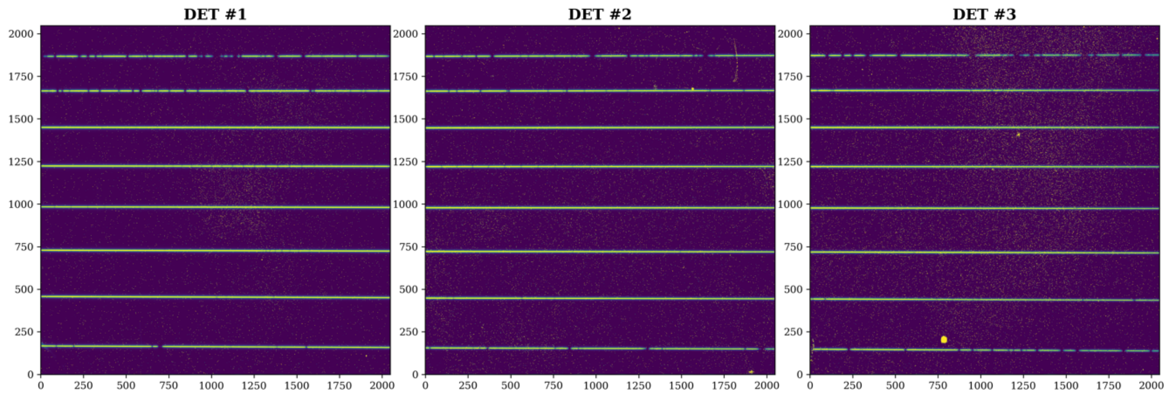

Figure 34: Illustration of the science detectors mosaic (H1582 setting).

4.6.6 Spectral resolving power

Spectral resolving power for the 0.2" slit measured during commissioning was significantly lower 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, **users should not expect more than *R*=80,000**. Full characterisation of the issue is ongoing, and several options exist for recovering the expected spectral resolution.

4.6.7 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 4 m s^{-1} has been attained for a sequence of short exposures (20 sec) in the laboratory by

[2] http://archive.eso.org/wdb/wdb/eso/crires/form

employing the short gas cell (SGC) as a simultaneous wavelength calibrator with the 0.2” slit (i.e., R~80,000). However, this value has not been confirmed on sky so far; the best RV precision that has been attained with CRIRES on sky is 10 m s^{-1}.

For this reason, **we advise users to not expect any RV precision better than 10 m s^{-1}** for exposure times `DIT x NDIT` ≤ 120s. For longer exposure times, the RV precision might be even worse due to grating drifts. We note that the measured error of the RV measurements does also depend on factors like the number of stellar absorption lines observed, the broadening due to the stellar rotation and the signal-to-noise ratio.

Note that the pipeline does not calculate any RV values; data analysis for any CRIRES RV data is left to the user. For this reason, we will only accept proposals with a clear outline of the data analysis strategy when employing the gas cell.

Without a simultaneous wavelength calibrator during observations, 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 ~ 50 m s^{-1}).

For this reason, we recommend making use of the telluric absorption lines of the Earth’s atmosphere as a long-term stable, simultaneous wavelength reference instead of employing attached wavelength calibrations. In most wavelength settings, a large number of these lines come for free and will be directly imprinted onto the science data. Figueira et al. (2010; A&A, 515, 106) demonstrated that telluric lines are intrinsically stable down to 10 m s^{-1} (rms). Again, we recommend keeping the exposure times short (DIT x NDIT ≤ 120s) to avoid the effects of grating drifts.

4.7 Throughput

The overall throughput of CRIRES has been measured on the spectro-photometric standard Pi2 Ori 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 slit loss, by the theoretical. Figure 35 shows the overall efficiency measured on the observed spectro-photometric 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 spectro-photometric standards is part of the instrument monitoring plan, and as such the results shown in Figure 35 should be regarded as preliminary.

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

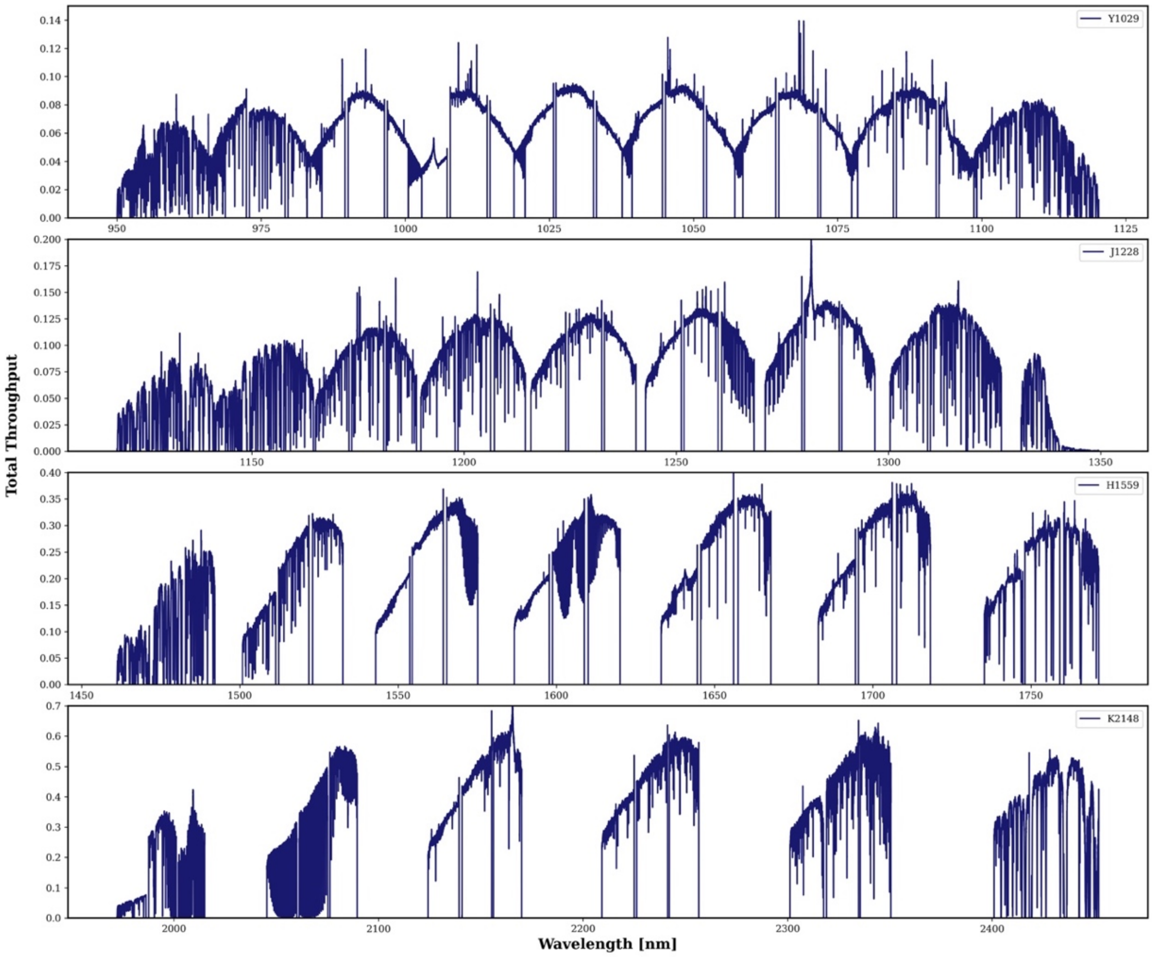

Figure 35: Total observed throughput in 4 different settings. Results are from the commissioning run in January 2021

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5. PHASE I: Observing Proposal Preparation

5.1 General information

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 call[3], 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 rationale 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 §5.6)
- Observing constraints set (see §5.3), consisting of Turbulence Category, Precipitable Water Vapour (PWV), Moon phase, Sky transparency and Airmass.
- Observing mode: Service or Visitor
- Proprietary time (see https://archive.eso.org/cms/eso-data-access-policy.html)
- Time constraint for scheduling (if applicable)

5.2 Instrument modes offered in P109

The properties of the CRIRES modes are summarized in Table 6.

Table 6: Summary of the instrument modes

Instrument Mode	Observing Wavelength	Resolution
Spectroscopy (AO and NoAO)	29 settings (950 nm – 5300 nm)	40,000 (0.4” slit) and 80,000 (0.2” slit)
Polarimetry (AO and NoAO; linear & circular)	13 settings (950 nm – 2500 nm)	40,000 (0.4” slit) and 80,000 (0.2” slit)

Note the following restrictions:

- For polarimetry, the TARGET must be the SVGS and NGS.
- For spectro-astrometry, the TARGET must be the SVGS and NGS
- Metrology is offered in the YJHKL-bands only.

[3] 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)

5.3 User Constraints

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. **Hence, at a later stage it is not possible to specify constraints more stringent than at Phase I.**

For time-critical observations (e.g. transits), we strongly recommend to relax the user constraints whenever possible / allowed to increase their chance of execution.

5.3.1 Turbulence Category

For CRIRES NoAO observations, the TCs are defined using the percentiles of the seeing distribution as listed in Table 7.

Table 7: Turbulence categories for CRIRES NoAO 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 8).

Table 8: 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

Note the following restrictions:

- AO observations with TC = 100% are not possible.
- Any AO NGS (AO Natural Guide Stars) fainter than R > 12 will require a TC ≤ 30%.
- Any off-slit AO NGS being >10 arcsec away from the target will require a stringent TC (if fainter than R > 9, then a TC <= 20% is required).
- Any SVGS (Slit Viewer Guide Stars) fainter than H > 13 will require a TC ≤ 30%.

5.3.2 Airmass (X)

The quality of the AO correction strongly depends on the airmass, and the AO system works best at an airmass ≤1.4; for this reason, **we strongly recommend limiting AO observations to an airmass up to 1.4**, and airmass values > 2.0 should be avoided whenever employing AO.

For higher airmass values than 1.4, the AO performance rapidly decreases and the AO correction will be marginal; the AO loop may not close or become unstable while observing. Consequently, for AO observations with an airmass constraint > 1.4, the Turbulence Category either should be set to a stringent value, or the NoAO mode should be requested instead. Note the two following restrictions:

- If the AO NGS that is more than 10 arcsec away from the target, then the largest allowed airmass constraint is 1.4.
- If the AO NGS is fainter than R=12, then the largest allowed airmass constraint is 1.4.

In addition, keep in mind that observations with the derotator in SKY mode can be strongly affected by differential refraction when observing at high airmass.

5.3.3 Precipitable Water Vapour (PWV)

The PWV is a mandatory user-definable constraint in p1 and p2:

- For observation in the YJH bands (<2000 nm), any PWV value below 5 mm requires a justification in the proposal
- For observations in the K band (2000-2500 nm), we recommend setting the PWV constraint to 2 - 4 mm; any PWV value below 2 mm requires a justification in the proposal.
- For L and M-band observations (>2500 nm), the PWV constraint must be set to a value equal or smaller than 2.5 mm.

The transmission of the Earth's atmosphere in the J, H, K, L and M bands is shown in Figure 35. In order to facilitate the identification of sky regions affected by Precipitable Water Vapour (PWV) lines, *Figure* ***37*** shows the atmospheric transmission spectrum only including water absorption lines.

It is extremely important that users check if their astronomical lines of interest fall on top of strong telluric features as their data may be useless if this occurs (see Figure 38).

The amount of telluric absorption varies non-linearly with zenith distance and PWV (see Figure 39). 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 38). 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.

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

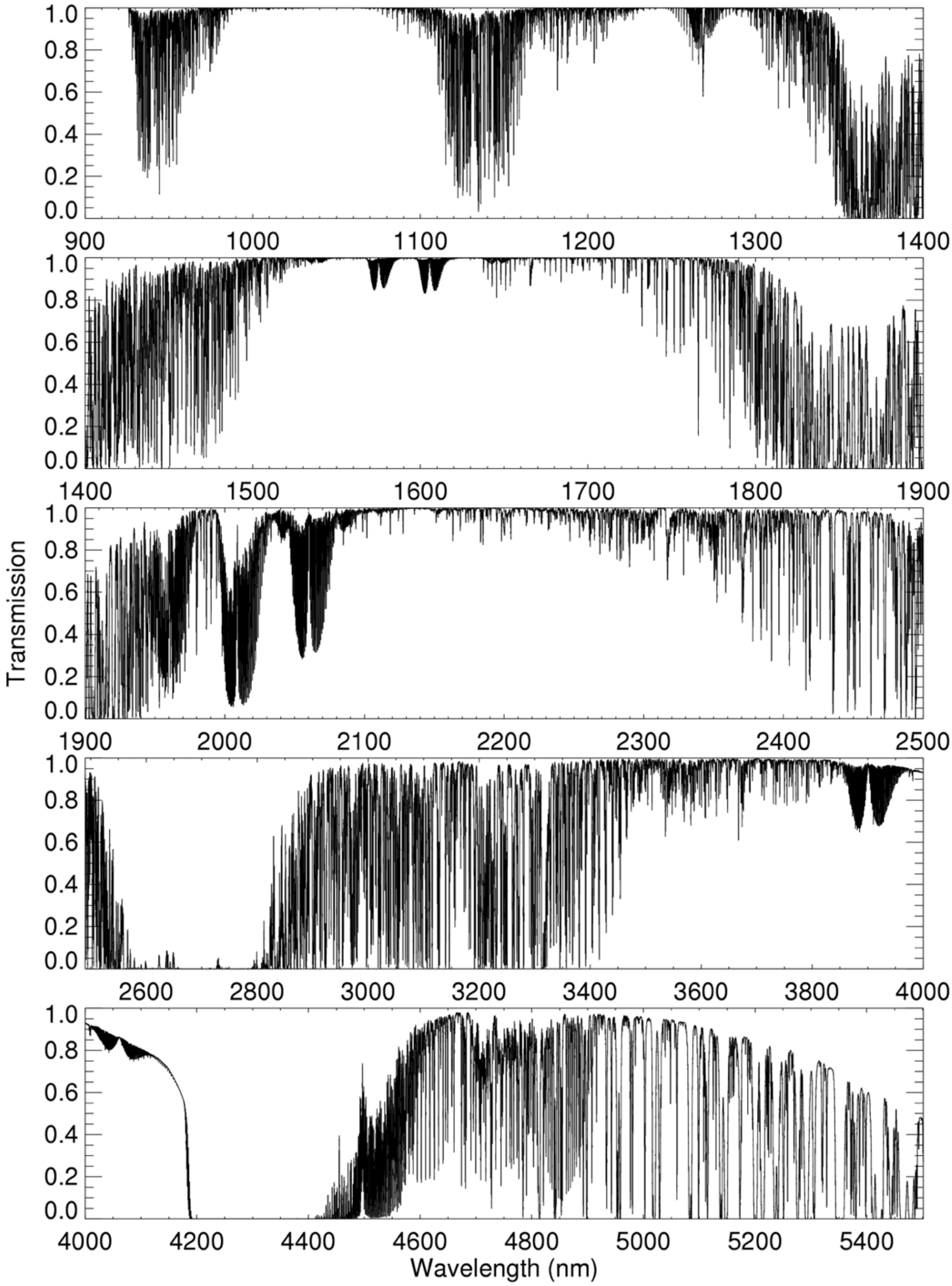

Figure 36: Atmospheric transmission from 900-5500nm computed by PCLnWin/HITRAN for Paranal atmosphere, PWV = 2.5mm, at zenith and smoothed to a resolution of $\lambda/\Delta\lambda$ = 10,000.

