



# VLT/ERIS

## ERIS User Manual

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**Original authors:** Y. Dallilar, K. Kravchenko, W. Taylor, S. Esposito, R. Davies, E. Sturm

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### Change Record

Version	Date	Section affected	Comment
111.0	25/08/2022	–	Initial release for P111
111.1	24/01/2023	2.4.1.1	Updated readout noise values (NIX)
		2.4.1.3	Added recommendation for jitter box size
		2.5.6.1	Updated readout noise values (SPIFFIER)
		3.4	Added offsets between SPIFFIER FoVs
		4.2.3.1	PA of North for APP observations
		4.3.1.2	Updated bright limits for IFS
		6.4	Instrument overheads updated
		7.1.2	PA of North for APP, FPC, SAM observations
		7.2	Telescope guide star now mandatory
		7.3	Revised SPIFFIER acquisition procedure
		7.4.2	Changed DETECTOR offset convention
		7.7.1	Added information about telluric standards

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# 1 Introduction

## 1.1 Scope

The ERIS User Manual provides comprehensive information about the technical characteristics of the instrument, the observations procedures and the reduction of ERIS data. The intended audience is Paranal staff who are new to ERIS and will be supporting observations, and also the science users in the community. This is a draft version presented for PAE and is based on the ERIS OCD as well as the SINFONI and NACO user manuals.

In addition to this User Manual, complementary information about ERIS will also be provided on the ERIS webpage at <http://www.eso.org/sci/facilities/paranal/instruments/eris/> which you are invited to visit regularly for any last-minute updates.

## 1.2 Contents of this Manual

This document gives an overview of the ERIS instrument and its subsystems. Necessary information will be provided for observation planning and performing observations with ERIS. Additional details will be given on the instrument software and on the operation modes offered during the corresponding period including example observing runs for guidance.

## 1.3 Latest news and Changes

## 1.4 Reference Documents

	Document Number	Document Title	Issue	Date
RD1	ESO-476948	ERIS Calibration Plan	111.0	25/08/2022
RD2	ESO-476499	ERIS Template Manual	111.1	14/12/2022

## 1.5 Abbreviations and Acronyms

4LGSF	4 Laser Guide Star Facility (a sub-system of the AOF)
ADI	Angular Differential Imaging
AO	Adaptive Optics
AOF	Adaptive Optics Facility
APP	Apodizing Phase Plate
CU	Calibration Unit
DL	Diffraction Limit
DSM	Deformable Secondary Mirror
ESO	European Southern Observatory
IFU	integral Field Unit
PAE	Preliminary Acceptance Europe
SF	Spatial Filter
SPARTA	Standard Platform for Adaptive Optics Real Time Applications
UT	Unit Telescope
VLT	Very Large Telescope
WFS	WaveFront Sensor

ERIS, NACO, SINFONI, NIX, SPIFFI, SPIFFIER, XSHOOTER, VISIR, and SPHERE are names of instruments or cameras.

## 2 Technical Instrument description

### 2.1 Instrument Overview

ERIS is a Cassegrain instrument that will take over the fundamental adaptive optics capabilities at the VLT previously provided by NACO and SINFONI (and operationally has many similarities to those instruments). ERIS instrument has two science cameras; SPIFFIER, an integral field spectrograph covering J to K bands, and NIX, an imager covering J to M bands.

During science operations, users will select either ERIS-NIX or ERIS-SPIFFIER for their observations. ERIS is mounted on UT4 and makes use of the AOF: any one of the four lasers in the 4LGSF can be used to generate a LGS when required (but only one laser at the time), the real-time computer uses SPARTA, and the wavefront correction is done by the DSM.