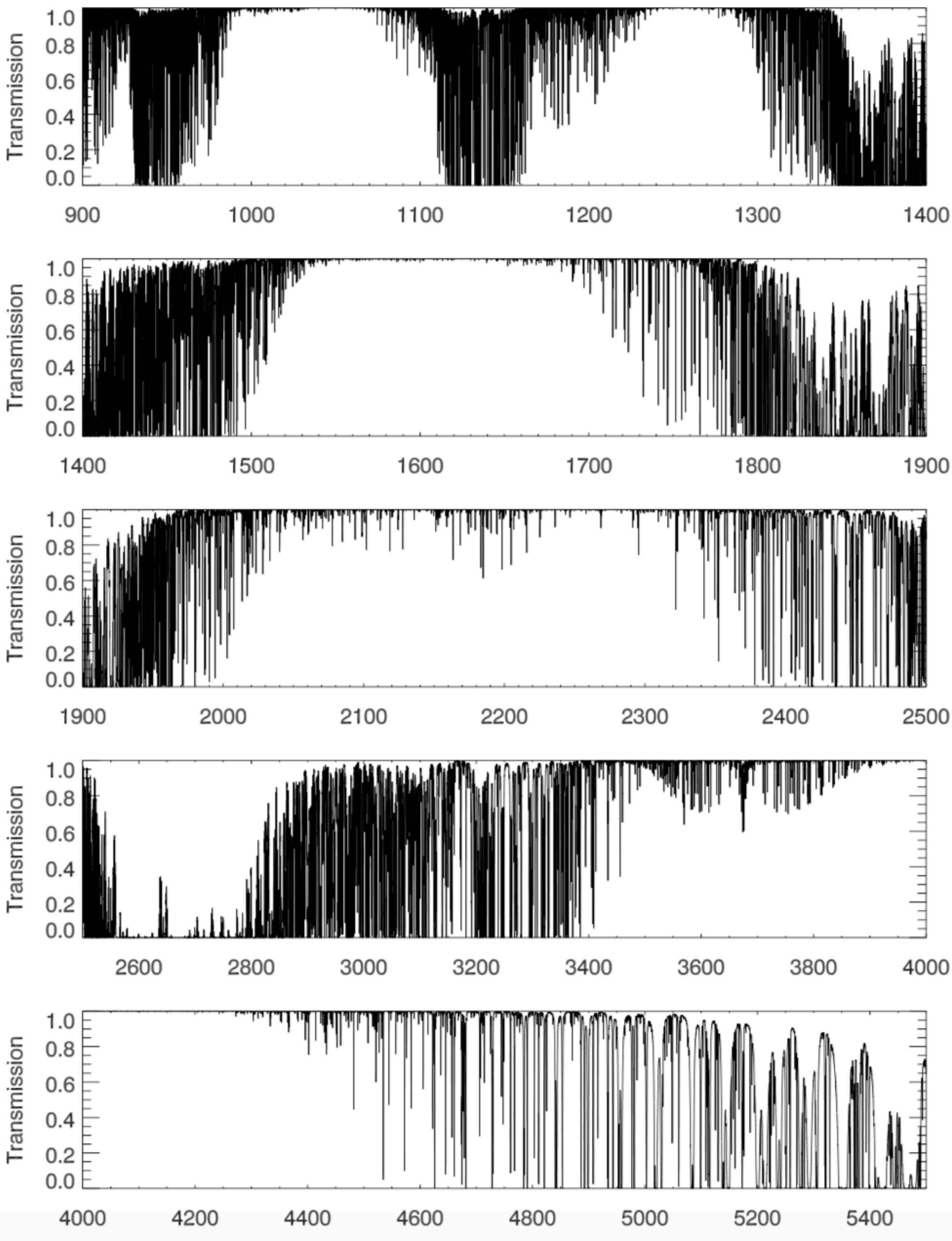

Figure 37: PWV sensitive atmospheric transmission from 900-5500nm computed with RFM/HITRAN for Paranal atmosphere, PWV=2.5 mm at zenith at resolution of λ/Δλ = 10,000.

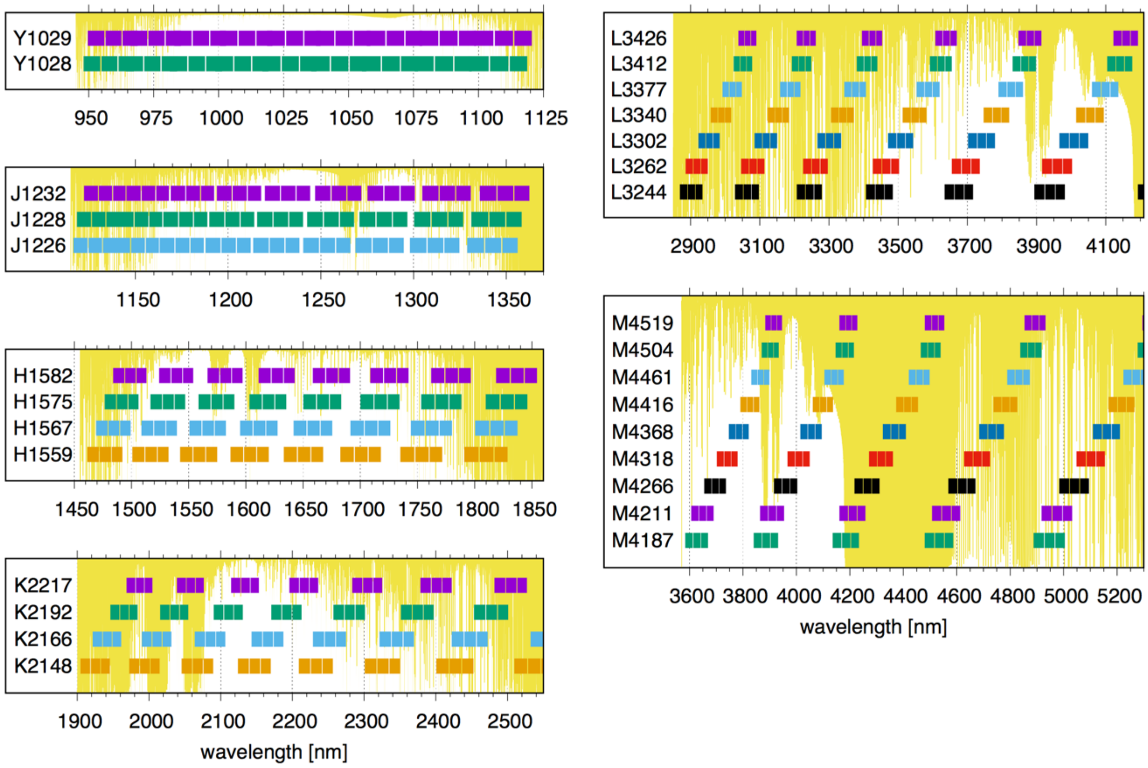

Figure 38: CRIRES wavelength settings compared to the atmospheric transmission.[4]

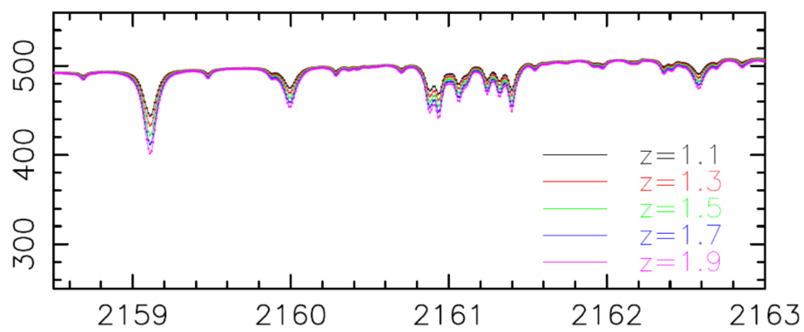

Figure 39: Effect of changes in airmass on PWV absorption produced by the CRIRES ETC.

5.3.4 Lunar Illumination

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.

[4] *A high-resolution version of this figure can be found online: http://www.eso.org/sci/facilities/paranal/instruments/crires/img/CRIRES-wavelength-settings2021.png*

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 ≤ FLI ≤ 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 may affect the quality of the AO correction if the AO natural guide star is fainter than R=14 mag. In this case, reducing the FLI constraint to 0.7 is recommended.

5.3.5 Sky Transparency

- 'Variable, thick cirrus' is only possible in NoAO mode.
- 'Variable, thin cirrus' usually do not affect CRIRES observations of bright objects (H<10).
- 'Clear' 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. It is recommended to request 'Clear' conditions for AO observations with AO stars fainter than R=10.
- 'Photometric' conditions should be only requested for observations requiring accurate flux calibration of the spectra.

5.4 Observing Strategy

5.4.1 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.

5.4.1.1 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*.

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. Given that in spectroscopy mode the slit length is 10 arcsec, a nodding throw of 9 arcsec will put both beams close to the edges of the slit. For larger nodding throws, both beams will be outside the slit (this can be useful when studying extended objects). The maximum allowed nodding throw in spectroscopy is 30 arcsec, and any nodding throw larger than 8 arcsec requires a waiver in service mode.

In spectro-polarimetry mode the nodding throw is fixed at 2.5”. The number of defined AB pairs affects the total amount of overheads, therefore already at Phase 1 we strongly encourage the user to carefully plan the observing strategy.

We note in passing that no M2 chopping can be done with CRIRES.

5.4.1.2 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.

5.4.2 Flux calibration and telluric correction

5.4.2.1 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 spectro-photometric standard.

The spectro-photometric standard and the telluric standard can be the same star. Note that CRIRES, as spectrometers in general, is not meant to provide high absolute spectro-photometric accuracy due to slit losses. A list of spectro-photometric standards supported by the pipeline is provided in Table 14.

The Observatory does <u>not</u> take observations of telluric or spectro-photometric 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 spectro-photometric standard stars is charged to the observer and must be accounted in the amount of time requested during Phase 1.

5.4.2.2 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 by Smette et al. (2015, A&A 576, A77). For the interested reader we also recommend the article by Seifahrt et al. (2010, A&A, 524, 11), as this work discusses the performance and limitations of the technique to synthesize telluric absorption and emission line spectra in general.

A standalone MOLECFIT version for CRIRES is being developed. Please check the CRIRES 'News' page for updates on that.

5.4.2.3 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, except for 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 with spectral type G0V to G4V 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.

5.4.2.4 Catalogues

The CRIRES tools web page http://www.eso.org/instruments/crires/tools provides catalogues listing suitable telluric and spectro-photometric standards.

5.5 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 (S/N ratio) given the *Target* properties, the *Instrument* setup and the constraints set, i.e., *Sky*, *Seeing and IQ* (see Figure 40).

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.

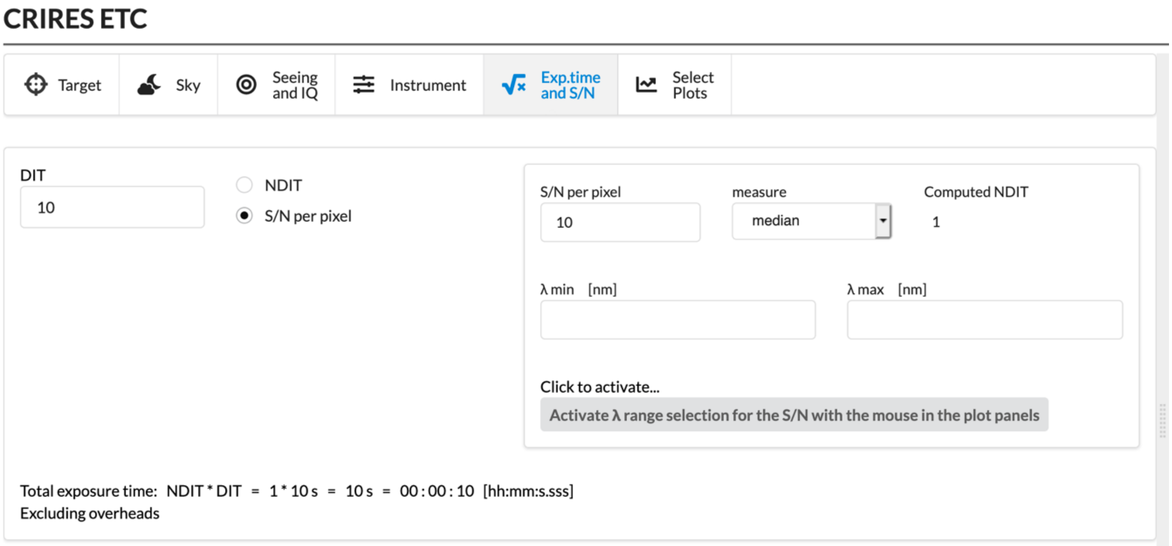

Figure 40: Screenshot of the CRIRES ETC Exp.Time tab. User requests the desired S/N ratio by using a given DIT and the ETC returns the total exposure time (DITxNDIT) needed.

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 (FLI) ranging from 0 (New Moon) to 1 (Full Moon) and PWV (see Sections 5.3.2 - 5.3.5).
- 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 S/N ratio 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 S/N ratio determination to a few 10%.

- Because the AO correction degrades with airmass, we strongly recommend limiting AO observations to airmass values of 1.4. This is especially important for off-slit NGS, as the AO correction further degrades with increasing distance between NGS and the slit.

Seeing and IQ tab:

- For NoAO observations, the desired seeing condition is defined either in terms of requested Turbulence Category (TC) or Image Quality (IQ) at a given reference wavelength. The ETC provides automatic conversion between the TC (Phase 1 constraint) and IQ (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 both Phase 1 and 2. AO observations are restricted to TC= 10%, 20%, 30%, 50%, 70% and 85%. S/N ratio calculations for larger values in this mode are not supported by the ETC as AO in those conditions would result in marginal 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 system[5].

Instrument tab:

- The instrument setup is defined in terms of setting (i.e., Y1029; see Table 19, column 1), and grating orders. For observations below 1400 nm, mind the wavelength regions of the optical ghosts on the detector (see Section 4.6.1.1), as they are not displayed in the ETC.

Exp.Time and S/N tab:

- Requested output can be either the exposure time to achieve a given signal-to-noise ratio (S/N ratio) or the S/N ratio achieved for a given exposure time. In both cases the DIT needs to be specified.
- The S/N ratio is given per spectral pixel in the spectral dispersion (and not per resolution element); the S/N ratio is calculated by integration over a box being a) one detector pixel wide in spectral dispersion and b) a user-defined number of pixels long in cross-dispersion direction ("Extraction Aperture").
- For polarimetry, all calculations are based on one of the two polarized beams only, and all values are shown for one exposure (i.e., nothing combined).
- *Extraction Aperture*: this is the number of detector pixels along the slit to be used for S/N ratio calculation. In the L and M-bands, users should carefully select the Extraction Aperture to avoid contamination from the dominating thermal background (this will happen if it is set to a large value).
- ETC outputs the on-source integration time only. Depending on observing technique and accounting for overheads, the total execution time can be much longer (see Section 5.6).

[5] 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

Select Plots tab:

- By default, the ETC displays the S/N ratio per spectral pixel, however the user can request different plots related to the sky and/or target signal, and to the throughput efficiencies.
- It is always useful to ask the ETC to show the S/N ratio as a function of wavelength due to the presence of numerous telluric features: a small difference in the requested wavelength can lead to very different S/N ratio for a given total integration time or, alternatively, very different integration time for a requested S/N ratio.
- From the ETC page users can access to a python script that allow to download the output of the requested plots in ascii file. These scripts can be found under the "Tools" tab.
- **All wavelengths displayed in the ETC are in vacuum**.

5.6 Instrument overheads

In Phase 1 users are requested to provide the total execution time, which is given by the total exposure time on target (i.e., open-shutter time) plus the overheads. The estimated overheads related to both telescope and instrument are listed in the following table.

Table 9: Telescope and Observation overheads. (*) If the metrology is enabled in the acquisition template, but not the science template(s), then no overheads associated to the metrology apply. (**) If done during acquisition or in parallel with a change of the wavelength setting, the corresponding overhead listed here does not apply. (***) The derotator cannot move beyond 359.9 degrees. Thus, changing the derotator position angle from, for example, 350 to 10 degrees will take 74 seconds, as it will rotate by 340 degrees.

	Action	Times (s)
Telescope	Preset	360
CRIRES	Acquisition with AO	240
CRIRES	Acquisition without AO	150
CRIRES	Read-out for one exposure	2.4 + 1.43 x (NDIT-1)
CRIRES	Nodding cycle	28
CRIRES	Change of wavelength setting	80
CRIRES	Metrology in Y, J and H*	110
CRIRES	Metrology in K*	160
CRIRES	Metrology in L*	200
CRIRES	Attached wavelength calibration	180
CRIRES	Attached lamp flat	90
CRIRES	Change of derotator position angle**	2 + 76 x abs(PA1-PA2) / 360***
CRIRES	Change of polarimeter setting**	23
CRIRES	Generic Offset	14

Example: The shortest possible overheads for a CRIRES OB are the following. 360s telescope preset, plus 150s target acquisition in NoAO mode, plus the read-out time for one exposure with NDIT=1 being 2.4s. Hence, the overheads for this OB will be 512.4s.

An alternative way to easily calculate the overhead is to create a CRIRES mock OB by using p2demo available at: https://www.eso.org/p2demo. Under the CRIRES programme ID 60.A-9253(K), the folder named USD-Tutorials provides examples of OBs specifically designed for different observing strategies (note that not all observing templates have been implemented yet). These OBs can be copied into a new folder and then modified regarding the exposure time, number of exposures and the observing strategy. Remember to employ the latest version of the Exposure Time Calculator (ETC) for the estimate of the exposure time.

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/crires/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/crires/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 of 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 it may happen that the telescope cannot be pointed at their main targets. For this reason, it is strongly recommended to prepare backup targets with declinations smaller and larger than –24.6 degrees. **Any backup target needs to be approved well 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 Target acquisition templates

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 / calibration templates.

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

The first template to be included in the OB is the acquisition template, 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:

- The target object (TRG): it can be either an extended object or a point-like source with a relevant wavelength between 950nm and 5300nm

- 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.
- The AO natural guide star (NGS): when the AO correction is required, the NGS can be 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 for spectro-polarimetry and for spectro-astrometry, the NGS must be the target).

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 AO NGS specified by the user. Once the AO 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 closed (if AO mode) and the guiding is active, therefore the telescope offsets to the target, which is manually centred on the slit.

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 10 summarises the list of available acquisition templates.

Table 10: Summary of available CRIRES acquisition templates

INSTRUMENT MODE	TEMPLATE NAME	COMMENT
Spectroscopy	CRIRES_spec_acq_NGS	AO assisted spectroscopy
	CRIRES_spec_acq_NoAO	Seeing limited spectroscopy
	CRIRES_spec_acq_NGS_difftrack	AO assisted spectroscopy with differential tracking
	CRIRES_spec_acq_NoAO_difftrack	Seeing limited spectroscopy with differential tracking
Polarimetry	CRIRES_pol_acq_NGS	AO assisted polarimetry
	CRIRES_pol_acq_NoAO	Seeing limited polarimetry

6.3.1 Target details

In the ***p2/Target tab***, the user is expected to provide the following TARGET details[6]:

▪ **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 (§ 6.8).

6.3.2 Optional - Telescope Guide Star (VLT-GS) details

In the following, we describe all parameters present in the **acquisition templates** that the user is requested to define according to the selected instrument mode. The Telescope Guide Star details are optional, and users are encouraged to leave the VLT-GS selection to the telescope operator.

▪ **Telescope guide star selection** (TSF: TEL.AG.GUIDESTAR): if set to CATALOGUE, then the Telescope Control System will semi-automatically search for telescope guide stars which can be selected by the telescope operator. However, if the user wishes to provide the coordinates of the telescope guide star, then TEL.AG.GUIDESTAR should be set to SETUPFILE. However, **users are encouraged to leave the VLT-GS selection to the telescope operator** (TEL.AG.GUIDESTAR=CATALOGUE), as they are in the best position to pick the most suitable stars for the real-time conditions.

▪ **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 2' and 11' from the target and possibly be isolated. Fainter GS may only work in good conditions.

[6] For observations of moving object, the target position and motion are provided through tracking table, see dedicated section (§ 6.8)

We recommend to users who wish to specify the telescope guide star to use the ‘ObsPrep’ tab when editing an OB in the P2 tool. ‘ObsPrep’ will allow the user to interactively select a telescope guide star and will automatically update the coordinate values in the OB.

6.3.3 Slit Viewer Guide Star (SVGS) details

▪ **Magnitude of Slit Viewer Guide star** (TSF: SEQ.SVGS.HMAG): Uses need to specify the H-band magnitude of the SV guide star to allow for the correct setting of the integration time of the slit viewer camera.

▪ **RA/DEC offset between target and SV guide star** (TSF: TEL.TARG.OFFSETALPHA, TEL.TARG.OFFSETDELTA) correspond to the offsets, **in units of arcsec** (mind the difference between sec and arcsec in RA), necessary to move from the target to the SVGS. **If the SVGS is the target, then these values must be left unchanged at 0.**

Let α(SVGS) and δ(SVGS) be the coordinates of the SVGS, then he sign convention is as follows:

TEL.TARG.ALPHA + TEL.TARG.OFFSETALPHA = α(SVGS)
TEL.TARG.DELTA + TEL.TARG.OFFSETDELTA = δ(SVGS)

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 27). These parameters must be provided if no differential tracking is needed.

We recommend using the ‘ObsPrep’ tool in P2 when selecting an SV guide star. This tool allows the user to interactively select a telescope guide star, and ‘ObsPrep’ will automatically update the coordinate values in the acquisition template.

▪ **Use the last sky measurement for the SV** (TSF: SEQ.SV.USELASTSKY): 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. This is the default value for this keyword (SEQ.SV.USELASTSKY=F). When observing brighter targets, however, one can use the last sky measurement (SEQ.SV.USELASTSKY=T).

▪ **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. The convention for these RA, DEC offsets is:

TEL.SKY.OFFSETALPHA = α_{SKY} - α(target)
TEL.SKY.OFFSETDELTA = δ_{SKY} - δ(target)

6.3.4 AO star (NGS) details

▪ **Target = AO guide star** (TSF: SEQ.NGS.ISTARGET) is a flag to be set to YES (i.e., SEQ.NGS.ISTARGET = T) 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). For Polarimetry, the Target must be the AO guide star.

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

We recommend using the 'ObsPrep' tool in P2 when selecting an AO guide star. This tool allows the user to interactively select a telescope guide star, and 'ObsPrep' will automatically update the coordinate values in the acquisition template.

▪ **AO guide star: B-R colour 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).

▪ **AO guide star magnitude** (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 considered. 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 (R>14) that the MACAO can acquire, in which case a smaller value is to be given. Note that the AO correction will not work for S/N<500, as the AO correction will then be dominated by noise.

▪ **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 (WFS). The sky measurement is used to determine the S/N ratio of the WFS 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; in this case, **users must ensure that no object is located at the sky offset position** (SEQ.NGS.SKYALPHA and SEQ.NGS.SKYDELTA), as otherwise the MACAO APDs could be damaged. This is very important when observing 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 AO NGS is also the SVGS, otherwise to NO. Note that this parameter is irrelevant for differential tracking.

Pay attention to the following five possible combinations:

If **target = AO NGS = SVGS** (mandatory for polarimetry and spectro-astrometry!), then:

- **Target == AO Guide Star** must be set to **yes**
- **SV Guide Star == AO Star** must be set to **yes**
- **RA/DEC of AO guide star** must be left unchanged at 00:00:00.000.
- **RA/DEC offset between the target and SV guide star** must be left unchanged at 0.

If **target = AO NGS ≠ SVGS**, then:

- **Target == AO Guide Star** must be set to **yes**
- **SV Guide Star == AO Star** must be set to **no**
- **RA/DEC of AO guide star** must be left unchanged at 00:00:00.000.
- **RA/DEC offset between the target and SV guide star** must be provided (in arcsec)

If **target = SVGS ≠ AO NGS**, then:

- **Target == AO Guide Star** must be set to **no**
- **SV Guide Star == AO Star** must be set to **no**
- **RA/DEC of AO guide star** must be set to the coordinates of the AO NGS.
- **RA/DEC offset between the target and SV guide star** must be left unchanged at 0.

If **AO NGS = SVGS ≠ target**, then:

- **Target == AO Guide Star** must be set to **no**
- **SV Guide Star == AO Star** must be set to **yes**
- **RA/DEC of AO guide star** must be set to the coordinates of the AO NGS.
- **RA/DEC offset between the target and SV guide star** must be left unchanged at 0.

If **target ≠ SVGS ≠ AO NGS** (all three stars are different), then:

- **Target == AO Guide Star** must be set to **no**
- **SV Guide Star == AO Star** must be set to **no**
- **RA/DEC of AO guide star** must be set to the coordinates of the AO NGS.
- **RA/DEC offset between the target and SV guide star** must be provided (in arcsec)

6.3.5 Instrument details

▪ **Entrance slit width** (TSF: INS.SLIT1.NAME): w_0.2 or w_0.4, respectively for a minimum spectral resolution of R = λ/Δλ = 80 000 or R = 40 000.

▪ **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 19. 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 of the telescope is compensated ("field stabilized").

The **SKY** mode is relevant for extended sources or for placing multiple objects simultaneously on the slit. The SKY mode must be used with the Spectro-Astrometry and Generic Offsets templates. Likewise, **the SKY mode must be used whenever employing an off-slit SV guide star and/or off-slit AO NGS.**

The **ELEV** mode should be used for point sources, as it reduces slit loss introduced by differential refraction. This is particularly important when SV guiding is done in one band (e.g., in K) and the observations in another one (e.g., M). It can be only used for on-slit guiding (i.e., SVGS = Target).

▪ **Position angle** (TSF: INS.DROT.POSANG) sets the position angle (PA) of the slit when the SKY derotator mode is selected. The PA is counted from North (0 deg) via East (90 deg).

▪ **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.

▪ **Run Metrology?** (TSF: SEQ.METROLOGY.ST): To ensure the highest reproducibility of the slit image position on the detector, the Metrology (see Section 4.6.2) should be activated (SEQ.METROLOGY.ST="Yes") in the acquisition template. When activated there, no additional overheads are produced as the Metrology runs in parallel to the target acquisition. Note that the metrology is only available for wavelength < 4000 nm (YJHKL bands). **Note that without employing metrology, the spectrum may be shifted by 5-10 pixel.**

6.3.6 Differential Tracking parameters

▪ **Reference star tracking table file** (TSF: SEQ.TRACK.REF) and **Target tracking table file** (TSF: SEQ.TRACK.TARG): These parameters expect the names of PAF files. PAF files are ASCII files compatible with the VLT parameter file (PAF) format and contain the ephemeris of the right ascension and declination used as a reference object ("AO star" and "slit viewer guiding star") and the target, respectively. These files can be prepared by using the online tool available at:

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

In these files, it is important to **make sure that the PAF.NAME is different in both files**, as otherwise this can lead to problems during target acquisition.

6.3.7 Spectro-Polarimetry

- **Polariziation Stokes Parameter** (TSF: `INS.POL.TYPE`) sets the Stokes parameter (V, Q or U).

6.4 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 (NDIT) averaged to create an exposure. In addition, it defines the number of exposures to be taken in different positions for background subtraction purpose.

As mentioned in §5.4.1.1, 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. This can be done with generic offsets.

In addition, CRIRES offers the possibility of using the spectro-astrometry 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).

Table 11: Overview of the available CRIRES observing templates

INSTRUMENT MODE	TEMPLATE NAME	COMMENT
Spectroscopy	CRIRES_spec_obs_AutoNodOnSlit	Exposures are taken by nodding the target along the slit (recommended for point sources)
	CRIRES_spec_obs_GenericOffset	Exposures can be taken along and/or off the slit, depending on the user defined offsets pattern (recommended for extended object). Only possible with SKY derotator mode.
	CRIRES_spec_obs_SpectroAstrometry	Exposures are taken by nodding the target along the slit and repeated at any user-defined position angle. Not compatible with differential tracking. Only on-slit guiding / AO NGS possible.

Polarimetry	CRIRES_pol_obs_AutoNodOnSlit	Linear and circular polarimetry taken along the slit. Only on-slit guiding / AO NGS possible.

The science observing templates must match the instrument mode (*'Spectroscopy' or 'Polarimetry'*) defined in the acquisition template. For example, the acquistion template *CRIRES_spec_acq_NGS* (spectroscopy mode) will not work with the observing template *CRIRES_pol_obs_AutoNodOnSlit* (polarimetry mode). *Table **11*** provides a summary of the available observing templates as a function of the instrument modes.

In the following, we describe the parameters present in the **observing templates** that have not been introduced already in §6.3 and that the user is requested to define.

6.4.1 Exposure Time details

- **DIT** (TSF: DET1.DIT) defines the exposure time of an individual detector integration time, in seconds. Only the following DITs are allowed in service mode: 1.4, 2, 3, 5, 7, 10, 15, 20, 30, 45, 60, 75, 90, 120, 150, 180, 240, 300, 450, 600 or 900s.

Any DIT<1.427 will be automatically converted to the minimum DIT of 1.427s; DITs ≥600s require a waiver because of the high risk of not meeting atmospheric quality requirements. We recommend to set the DIT to such a value so that the detector counts remain **well below the saturation limit**, but at the same time the number of detector read-outs (NDIT x exposures) is kept as low as possible. Otherwise, the signal-to-noise ratio of the observations may be strongly affected by the read-out-noise. The optimum setting shall be evaluated by using the Exposure Time Calculator (ETC).

Owing to the bright thermal background in the L- and M-bands, any DITs longer than the ones specified in *Table **12*** will result in saturation of the detectors and will require a waiver.

Table 12: longest possible DITs for selected wavelength settings without saturation.

wavelength setting	DIT	
	0.2" slit	0.4" slit
3244.424 3262.140	90s	45s
all M-band settings	20s	10s

- **NDIT** (TSF: DET1.NDIT) determines the number of individual integrations averaged into one exposure; therefore, DET1.NDIT x DET1.DIT sets the exposure time of one exposure, which is then written into a FITS file. The individual integrations (NDITs) are not stored in the FITS file. Note that for each NDIT, the detector read-out noise listed in applies, and a large number of detector read-outs can affect the overall signal-to-noise ratio of the observations.

NDIT >1 should be used for DITs ≤ 30 sec to keep the overheads for the detector read-out short. For longer DITs, however, we recommend to set NDIT=1, and to increase the number of exposures (SEQ.NEXPO) and nodding cycles (SEQ.NABCYCLES) instead. We have seen that such a setting slightly improves the signal-to-noise ratio in the reduced data.

6.4.2 Nodding details

▪ **Number of exposures per nodding position** (TSF: SEQ.NEXPO): is the number of exposures at any single nodding (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 the slit centre only, without any nodding applied. If set to a value ≥1, positions A and B are each visited SEQ.NABCYCLES times, and the total integration time of the CRIRES_spec_obs_AutoNodOnSlit template is given by:

DET1.NDIT x DET1.DIT x SEQ.NEXPO x SEQ.NABCYCLES x 2,

whereas in staring mode (SEQ.NABCYCLES = 0):

DET1.NDIT x DET1.DIT x 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 but must be smaller than the slit length of 10". The nodding positions are located symmetrically (at SEQ.NODTHROW/2) around the centre of the slit. Because of the extended wings of the PSF a nodding throw of 6'' is recommended.

Important information for off-slit guiding: the SV guide star must always be visible in the field of view of the SV detector (*Figure **27***). Users must ensure that this is the case when employing nodding.

▪ **Jitter width** (TSF: SEQ.JITTER.WIDTH): refers to the small offset added to each nodding offset (see §5.4.1.2). 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 for 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.

Examples for Nodding with different numbers of nodding cycles:

1. If SEQ.NABCYCLES = 1, then the telescope first points up along the slit to the A position, which is at a distance equal to SEQ.NODTHROW/2 (if SEQ.JITTER.WITDH = 0) from the slit centre. After SEQ.NEXPO exposures, the telescope nods to the B position: it points down along the slit 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, then 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.

6.4.3 Generic-offsets details

Remember to set the derotator mode (TSF: INS.DROT.MODE) to SKY in the acquisition template.

▪ **Number of offset positions** (TSF: SEQ.NOFF) 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', with SEQ.OFFSET.COORDS = DETECTOR, then the list of offsets will be '0 0 0 0 0' along the X direction, '0 10 -10 0 10' along the Y direction. At the end of the template, the telescope will go back to the start location.

▪ **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. If the sum of O and S measurement is less than the **Number of offset positions** (SEQ.NOFF), then the sequence will be repeated until the total number of offsets is reached. For example, SEQ.NOFF=7 with SEQ.OBSTYPE.LIST='O O S ' would result in an observing pattern 'O O S O O S O'.

Likewise, if the sum of O and S measurements is larger than SEQ.NOFF, then the sequence will be capped when reaching SEQ.NOFF.

▪ **Lists of offsets in RA/DEC or X/Y** (TSF: SEQ.OFFSET1.LIST, SEQ.OFFSET2.LIST) refer to the list of offsets being in arcseconds. At the first position, 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. **Subsequent offsets are made relative to the last telescope offset.**

▪ **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 (unit: arcsec) or DETECTOR (unit: pixel) coordinates. Keep in mind the pixel scale of the SV detector is 0.0373 arcsec / px.

If SEQ.OFFSET.COORDS = **DETECTOR**, then a positive value in SEQ.OFFSET1.LIST (X) means that the telescope will point perpendicularly to the slit towards left (towards E if the position angle is 0), thereby moving the target from left to right on the SV detector. Similarly, with a positive value in SEQ.OFFSET2.LIST (Y) the telescope will point down, parallel to the slit (towards S if the PA is 0), thereby moving the target up on the SV detector (see *Figure **41***).

If SEQ.OFFSET.COORDS = **SKY**, then a positive value in SEQ.OFFSET1.LIST (RA) means that the new pointing of the telescope will be towards the East (the target moves West on the SV detector); similarly, a positive value in SEQ.OFFSET2.LIST (DEC) means that the new pointing of the telescope will be towards the North (the target moves South on the SV; *Figure **42***).

In case of off-slit guiding, users must **make sure that the SV guide star is within the SV field of view at all times** (*Figure **27***)!

- **Number of exposures on each position** (TSF: SEQ.NEXPO): gives the number of exposures per offset position

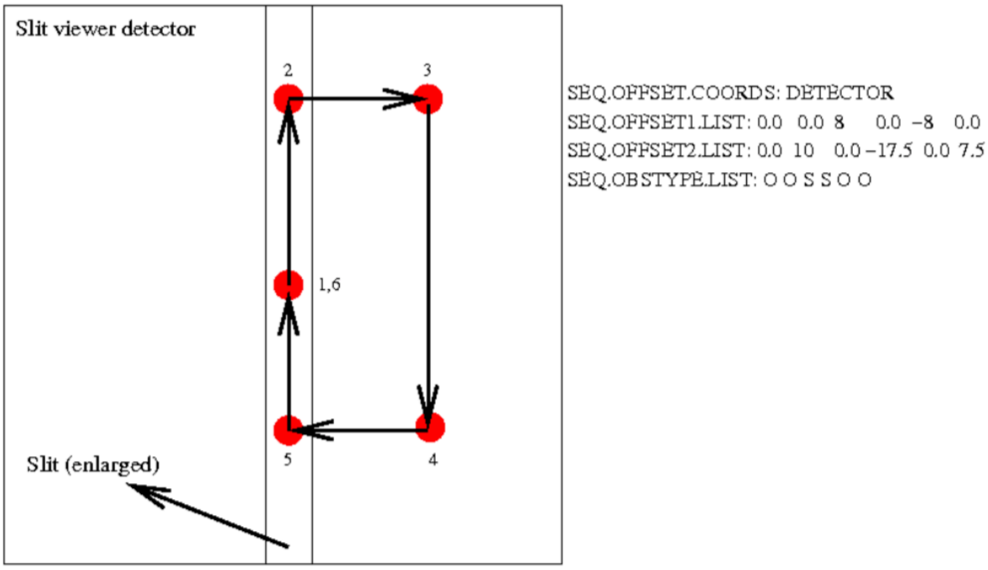

Figure 41: Illustration showing the apparent locations of the target relative to the slit centre, as seen from the SV detector for the given parameters, for the case of DETECTOR coordinate offsets. Offsets in X are perpendicular to the slit, while offsets in Y are always parallel to the slit. All motions are made in detector coordinates in pixel units (keep in mind that the pixel scale of the SV detector is 0.0373 arcsec / px).

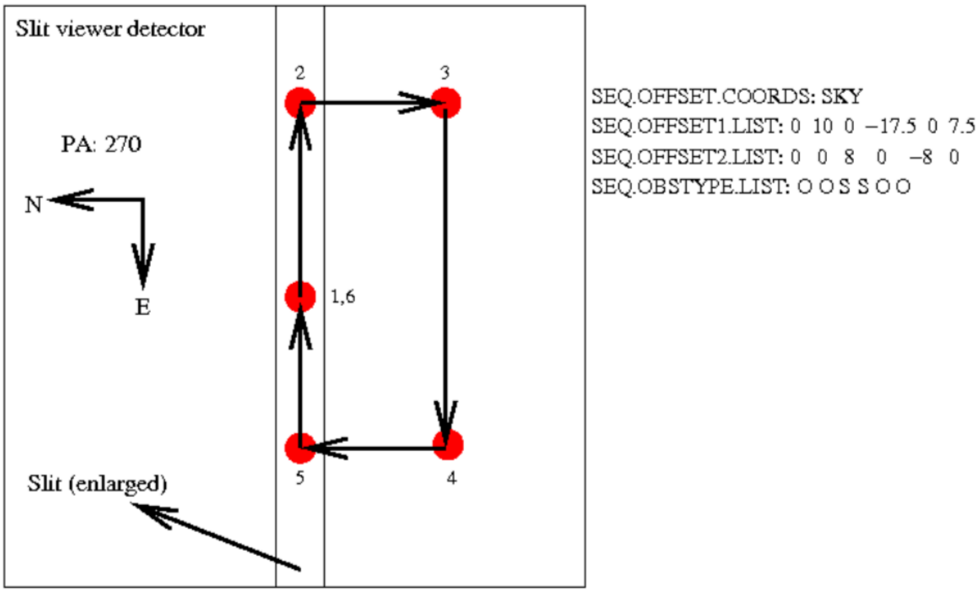

Figure 42: Illustration showing the apparent locations of the targets relative to the slit centre, as seen on the SV detector for the given parameters in the SKY coordinate offsets in arcsec units. If the telescope moves North, the target moves South relative to the slit centre.

The total integration time of one exposure in an OBJECT location is DET1.NDIT.OBJECT x DET1.DIT. Similarly, the total integration time of one exposure in SKY location is DET1.NDIT.SKY x 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. The total exposure time for one generic offset template is:

DET1.NDIT.OBJECT x DET1.DIT x SEQ.NEXPO x N_{Obj} + DET1.NDIT.SKY x DET1.DIT x SEQ.NEXPO x N_{Sky}

where N_{Obj} is the number of object positions and N_{Sky} is the number of sky positions.

6.4.4 Spectro-astrometry details

The CRIRES_spec_obs_SpectroAstrometry template allows to apply the spectro-astrometry technique without having to re-acquire the target for each position angle. Note that the derotator mode (TSF: INS.DROT.MODE) needs to be set to SKY in the acquisition template, and that the TARGET must be the SVGS and the AO NGS. For this reason, the CRIRES_spec_obs_SpectroAstrometry template cannot be used with differential tracking.

- **List of position angles** (TSF: INS.DROT.POSANG.LIST) is the list of position angles at which the nodding sequence is repeated. Note that these values of the position angles are in the range between 0 and 360, where 0 corresponds to North and 90 to East. When calculating the overheads, keep in mind that the derotator can only move between 0 and 359.9 degrees.
- **Reset jitter for each DROT posang** (TSF: SEQ.JITTER.RESET). Only relevant if SEQ.JITTER.WIDTH (Jitter width) is not zero. If this parameter is set to **yes** (i.e., SEQ.JITTER.RESET=T), then the list of jitter positions calculated by the observation software is repeated identically, in detector coordinates, for each value of the slit position angle

In the spectro-astrometry case, the total exposure time for one observing template with nodding is:

2 x SEQ.NABCYCLES x DET1.NDIT x DET1.DIT x SEQ.NEXPO x N_{posang}

where N_{posang} is the number of position angles defined in INS.DROT.POSANG.LIST. For the stare-mode (SEQ.NABCYCLES=0), the total exposure time is:

DET1.NDIT x DET1.DIT x SEQ.NEXPO x N_{posang}.

6.4.5 Spectro-polarimetry details

Remember that for observations with polarimetry, the CRIRES_pol_acq_NGS acquisition template must be used.

▪ **Polariziation Stokes Parameter** (TSF: INS.POL.TYPE) sets the desired Stokes parameter (Q, U or V). Note that a sequence of multiples of four exposures is always taken (i.e., for SEQ.NEXPO = 1, four exposures are taken), with the following polarimeter rotation angles:

For Stokes V at 0, 180, 180 and 0 degrees,
for Stokes Q at 0, 90, 180 and 270 degrees, and
for Stokes U at 45, 135, 225 and 315 degrees.

Note that these values are for INS.ROT.POSANG=0.

▪ **Polarimeter: rotation angle** (TSF: INS.ROT.POSANG) sets the initial reference angle on the sky for linear polarization (Stokes Q and U) - this can be useful when observing extended objects. This value is added to the aforementioned rotation sequence; the allowed range is from -180 to 180 degrees. Note that this parameter must be kept at 0, as currently extended objects cannot be observed in polarimetry mode.

▪ **Number of exposures per nodding position** (TSF: SEQ.NEXPO): gives the total number of Stokes cycles per nodding position, with one cycle always being 4 exposures. For example, for SEQ.NEXPO = 2 and INS.POL.TYPE = Q, eight exposures are taken, with the polarimeter rotation sequence 0, 90, 180 and 270 executed twice.

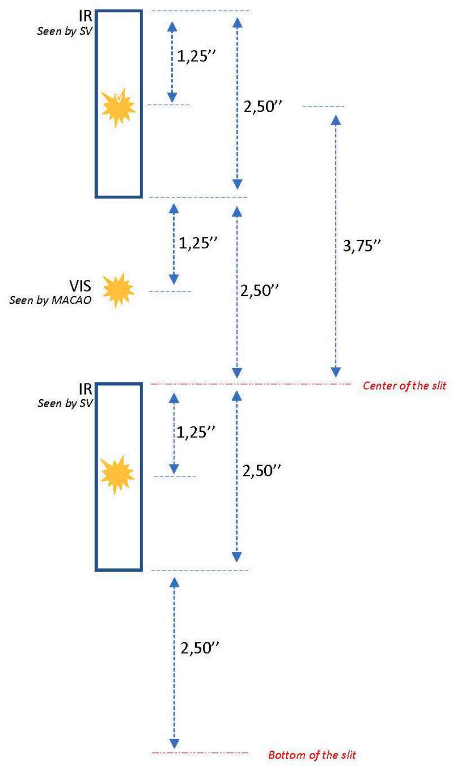

Figure 43: Illustration how the polarized image is split (corresponding to Decker24).

Nodding with polarimetry:

Nodding in polarimetric mode is more restrictive relative to the other modes. To avoid crosstalk from the extended wings of the two simultaneously recorded orthogonal polarisation states or contributions from the 0th order of unpolarised light, the polarised beams are separated by 5'' by a decker with 2.5'' slits cut at the expected position of the two beams (*Figure **43***). Since the locations of these slits are fixed, the allowable nod throw `SEQ.NODTHROW` is also fixed at a value of 2.5''. No jitter can be applied for polarimetry.

For polarimetry, the total exposure time for one observing template with nodding (`SEQ.NABCYCLES` ≥ 1) is consequently:

`DET1.NDIT x DET1.DIT x SEQ.NEXPO x SEQ.NABCYCLES x 2 x 4,`

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

`DET1.NDIT x DET1.DIT x SEQ.NEXPO x 4.`

6.5 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.

6.6 Attached night-time calibrations

Darks, flat fields and wavelength calibrations are taken during daytime as part of the calibrations plan (see §7.1 for more details).

However, depending on the science goal, additional calibrations can be requested during the night as well. For instance, dedicated templates 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 should supply a telluric standard star OB. If the science requires accurate flux calibration, then the user must provide a spectro-photometric standard star OB.

Table 13: Templates for attached calibrations.

INSTRUMENT MODE	TEMPLATE NAME	COMMENT
Spectroscopy	CRIRES_spec_cal_AutoNodOnSlit	Exposures are taken by nodding a user-specified telluric star along the slit.
	CRIRES_spec_cal_LampFlats	Attached flat field calibration template
	CRIRES_spec_cal_Wave	Attached wavelength calibration template
	CRIRES_spec_cal_SkyObs	Observations of sky lines
Polarimetry	CRIRES_pol_cal_AutoNodOnSlit	Observations of a user-defined polarimetric standard star

The name of any night-time calibration OBs must have the prefix 'CAL_'. The time required to perform these additional night-time calibrations will be charged to the user's observing programme.

In p2, these templates are located in the Template Type 'calib'. *Table **13*** lists the templates for attached calibrations. Note that for polarimetry mode the same templates as for spectroscopy can be used.

6.6.1 Spectro-photometric standard star or telluric observations

Any OB for either a telluric or a spectro-photometric standard star must consist of an acquisition template (see Table 10) 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 §6.4.

Telluric standard stars should be observed immediately following the corresponding science OB, within 20 degrees angular distance to the science target. To this end, for service mode operations, the science OB and the OB of the telluric standard should be placed into a concatenation container.

Note that data products obtained with this calibration template are automatically recognized by the pipeline as standard star observations. If the selected star is in the list of spectro-photometric standards supported by the pipeline (see *Table **14***), then the pipeline will output also the sensitivity and total throughput (i.e., spectrograph, telescope, Earth atmosphere).

Table 14: Spectro-photometric 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
HR1544	04:50:36.73	08:54:00.5	4.29	-0.07
HR3454	08:43:13.48	03:23:55.2	4.37	-0.27

HR4468	11:36:40.9	-09:48:08	4.64	-0.04
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
HR8634	22:41:27.73	10:49:52.6	3.43	-0.1

6.6.2 Flat field calibrations

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 recommend 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. 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). We recommend leaving the default value of 10'000 ADU unchanged for flat-fielding. The maximum flux parameter is used to automatically calculate the appropriate DIT given the requested NDIT.

6.6.3 Wavelength calibration template

The reproducibility of the wavelength setting between night-time observations and day-time calibrations is about 0.2 px if the metrology is employed. If the metrology is not employed during night-time, then the reproducibility is >5 px.

Due to drifts of the Echelle grating, exposures or observing sequences longer than 15 minutes might be affected by systematic wavelength shifts corresponding to velocities on the order of a few times 100 m/s. In this case, the telluric lines imprinted on the observed spectra can serve as useful long-term stable wavelength reference (they come for free), as these lines are intrinsically stable down to 10 m/s (rms).

If the use of telluric lines as simultaneous wavelength reference is not possible, then users can insert the **CRIRES_spec_cal_Wave** template before and/or after any science observing template.

Possible observing strategies could be, for example:

- Acquisition template (Metrology=Yes) - Science template (Metrology=No) - Wavelength calibration (source=UNE+FPET; Metrology=No)
- Acquisition (Metrology=No) - Wavelength calibration (source=UNE+FPET; Metrology=No) - Science template (Metrology=No) - Wavelength calibration (source=FPET; Metrology=No)

Most of the parameters to be defined in this template are described in §6.3 and §6.6.2; we describe the following template-specific parameters and settings here.

▪ **Wavelength calibration source** (TSF: INS.LAMP) selects the wavelength calibration source. Possible choices are:

- **FPET** for wavelength calibration <2500 nm. Keep in mind that the FPET alone does not serve as absolute wavelength reference (see UNE+FPET).
- **UNE** for the Uranium Neon lamp (<2500 nm), which provides an absolute wavelength reference.
- **UNE+FPET** takes two exposures, the first one with the UNE lamp and the second one with the Fabry-Perot Etalon (<2500 nm). The UNE lamp is taken to establish the zero-point of the FPET (recommended setup for wavelength calibration).
- **HALOGEN** in combination with any of the **gas cells** (INS.OPTI1.NAME = GAS_SGC or GAS_N2O).

▪ **Optical Element** (TSF: INS.OPTI1.NAME) allows to insert any gas cell (GAS_SGC or GAS_N2O) into the light path. If the wavelength calibration source is "UNE" or "UNE+FPET", then INS.OPTI1.NAME must be "FREE".

▪ **Maximum Flux** (TSF: SEQ.MAXFLUX) sets the flux level of the calibration sources. It should be set to 20'000 ADU for all calibration sources except for the UNE, which should be set to 100'000 ADU. **Maximum Flux2** (TSF: SEQ.MAXFLUX2) is only relevant if INS.LAMP = UNE+FPET, as it allows to individually set the flux level of the FPET following the UNE.

▪ **Number of cleaning darks** (TSF: SEQ.NCD): if set >0, then the specified number of cleaning darks will be taken, with the goal to remove persistence from the detector after the use of the UNE lamp (we recommend to set SEQ.NCD = 6). The DIT of the cleaning darks is hardcoded (20s), and they are not stored in the archive. Note that if INS.LAMP = UNE+FPET, then cleaning darks are taken after the UNE calibrations and additionally after the FPET calibrations. If SEQ.NCD = 0, then no cleaning darks will be taken.

6.6.4 Sky observations

Observed sky lines which can be identified by HITRAN have the advantage that wavelength calibration is done from the science observations themselves. 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. All parameters to be defined in this template have already been described in § 6.3 and §6.4.

6.6.5 Polarimetric standard stars

Any OB for a polarimetric standard star must consist of an acquisition template (see Table 10) and of the calibration template **CRIRES_pol_cal_AutoNodOnSlit**. The latter is very similar to the observing template CRIRES_pol_obs_AutoNodOnSlit described in §6.4.5.

A list of zero-polarization standard stars and polarized standard stars is provided in *Table* ***15*** and *Table* ***16***, respectively.

Table 15: zero polarized standard stars

Object	Comments
HD 10700	Tau Cet, G8V
HD 146233	18 Sco, G2Va, solar twin

Table 16: Preliminary list of polarimetric standard stars

Object	Comments
HD 24712	Stokes VQU standard, A9VpSrEuCr
HD 101065	Stokes V standard, Przybylski's Star, F8/G0p
HD 137509	Stokes VQU standard, Beta CrB, F2VpSrCrEuSi
HD 154708	Stokes V standard, ApSrEu
HD 201601	Stokes VQU standard, Gamma Equ, A9VpSrCrEu
GJ 551	Stokes V standard, Proxima Cen, M5.5Ve
TW Hya	Stokes V in He 1083 & K-band, K6Ve
GQ Lup	Stokes V in He 1083 & K-band, K7Ve

6.7 OB constraint set and Quality Control

In the ***p2/Constraint Set* tab**, users need to define the suitable observing conditions for the OB execution. We remind here that users are not allowed to define the OB constraint set more stringent than what had been requested in the proposal; **at Phase 2, observing constraints can only be relaxed.**

I. **AIRMASS** (X): see Section 5.3.2.

II. **LUNAR ILUMINATION** (FLI): see Section 5.3.4.

III. **SKY TRANSPARENCY**: see Section 5.3.5.

IV. **IMAGE QUALITY** (IQ): Defined as the FWHM of a long exposure stellar image 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. **The IQ is only relevant for NoAO observations**. User must use the IQ value calculated by the ETC for the requested airmass constraint, requested Turbulence category and wavelength setting. In case of multiple wavelength settings in the OB, the IQ value for the bluest wavelength setting in the OB should be adopted.

V. **TURBULENCE** (TC): see §5.3.1. **At Phase 2, the TC constraint is only relevant for observations in the AO mode.**

VI. **PRECIPITABLE WATER VAPOUR** (PWV): see Section 5.3.3.

Data acquired at the telescope are reduced in real-time (by using a standard calibration set) in order to provide a first quality control of observations. While in Visitor Mode this quality control is left to the visiting astronomer, in Service Mode this is done by the night-time crew on Paranal. This quality control checks for the fulfilment of the OB constraint set: OB executed fully within constraints will be classified as “A”, while at least one constraint violated by up to 10% in value or time will result in grade “B”. OBs that are observed well out of constraints (>10%) will have to be repeated.

6.8 Ephemeris of moving targets

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

6.9 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).

6.10 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

For very faint AO NGS (R>14) **or when employing AO at high airmass** (>1.4), PIs are encouraged to put a note into the README file, stating: For the case that the AO loop is unstable or does not close, the night-time operator may switch to NoAO mode.

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.

In the YJHKL bands, the daily calibrations are always taken with metrology. *Table* ***17*** lists the regular standard calibration typically taken in the morning after the observations, which *Table* ***18*** shows the long-term calibrations for instrument stability monitoring.

Table 17: Standard calibrations

Calibration	Number	Matching parameters	Validity
Darks for staring mode	3	wavelength, DIT	1 day
Flats	3	wavelength, slit width	1 day
Wavelength YJHK (FP etalon)	1	wavelength, slit width	1 day
Wavelength YJHK (UNe lamp)	1	wavelength, slit width	1 day
Wavelength LM (N_2O gas cell)	1	wavelength, slit width	1 day
SGC spectrum for data taken with the SGC	1	wavelength, slit width	1 day

Table 18: Instrument monitoring calibrations and long-term calibrations

Calibration	Purpose	Frequency
Spectral resolution (day)	Monitoring of the spectral resolving power	2 / week
RV standard stars (night)	Monitoring of radial velocity stability	1 / week
Efficiency monitoring (night)	Throughput monitoring with standards	1 / 30 days
Deep Flats (day)	Provide high S/N flats in the YJHKL bands to the exoplanet community	1 / 90 days
Polarimetric calibrations (day)	Monitoring of the polarimeter with the FP etalon	1 / 180 days

Polarized standard stars (night)	Monitoring of polarimetric performance	1 / 180 days
Distortion map (day)	Monitoring of the spatial resolution along the slit	1 / 180 days

7.2 Wavelength Settings

The properties of the 29 CRIRES wavelength settings are listed in *Table **19***:

Table 19: Wavelength coverage of CRIRES settings for the three detectors. Orders marked with an asterisk (*) are not complete as being located at the detector edge (i.e., parts of the slit are outside the detector) or at the wavelength cut-off at 5300nm.

Name Ref Wave	Wavelength Range Order Min – Max [nm]			Order
	Detector 1	Detector 2	Detector 3	
Y1029 **1029.310**	949.556 - 955.964 965.933 - 972.448 982.886 - 989.517 1000.440 - 1007.190 1018.630 - 1025.501 1037.497 - 1044.479 1057.032 - 1064.166 1077.359 - 1084.595 1098.447 - 1105.819	956.425 - 962.541 972.924 - 979.130 989.998 - 996.313 1007.674 - 1014.102 1025.986 - 1032.532 1044.969 - 1051.636 1064.663 - 1071.457 1085.091 - 1092.017 1106.338 - 1113.370	962.963 - 968.753 979.573 - 985.463 996.759 - 1002.754 1014.553 - 1020.655 1032.986 - 1039.200 1052.096 - 1058.426 1071.912 - 1078.362 1092.500 - 1099.051 1113.871 - 1120.543	**59** **58** **57** **56** **55** **54** **53** **52** **51**
Y1028 **1027.632**	948.027 - 954.469 964.367 - 970.921 981.276 - 987.946 998.782 - 1005.572 1016.919 - 1023.833 1035.720 - 1042.762 1055.221 - 1062.397 1075.463 - 1082.777 1096.487 - 1103.946	954.912 - 961.050 971.371 - 977.616 988.402 - 994.757 1006.036 - 1012.505 1024.304 - 1030.892 1043.241 - 1049.951 1062.884 - 1069.721 1083.272 - 1090.242 1104.448 - 1111.555	961.483 - 967.312 978.056 - 983.986 995.205 - 1001.239 1012.960 - 1019.103 1031.353 - 1037.609 1050.421 - 1056.793 1070.198 - 1076.692 1090.726 - 1097.345 1112.047 - 1118.796	**59** **58** **57** **56** **55** **54** **53** **52** **51**
J1232 **1232.490**	1122.121 - 1129.638 1145.040 - 1152.711 1168.906 - 1176.737 1193.802 - 1201.786 1219.734 - 1227.908 1246.813 - 1255.169 1275.162 - 1283.670 1304.776 - 1313.473	1130.195 - 1137.352 1153.271 - 1160.575 1177.303 - 1184.759 1202.356 - 1209.966 1228.475 - 1236.257 1255.760 - 1263.710 1284.260 - 1292.398 1314.090 - 1322.387	1137.855 - 1144.645 1161.089 - 1168.019 1185.280 - 1192.356 1210.493 - 1217.720 1236.797 - 1244.182 1264.265 - 1271.798 1292.939 - 1300.661 1322.970 - 1330.842	**50** **49** **48** **47** **46** **45** **44** **43**
J1228 **1228.488**	1118.324 - 1125.929 1141.162 - 1148.915 1164.943 - 1172.869 1189.744 - 1197.829 1215.616 - 1223.864 1242.588 - 1251.044 1270.837 - 1279.443 1300.359 - 1309.164 *1331.262 - 1340.268**	1126.482 - 1133.728 1149.483 - 1156.873 1173.439 - 1180.990 1198.404 - 1206.117 1224.448 - 1232.329 1251.638 - 1259.696 1280.047 - 1288.288 1309.780 - 1318.214 *1340.892 - 1349.528**	1134.240 - 1141.130* 1157.408 - 1164.437 1181.526 - 1188.696 1206.661 - 1213.979 1232.882 - 1240.355 1260.256 - 1267.894 1288.857 - 1296.658 1318.757 - 1326.768 *1350.059 - 1358.261**	**50** **49** **48** **47** **46** **45** **44** **43** **42***

J1226	1116.376 - 1124.028	1124.586 - 1131.879	1132.404 - 1139.333	**50**
1226.466	1139.175 - 1146.984	1147.551 - 1154.994	1155.521 - 1162.592	**49**
	1162.922 - 1170.895	1171.466 - 1179.065	1179.598 - 1186.818	**48**
	1187.667 - 1195.821	1196.391 - 1204.153	1204.700 - 1212.078	**47**
	1213.484 - 1221.805	1222.389 - 1230.320	1230.864 - 1238.399	**46**
	1240.463 - 1248.942	1249.534 - 1257.642	1258.205 - 1265.874	**45**
	1268.607 - 1277.307	1277.901 - 1286.194	1286.754 - 1294.634	**44**
	1298.103 - 1306.964	1307.579 - 1316.065	1316.608 - 1324.672	**43**
	1328.957 - 1338.011*	1338.632 - 1347.322*	1347.898 - 1356.153*	**42***
H1582	1445.816 - 1455.279*	1455.983 - 1464.983*	1465.615 - 1474.143*	**39***
1582.339	1483.886 - 1493.600	1494.303 - 1503.540	1504.196 - 1512.948	**38**
	1524.018 - 1533.983	1534.694 - 1544.182	1544.856 - 1553.849	**37**
	1566.338 - 1576.594	1577.320 - 1587.072	1587.753 - 1596.995	**36**
	1611.072 - 1621.622	1622.362 - 1632.393	1633.090 - 1642.598	**35**
	1658.417 - 1669.279	1670.034 - 1680.364	1681.072 - 1690.860	**34**
	1708.666 - 1719.809	1720.604 - 1731.216	1731.961 - 1742.011	**33**
	1761.989 - 1773.460*	1774.254 - 1785.232	1785.993 - 1796.346	**32**
H1575	1438.643 - 1448.280*	1448.985 - 1458.160*	1458.815 - 1467.521*	**39***
1574.798	1476.520 - 1486.412	1487.136 - 1496.554	1497.217 - 1506.154	**38**
	1516.453 - 1526.606	1527.333 - 1537.007	1537.693 - 1546.868	**37**
	1558.568 - 1569.012	1569.749 - 1579.693	1580.390 - 1589.825	**36**
	1603.114 - 1613.827	1614.581 - 1624.811	1625.515 - 1635.222	**35**
	1650.209 - 1661.271	1662.028 - 1672.560	1673.282 - 1683.274	**34**
	1700.199 - 1711.543	1712.326 - 1723.178	1723.935 - 1734.219	**33**
	1753.219 - 1764.973	1765.743 - 1776.935	1777.710 - 1788.284	**32**
H1567	1431.264 - 1441.067*	1441.764 - 1451.115*	1451.786 - 1460.681*	**39***
1567.099	1468.921 - 1478.991	1479.728 - 1489.326	1490.004 - 1499.123	**38**
	1508.660 - 1518.984	1519.730 - 1529.589	1530.274 - 1539.641	**37**
	1550.547 - 1561.179	1561.937 - 1572.071	1572.773 - 1582.401	**36**
	1594.869 - 1605.765	1606.549 - 1616.973	1617.703 - 1627.595	**35**
	1641.760 - 1652.978	1653.768 - 1664.500	1665.224 - 1675.421	**34**
	1691.468 - 1703.015	1703.836 - 1714.860	1715.612 - 1726.110	**33**
	1744.251 - 1756.147	1756.998 - 1768.360	1769.137 - 1779.974	**32**
H1559	1423.591 - 1433.581	1434.573 - 1444.098*	1444.772 - 1453.833*	**39***
1559.245	1461.242 - 1471.488	1472.227 - 1482.004	1482.699 - 1492.000	**38**
	1500.747 - 1511.272	1512.037 - 1522.087	1522.775 - 1532.329	**37**
	1542.470 - 1553.261	1554.027 - 1564.350	1565.067 - 1574.887	**36**
	1586.512 - 1597.640	1598.417 - 1609.036	1609.758 - 1619.860	**35**
	1633.182 - 1644.601	1645.382 - 1656.315	1657.081 - 1667.458	**34**
	1682.632 - 1694.385	1695.228 - 1706.454	1707.246 - 1717.929	**33**
	1735.150 - 1747.258	1748.066 - 1759.684	1760.464 - 1771.517	**32**
K2217	1968.499 - 1980.621	1981.417 - 1992.906	1994.005 - 2004.852	**29**
2216.704	2038.829 - 2051.386	2052.289 - 2064.190	2065.031 - 2076.268	**28**
	2114.306 - 2127.330	2128.304 - 2140.648	2141.736 - 2153.390	**27**
	2195.651 - 2209.177	2210.142 - 2222.963	2223.836 - 2235.941	**26**
	2283.444 - 2297.513	2298.471 - 2311.806	2312.727 - 2325.318	**25**
	2378.509 - 2393.166	2394.120 - 2408.014	2408.723 - 2421.842	**24**
	2481.614 - 2496.911*	2497.956 - 2512.456*	2513.474 - 2527.165*	**23***
K2192	1946.075 - 1958.768	1959.640 - 1971.708	1972.430 - 1983.863	**29**
2192.449	2015.418 - 2028.566	2029.659 - 2042.160	2042.896 - 2054.739	**28**
	2090.025 - 2103.662	2104.684 - 2117.649	2118.553 - 2130.837	**27**
	2170.457 - 2184.620	2185.625 - 2199.091	2200.008 - 2212.766	**26**
	2257.231 - 2271.963	2272.986 - 2286.993	2287.937 - 2301.207	**25**
	2351.333 - 2366.680	2367.527 - 2382.120	2383.170 - 2396.995	**24**
	2453.355 - 2469.372	2470.102 - 2485.331	2486.638 - 2501.068	**23**
K2166	1921.468 - 1934.743*	1935.656 - 1948.315*	1949.210 - 1961.242*	**29***
2166.016	1990.149 - 2003.901	2004.889 - 2018.001	2018.721 - 2031.185	**28**
	2063.682 - 2077.944	2079.036 - 2092.637	2093.441 - 2106.368	**27**

	2143.293 - 2158.106	2158.896 - 2173.022	2173.988 - 2187.413	**26**
	2228.779 - 2244.187	2244.979 - 2259.672	2260.896 - 2274.862	**25**
	2321.520 - 2337.572	2338.543 - 2353.850	2355.133 - 2369.682	**24**
	2422.230 - 2438.981	2440.074 - 2456.048	2457.226 - 2472.411	**23**
K2148	1972.235 - 1986.384	1987.314 - 2000.830	2001.875 - 2014.745	**28**
2147.646	2045.312 - 2059.987	2061.030 - 2075.049	2076.029 - 2089.381	**27**
	2123.972 - 2139.213	2140.312 - 2154.839	2155.840 - 2169.707	**26**
	2208.947 - 2224.800	2225.872 - 2241.016	2242.054 - 2256.443	**25**
	2300.869 - 2317.384	2318.501 - 2334.284	2335.216 - 2350.242	**24**
	2400.801 - 2418.000	2419.032 - 2435.497	2436.585 - 2452.268	**23**
L3426	2886.255 - 2902.981	2904.117 - 2919.916	2921.038 - 2935.895	**20**
3425.891	3038.136 - 3055.744	3056.954 - 3073.585	3074.758 - 3090.399	**19**
	3206.866 - 3225.455	3226.735 - 3244.293	3245.533 - 3262.046	**18**
	3395.411 - 3415.096	3416.454 - 3435.048	3436.364 - 3453.851	**17**
	3607.472 - 3628.391	3629.837 - 3649.596	3650.998 - 3669.580	**16**
	3847.734 - 3870.051	3871.596 - 3892.676	3894.174 - 3913.999	**15**
	4122.208 - 4146.123	4147.781 - 4170.370	4171.978 - 4193.223	**14**
L3412	2873.100 - 2890.470	2891.350 - 2907.850	2908.650 - 2924.220	**20**
3411.608	3024.390 - 3042.660	3043.590 - 3060.950	3061.790 - 3078.180	**19**
	3192.460 - 3211.750	3212.730 - 3231.040	3231.930 - 3249.220	**18**
	3380.290 - 3400.700	3401.740 - 3421.120	3422.060 - 3440.360	**17**
	3591.560 - 3613.230	3614.340 - 3634.920	3635.920 - 3655.360	**16**
	3830.950 - 3854.050	3855.220 - 3877.160	3878.230 - 3898.950	**15**
	4104.440 - 4129.170	4130.430 - 4153.920	4155.060 - 4177.240	**14**
L3377	2842.872 - 2860.751	2861.977 - 2878.942	2880.138 - 2896.176	**20**
3376.965	2992.466 - 3011.288	3012.584 - 3030.445	3031.707 - 3048.592	**19**
	3158.663 - 3178.534	3179.904 - 3198.760	3200.094 - 3217.920	**18**
	3344.379 - 3365.421	3366.874 - 3386.842	3388.258 - 3407.136	**17**
	3553.261 - 3575.622	3577.168 - 3598.387	3599.894 - 3619.954	**16**
	3789.923 - 3813.777	3815.429 - 3838.066	3839.676 - 3861.077	**15**
	4060.288 - 4085.850	4087.622 - 4111.880	4113.606 - 4136.540	**14**
L3340	2958.526 - 2978.186	2979.541 - 2998.251	2999.474 - 3017.224	**19**
3340.492	3122.841 - 3143.596	3145.028 - 3164.780	3166.001 - 3184.740	**18**
	3306.454 - 3328.433	3329.952 - 3350.869	3352.059 - 3371.903	**17**
	3512.973 - 3536.328	3537.944 - 3560.171	3561.284 - 3582.372	**16**
	3746.959 - 3771.875	3773.600 - 3797.313	3798.397 - 3820.894	**15**
	4014.270 - 4040.969	4042.820 - 4068.230	4070.039 - 4094.140	**14**
L3302	2922.620 - 2943.340	2944.400 - 2964.230	2965.200 - 2984.090	**19**
3302.210	3085.060 - 3106.920	3108.040 - 3128.960	3129.980 - 3149.920	**18**
	3266.590 - 3289.720	3290.900 - 3313.050	3314.130 - 3335.230	**17**
	3470.780 - 3495.340	3496.600 - 3520.120	3521.260 - 3543.670	**16**
	3702.140 - 3728.320	3729.660 - 3754.730	3755.950 - 3779.840	**15**
	3966.480 - 3994.510	3995.950 - 4022.790	4024.090 - 4049.660	**14**
	_4270.786 - 4300.750*_	_4302.820 - 4331.414*_	_4333.455 - 4360.656*_	**13***
L3262	2885.858 - 2907.162	2908.632 - 2929.010	2930.454 - 2949.891	**19**
3262.140	3046.143 - 3068.632	3070.186 - 3091.699	3093.225 - 3113.744	**18**
	3225.255 - 3249.070	3250.717 - 3273.497	3275.116 - 3296.845	**17**
	3426.712 - 3452.019	3453.771 - 3477.978	3479.700 - 3502.790	**16**
	3654.969 - 3681.965	3683.836 - 3709.660	3711.498 - 3736.131	**15**
	3915.740 - 3944.668	3946.673 - 3974.346	3976.316 - 4002.712	**14**
	_4216.551 - 4247.708*_	4249.860 - 4279.665	4281.782 - 4310.211	**13***
L3244	2869.170 - 2891.010	2892.130 - 2913.120	2914.140 - 2934.200	**19**
3244.424	3028.640 - 3051.690	3052.870 - 3075.020	3076.100 - 3097.260	**18**
	3206.860 - 3231.250	3232.500 - 3255.940	3257.080 - 3279.480	**17**
	3407.320 - 3433.230	3434.560 - 3459.440	3460.660 - 3484.450	**16**
	3634.470 - 3662.090	3663.500 - 3690.030	3691.320 - 3716.680	**15**

	3894.000 - 3923.560	3925.080 - 3953.480	3954.860 - 3982.010	**14**
	4192.604 - 4224.267	4226.457 - 4256.775	4258.929 - 4287.880	**13**
M4519	_3426.272 - 3445.062*_	_3446.342 - 3464.029*_	_3465.266 - 3481.837*_	**17***
4518.527	3640.452 - 3660.419	3661.778 - 3680.573	3681.885 - 3699.493	**16**
	3883.171 - 3904.473	3905.927 - 3925.979	3927.382 - 3946.168	**15**
	4160.532 - 4183.360	4184.922 - 4206.410	4207.919 - 4228.051	**14**
	4480.512 - 4505.100	4506.788 - 4529.934	4531.565 - 4553.251	**13**
	4853.737 - 4880.379	4882.215 - 4907.295	4909.068 - 4932.566	**12**
	5294.680 - 5323.750	5325.759 - 5353.127	5355.067 - 5380.709	**11***
M4504	3628.157 - 3648.483	3649.867 - 3669.026	3670.364 - 3688.340	**16**
4504.089	3870.057 - 3891.742	3893.223 - 3913.662	3915.094 - 3934.271	**15**
	4146.482 - 4169.720	4171.311 - 4193.215	4194.754 - 4215.305	**14**
	4465.383 - 4490.412	4492.132 - 4515.725	4517.388 - 4539.525	**13**
	4837.349 - 4864.470	4866.339 - 4891.904	4893.712 - 4917.699	**12**
	5276.806 - 5306.399	_5308.445 - 5336.340*_	_5338.319 - 5364.494*_	**11***
M4461	3591.380 - 3613.090	3614.190 - 3634.810	3635.810 - 3655.280	**16**
4461.195	3830.900 - 3854.040	3855.220 - 3877.210	3878.270 - 3899.030	**15**
	4104.610 - 4129.400	4130.660 - 4154.210	4155.350 - 4177.580	**14**
	4420.390 - 4447.070	4448.430 - 4473.780	4475.000 - 4498.940	**13**
	4788.740 - 4817.620	4819.090 - 4846.530	4847.860 - 4873.770	**12**
	5223.930 - 5255.410	5257.020 - 5286.920	_5288.370 - 5316.620*_	**11***
M4416	3553.308 - 3575.659	3577.187 - 3598.396	3599.884 - 3619.935	**16**
4415.885	3790.220 - 3814.065	3815.698 - 3838.325	3839.916 - 3861.307	**15**
	4060.946 - 4086.499	4088.253 - 4112.501	4114.210 - 4137.133	**14**
	4373.276 - 4400.798	4402.693 - 4428.810	4430.656 - 4455.347	**13**
	4737.582 - 4767.403	4769.461 - 4797.760	4799.765 - 4826.520	**12**
	5167.995 - 5200.534	5202.785 - 5233.663	5235.856 - 5265.049	**11**
M4368	3512.986 - 3536.332	3537.930 - 3560.148	3561.712 - 3582.784	**16**
4368.182	3747.211 - 3772.117	3773.825 - 3797.528	3799.197 - 3821.678	**15**
	4014.868 - 4041.557	4043.392 - 4068.792	4070.584 - 4094.675	**14**
	4323.657 - 4352.404	4354.385 - 4381.743	4383.679 - 4409.626	**13**
	4683.836 - 4714.984	4717.135 - 4746.778	4748.880 - 4776.996	**12**
	5109.377 - 5143.363	5145.714 - 5178.059	5180.357 - 5211.036	**11**
M4318	_3470.761 - 3495.089*_	_3496.759 - 3519.974*_	_3521.613 - 3543.695*_	**16***
4318.114	3702.172 - 3728.126	3729.908 - 3754.674	3756.420 - 3779.978	**15**
	3966.615 - 3994.426	3996.341 - 4022.879	4024.755 - 4049.999	**14**
	4271.696 - 4301.652	4303.719 - 4332.303	4334.327 - 4361.518	**13**
	4627.555 - 4660.012	4662.254 - 4693.226	4695.424 - 4724.887	**12**
	5047.995 - 5083.408	5085.860 - 5119.653	5122.056 - 5154.203	**11**
M4266	_3426.620 - 3452.170*_	_3453.480 - 3477.990*_	_3479.190 - 3502.590*_	**16***
4265.706	3655.170 - 3682.410	3683.810 - 3709.950	3711.220 - 3736.180	**15**
	3916.350 - 3945.520	3947.020 - 3975.010	3976.380 - 4003.110	**14**
	4217.680 - 4249.080	4250.690 - 4280.830	4282.290 - 4311.070	**13**
	4569.180 - 4603.170	4604.910 - 4637.540	4639.130 - 4670.280	**12**
	4984.480 - 5021.540	5023.440 - 5059.000	5060.730 - 5094.690	**11**
M4211	3606.250 - 3634.480	3635.930 - 3663.080	3664.400 - 3690.380	**15**
4210.988	3863.940 - 3894.170	3895.720 - 3924.800	3926.220 - 3954.050	**14**
	4161.240 - 4193.790	4195.460 - 4226.760	4228.280 - 4258.240	**13**
	4508.050 - 4543.280	4545.090 - 4578.980	4580.630 - 4613.060	**12**
	4917.810 - 4956.220	4958.190 - 4995.130	4996.930 - 5032.280	**11**
M4187	3583.792 - 3612.224	3614.169 - 3641.453	3643.368 - 3669.483	**15**
4186.838	3839.917 - 3870.385	3872.473 - 3901.711	3903.768 - 3931.753	**14**
	4135.428 - 4168.245	4170.499 - 4201.992	4204.217 - 4234.360	**13**
	4480.156 - 4515.715	4518.162 - 4552.286	4554.698 - 4587.360	**12**
	4887.494 - 4926.293	4928.969 - 4966.203	4968.841 - 5004.480	**11**

7.3 Template Signature Files

7.3.1 Acquisition TSF

Five acquisition templates are available:

- **CRIRES_spec_acq_NGS**: AO-assisted spectroscopy
- **CRIRES_spec_acq_NoAO**: Seeing limited spectroscopy
- **CRIRES_spec_acq_NGS_difftrack**: AO-assisted spectroscopy for differential tracking between two moving targets
- **CRIRES_spec_acq_NoAO_difftrack**: Seeing limited spectroscopy for differential tracking between two moving targets
- **CRIRES_pol_acq_NGS**: AO-assisted spectro-polarimetry

CRIRES_spec_acq_NGS		
To be specified:		
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.NGS.MAG	0.2 .. 15	R-band magnitude of the AO guide star
SEQ.SVGS.HMAG	-5 .. 20	H-band magnitude of the SV Guide Star
SEQ.SV.USELASTSKY	T F *(F)*	Use the last sky measurement for the SV
SEQ.METROLOGY.ST	T F *(F)*	Improve opto-mechanical positioning via metrology? (Recommended: yes)
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 gas cell
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 *(w_0.2)*	Entrance slit width
INS.WLEN.CWLEN	See Table 19	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
Fixed values:		
DPR.CATG	ACQUISITION	Data product category
DPR.TECH	IMAGE	Data product technique
DPR.TYPE	OBJECT	Data product type

CRIRES_spec_acq_NoAO		
To be specified:		
Parameter	Range *(default)*	Label
SEQ.SVGS.HMAG	-5 .. 20	H-band magnitude of the SV 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
SEQ.METROLOGY.ST	T F *(F)*	Improve opto-mechanical positioning via metrology? (Recommended: yes)
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 *(FREE)*	Optional gas cell
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 *(w_0.2)*	Entrance slit width
INS.WLEN.CWLEN	See Table 19	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.FLATTEN_DM	T F *(F)*	Flatten DM
SEQ.SV.GUIDE	T F *(T)*	SV guiding
SEQ.FLUX.TOLERANC	0.01..0.10 *(0.05)*	Flux Tolerance
Fixed Values		
DPR.CATG	ACQUISITION	Data product category
DPR.TECH	IMAGE	Data product technique
DPR.TYPE	OBJECT	Data product type

CRIRES_spec_acq_NGS_difftrack		
To be specified:		
Parameter	Range *(default)*	P2 label
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 *(T)*	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.SV.USELASTSKY	T F *(F)*	Use the last sky measurement for the SV?
SEQ.METROLOGY.ST	T F *(F)*	Improve opto-mechanical positioning via metrology? (Recommended: yes)
SEQ.NGS.MAG	0.2 .. 15	R-band magnitude of the AO guide star
SEQ.SVGS.HMAG	-5 .. 20	H-band magnitude of the SV Guide Star
Reference star tracking table file	Name of PAF file	Ephemeris file of reference object
Target tracking table file	Name of PAF file	Ephemeris file of target
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
INS.DROT.POSANG	0 .. 360 (0)	Derotator position angle
INS.OPTI1.NAME	FREE GAS_N20 GAS_SGC *(FREE)*	Optional gas cell
INS.SLIT1.NAME	w_0.2, w_0.4 *(w_0.2)*	Entrance slit width
INS.WLEN.CWLEN	See Table 19	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 TEL.TARG.ADDVELDELTA	-15..15 *(0.0)* -15..15 *(0.0)*	Diff RA Diff DEC
Hidden parameters:		
SEQ.PRESET SEQ.SV.GUIDE SEQ.FLUX.TOLERANC	T F *(T)* T F *(T)* 0.01..0.10 *(0.05)*	Preset flag SV guiding Flux Tolerance
Fixed values:		
DPR.CATG DPR.TECH DPR.TYPE	ACQUISITION IMAGE OBJECT	Data product category Data product technique Data product type

CRIRES_spec_acq_NoAO_difftrack		
To be specified:		
Parameter	Range *(default)*	P2 label
SEQ.SV.USELASTSKY	T F *(F)*	Use the last sky measurement for the SV?
SEQ.METROLOGY.ST	T F *(F)*	Improve opto-mechanical positioning via metrology? (Recommended: yes)
SEQ.SVGS.HMAG	-5 .. 20	H-band magnitude of the SV Guide Star
Reference star tracking table file	Name of PAF file	Ephemeris file of reference object
Target tracking table file	Name of PAF file	Ephemeris file of target
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
INS.DROT.POSANG	0 .. 360 (0)	Derotator position angle
INS.OPTI1.NAME	FREE GAS_N20 GAS_SGC *(FREE)*	Optional gas cell
INS.SLIT1.NAME	w_0.2, w_0.4 *(w_0.2)*	Entrance slit width
INS.WLEN.CWLEN	See Table 19	Standard wavelength setting
TEL.TARG.ALPHA TEL.TARG.DELTA TEL.TARG.EQUINOX	*(NODEFAULT)* *(NODEFAULT)* -2000..3000 *(2000)*	Right Ascension Declination 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
Fixed values:		
DPR.CATG	ACQUISITION	Data product category
DPR.TECH	IMAGE	Data product technique
DPR.TYPE	OBJECT	Data product type

CRIRES_pol_acq_NGS		
To be specified:		
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 *(T)*	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.NGS.MAG	0.2 .. 15	R-band magnitude of the AO guide star
SEQ.SVGS.HMAG	-5 .. 20	H-band magnitude of the SV Guide Star
SEQ.SV.USELASTSKY	T F *(F)*	Use the last sky measurement for the SV?
SEQ.METROLOGY.ST	T F *(F)*	Improve opto-mechanical positioning via metrology? (Recommended: yes)
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.POL.TYPE	V, Q, U *(V)*	Polarization Stokes parameter
INS.SLIT1.NAME	w_0.2, w_0.4 *(w_0.2)*	Entrance slit width
INS.WLEN.CWLEN	See Table 19	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
Fixed values:		
DPR.CATG	ACQUISITION	Data product category
DPR.TECH	IMAGE	Data product technique
DPR.TYPE	OBJECT	Data product type

7.3.2 Science observing TSF

Four science observing templates are available:

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

CRIRES_spec_obs_AutoNodOnSlit		
To be specified:		
Parameter	Range *(default)*	Label
DET1.DIT	1.4..900 *(NODEFAULT)*	DIT
DET1.NDIT	1..1000 *(1)*	NDIT
SEQ.NEXPO	1..100 *(10)*	Number of exposures per nodding position
SEQ.NABCYCLES	0..100 *(1)*	Number of nodding cycles
SEQ.NODTHROW	*0..30 (6)*	Nod throw along the slit
SEQ.JITTER.WIDTH	0..8 *(0)*	Jitter width
INS.METROLOGY.ST	T F *(F)*	Improve opto-mechanical positioning via metrology?
INS.OPTI1.NAME	FREE GAS_SGC GAS_N20	Gas cell
INS.WLEN.CWLEN	See Table 19	Standard wavelength setting
Hidden parameters:		
SEQ.POISSON	1..100 *(100)*	Poisson value
SEQ.NOD.DELAY	0.0..10.0 *(6.0)*	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		
To be specified:		
Parameter	Range *(default)*	Label
DET1.DIT	1.4..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.METROLOGY.ST	T F *(F)*	Improve opto-mechanical positioning via metrology?
INS.OPTI1.NAME	FREE GAS_N20 GAS_SGC	Gas cell
INS.WLEN.CWLEN	See Table 19	Standard wavelength setting
Hidden Parameters		
SEQ.NEXPOSKIP	0	Skip N positions
SEQ.NOD.DELAY	0.0..10.0 *(6)*	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	1.4..900 *(NODEFAULT)*	DIT
DET1.NDIT	1..1000 *(1)*	NDIT
INS.DROT.POSANGLIST	0.0..360.0 *()*	List of position angles
SEQ.NEXPO	1..100 *(10)*	Number of exposures per nodding position

SEQ.NABCYCLES	0..100 *(1)*	Number of nodding cycles
SEQ.NODTHROW	*0..30 (6)*	Nod throw along the slit
SEQ.JITTER.WIDTH	0..8 *(0)*	Jitter width
SEQ.JITTER.RESET	T F *(T)*	Reset jitter for each DROT posang
INS.METROLOGY.ST	T F *(F)*	Improve opto-mechanical positioning via metrology?
INS.DROT.POSANG.LIST	0.0..360.0	List of position angles in degrees
INS.OPTI1.NAME	FREE GAS_N20 GAS_SGC *(FREE)*	Gas cell
INS.WLEN.CWLEN	See Table 19	
Hidden parameters:		
SEQ.POISSON	1..100 *(100)*	Poisson value
SEQ.NOD.DELAY	0.0..10.0 *(6)*	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_pol_obs_AutoNodOnSlit		
To be specified:		
Parameter	Range *(default)*	Label
DET1.DIT	1.4..900 *(NODEFAULT)*	DIT
DET1.NDIT	1..1000 *(1)*	NDIT
SEQ.NEXPO	1..100 *(10)*	Number of exposures per nodding position
SEQ.NABCYCLES	0..100 *(1)*	Number of nodding cycles
INS.METROLOGY.ST	T F *(F)*	Improve opto-mechanical positioning via metrology?
INS.POL.TYPE	V, Q, U *(V)*	Polarization Stokes parameter
INS.ROT.POSANG	-180 .. 180 *(0)*	Initial polarimeter rotation angle for Stokes Q and U.
INS.WLEN.CWLEN	See Table 19	Standard wavelength setting
Hidden parameters:		
SEQ.POISSON	1..100 *(100)*	Poisson value

SEQ.JITTER.WIDTH	0..0 *(0)*	Jitter width
SEQ.NOD.DELAY	0.0..10.0 *(6.0)*	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:		
SEQ.NODTHROW	2.5	Nod throw along the slit
DPR.CATG	SCIENCE	Data product category
DPR.TECH	SPECTRUM	Data product technique
DPR.TYPE	OBJECT	Data product type

7.3.3 Calibration TSF

Available calibrations templates are:

- **CRIRES_spec_cal_AutoNodOnSlit**: attached telluric or spectro-photometric star
- **CRIRES_pol_cal_AutoNodOnSlit**: attached standard star for polarimetry
- **CRIRES_spec_cal_Wave**: wavelength calibration
- **CRIRES_pol_cal_Wave**: wavelength calibration with the polarimeter inserted
- **CRIRES_spec_cal_LampFlats**: flat field calibrations
- **CRIRES_spec_cal_Darks**: darks
- **CRIRES_spec_cal_SkyObs**: sky observations without telescope guiding

CRIRES_spec_cal_AutoNodOnSlit		
To be specified:		
Parameter	Range *(default)*	Label
DET1.DIT	1.4..900 *(NODEFAULT)*	DIT
DET1.NDIT	1..1000 *(1)*	NDIT
SEQ.NEXPO	1..100 *(10)*	Number of exposures per nodding position
SEQ.NABCYCLES	0..100 *(1)*	Number of nodding cycles
SEQ.NODTHROW	*0..30 (6)*	Nod throw along the slit
SEQ.JITTER.WIDTH	0..8 *(0)*	Jitter width
INS.METROLOGY.ST	T F *(F)*	Improve opto-mechanical positioning via metrology?
INS.OPTI1.NAME	FREE, GAS_SGC, GAS_N20 *(FREE)*	Gas cell
INS.WLEN.CWLEN	See Table 19	Standard wavelength setting

Hidden parameters:		
SEQ.POISSON	1..100 *(100)*	Poisson value
SEQ.NOD.DELAY	0.0..10.0 *(6.0)*	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	CALIB	Data product category
DPR.TECH	SPECTRUM	Data product technique
DPR.TYPE	OBJECT	Data product type

CRIRES_pol_cal_AutoNodOnSlit		
To be specified:		
Parameter	Range *(default)*	Label
DET1.DIT	1.4..900 *(NODEFAULT)*	DIT
DET1.NDIT	1..1000 *(1)*	NDIT
SEQ.NEXPO	1..100 *(10)*	Number of exposures per nodding position
SEQ.NABCYCLES	0..100 *(1)*	Number of nodding cycles
INS.METROLOGY.ST	T F *(F)*	Improve opto-mechanical positioning via metrology?
INS.POL.TYPE	V, Q, U *(V)*	Polarization Stokes parameter
INS.ROT.POSANG	-180 .. 180 *(0)*	Initial polarimeter rotation angle for Stokes Q and U.
INS.WLEN.CWLEN	See Table 19; <2500 nm only	Standard wavelength setting
Hidden parameters:		
SEQ.POISSON	1..100 *(100)*	Poisson value
SEQ.JITTER.WIDTH	0..0 *(0)*	Jitter width
SEQ.NOD.DELAY	0.0..10.0 *(6.0)*	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:		
SEQ.NODTHROW	2.5	Nod throw along the slit
DPR.CATG	CALIB	Data product category
DPR.TECH	SPECTRUM	Data product technique
DPR.TYPE	OBJECT	Data product type

CRIRES_spec_cal_Wave		
To be specified:		
Parameter	Range *(default)*	Label
DET1.NDIT	1..1000 *(1)*	NDIT
SEQ.NEXPO	1..100 *(1)*	Number of exposures
SEQ.MAXFLUX	*0..200000 (20000)*	Maximum Flux (in ADU)
SEQ.MAXFLUX2	*0..30000 (20000)*	Maximum Flux for FPET if 'UNE+FPET' is selected
SEQ.METROLOGY.ST	yes / *no (no)*	Run metrology?
SEQ.NCD	0 .. 20 (0)	Number of cleaning darks
INS.LAMP	FPET, UNE, UNE+FPET, HALOGEN, IR-EMITTER (UNE)	Wavelength calibration source
INS.OPTI1.NAME	FREE, GAS_N20, GAS_SGC, *(FREE)*	Insert gas cell? (optional)
INS.DECKER.POS	*Dek13, Dek24, Open (Open)*	Decker Position ('Open' for spectroscopy)
INS.SLIT1.NAME	w_0.2, w_0.4 (w_0.2)	Entrance slit width
INS.WLEN.CWLEN	See Table 19	Reference wavelength
Hidden parameters:		
SEQ.POISSON	1..100 *(100)*	Poisson value
SEQ.FLUX.TOLERANC	0.01..0.10 *(0.05)*	Flux Tolerance
Fixed values:		
DPR.CATG	CALIB	Data product category
DPR.TECH	SPECTRUM	Data product technique
DPR.TYPE	OBJECT	Data product type

CRIRES_pol_cal_Wave		
To be specified:		
Parameter	Range *(default)*	Label
DET1.NDIT	1..1000 *(1)*	NDIT
SEQ.NEXPO	1..100 *(1)*	Number of exposures
SEQ.MAXFLUX	*0..30000 (20000)*	Maximum Flux (in ADU)
SEQ.METROLOGY.ST	yes / *no (no)*	Run metrology?
INS.LAMP	FPET	Wavelength calibration source
INS.DECKER.POS	*Dek13, Dek24, Open (Open)*	Decker Position
INS.ROT.TUR	*HK_circular, YJ_circular, HK_linear, YJ_circular*	Polarimeter turret position

INS.ROT.POSANG	-180 .. 180 *(0)*	Polarimeter rotation angle
INS.SLIT1.NAME	w_0.2, w_0.4 (w_0.2)	Entrance slit width
INS.WLEN.CWLEN	See Table 19; <2500 nm only	Reference wavelength
Hidden parameters:		
SEQ.POISSON	1..100 *(100)*	Poisson value
SEQ.FLUX.TOLERANC	0.01..0.10 *(0.05)*	Flux Tolerance
INS.OPTI1.NAME	SPU	Insert polarimeter
INS.ROT.MODE	STAT	Rotator mode
Fixed values:		
DPR.CATG	CALIB	Data product category
DPR.TECH	SPECTRUM	Data product technique
DPR.TYPE	OBJECT	Data product type

CRIRES_spec_cal_LampFlats		
To be specified:		
Parameter	Range *(default)*	Label
DET1.NDIT	1..1000 *(1)*	NDIT
SEQ.NEXPO	1..100 *(1)*	Number of exposures
SEQ.MAXFLUX	*0..30000 (10000)*	Maximum Flux (in ADU)
SEQ.METROLOGY.ST	*yes / no (yes)*	Run metrology?
INS.DECKER.POS	*Dek13, Dek24, Open (Open)*	Decker Position for Polarimetry ('Open' for spectroscopy)
INS.SLIT1.NAME	w_0.2, w_0.4 (w_0.2)	Entrance slit width
INS.WLEN.CWLEN	See Table 19	Reference wavelength
Hidden parameters:		
SEQ.POISSON	1..100 *(100)*	Poisson value
SEQ.FLUX.TOLERANC	0.01..0.10 *(0.05)*	Flux Tolerance
Fixed values:		
DPR.CATG	CALIB	Data product category
DPR.TECH	SPECTRUM	Data product technique
DPR.TYPE	OBJECT	Data product type

CRIRES_spec_cal_Darks		
To be specified:		
Parameter	Range *(default)*	Label

DET1.DIT	1.4..900 *(NODEFAULT)*	DIT
DET1.NDIT	1..1000 *(1)*	NDIT
SEQ.NEXPO	1..100 *(3)*	Number of exposures
INS.SLIT1.NAME	w_0.2, w_0.4, closed (w_0.2)	Entrance slit width (should be set to closed)
INS.WLEN.CWLEN	See Table 19	Reference wavelength
Fixed values:		
DPR.CATG	CALIB	Data product category
DPR.TECH	SPECTRUM	Data product technique
DPR.TYPE	OBJECT	Data product type

CRIRES_spec_cal_SkyObs		
To be specified:		
Parameter	Range *(default)*	Label
DET1.DIT	1.4..900 (NODEFAULT)	DIT
DET1.NDIT	1..1000 *(1)*	NDIT
SEQ.NEXPO	1..100	Number of exposures
INS.OPTI1.NAME	FREE, GAS_SGC, GAS_N20 *(FREE)*	Gas cell
INS.SLIT1.NAME	w_0.2, w_0.4 (w_0.2)	Entrance slit width
INS.WLEN.CWLEN	See Table 19	Reference wavelength
Fixed values:		
DPR.CATG	CALIB	Data product category
DPR.TECH	SPECTRUM	Data product technique
DPR.TYPE	OBJECT	Data product type

7.4 Data format and reduction

7.4.1 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 integration (DIT) in seconds
HIERARCH ESO DET NDIT	Number of integrations (NDIT;. Remember: one exposure consists of DIT x 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 (only for polarimetry)
HIERARCH ESO INS POL TYPE	Stokes vector (only for polarimetry)
HIERARCH ESO INS1 OPTI1 NAME	Optical element (polarimeter = SPU, gas cell, ...) 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.

7.4.2 Format

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

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 ---