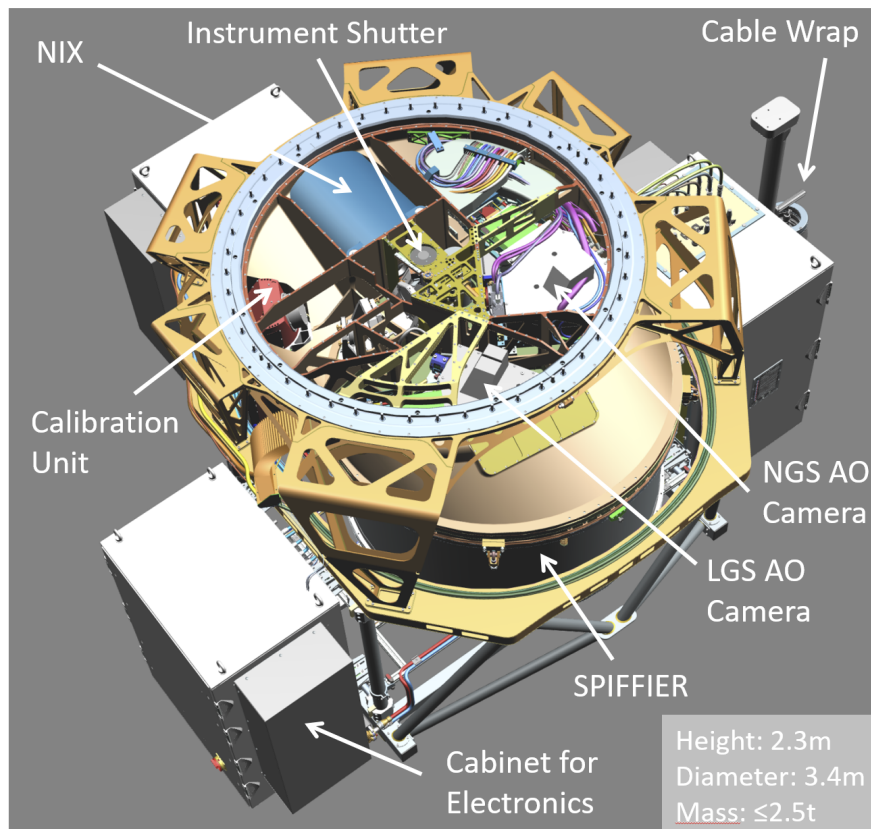


Figure 1: Overview of ERIS as it will appear when mounted on the Cassegrain focus of the UT. The main sub-systems are labeled: the central structure with the LGS and NGS WFS, the NIX imager, the upgraded IFU SPIFFIER, the Calibration Unit, and the Electronics.

As shown in Figure 1, ERIS comprises several distinct sub-systems:

- The **central structure** mounts to the Cassegrain adaptor/rotator. The structure contains the warm relay optics and an optical/infrared dichroic that reflects the visible light to the two wavefront sensors while transmitting the infrared light to either SPIFFIER or NIX. There are two switchable fold mirrors. One of them is used to select either telescope or calibration unit beam (for internal calibrations). The other mirror reflects the incoming beam to either SPIFFIER or NIX, noting that the instruments cannot be used simultaneously. This sub-system also houses a shutter that blocks the surrounding light during internal calibrations.
- The **Adaptive Optics (AO)** system provides corrected wavefronts in the J-M bands to NIX and SPIFFIER using the AOF. Its components are housed in the central structure.
- The **NIX** imager is a replacement for NACO. It provides diffraction limited imaging from J- to M-band over a field of up to 1 arcmin, as well as high contrast capabilities with coronagraphs and sparse aperture masks. It also includes a long-slit spectroscopic mode, covering L-band at a resolution of  $R \sim 900$ .



- **SPIFFIER** is an upgrade and refurbishment of SPIFFI, which was the IFU spectrometer of SINFONI. This subsystem provides integral field spectroscopy, with selectable pixel scale on the sky (25, 100, or 250mas) and spectral resolution (J, H, K bands or subsets thereof at  $R \sim 5000$  and  $\sim 10000$  respectively).
- The **Calibration Unit (CU)** provides various internal sources up to  $2.5 \mu\text{m}$  for daily calibrations and technical activities. Long wavelength (L & M band) calibrations with NIX are performed exclusively on-sky.

## 2.2 Adaptive Optics System

The AO module of ERIS provides two main adaptive modes:

1. NGS mode with on/off axis reference star. The search field for the NGS WFS reference star is a centered disk of 2 arcmin diameter. The NGS WFS patrols this FoV by using translation stages in conjunction with a periscope arm. The maximum Zenith distance is 70 degrees.
2. LGS mode with on axis LGS and off axis NGS for tip tilt sensing and truth sensing. The LGS WFS is fixed on axis and translates along the optical axis to accommodate for LGS source focus variable position at different Zenith pointing. The maximum Zenith angles is 60 degrees.

The AO module developed for the ERIS instrument is part of the warm optics, which comprises the relay optics from telescope input beam and the two AO WFSs for LGS and NGS respectively.

### 2.2.1 Warm Optics

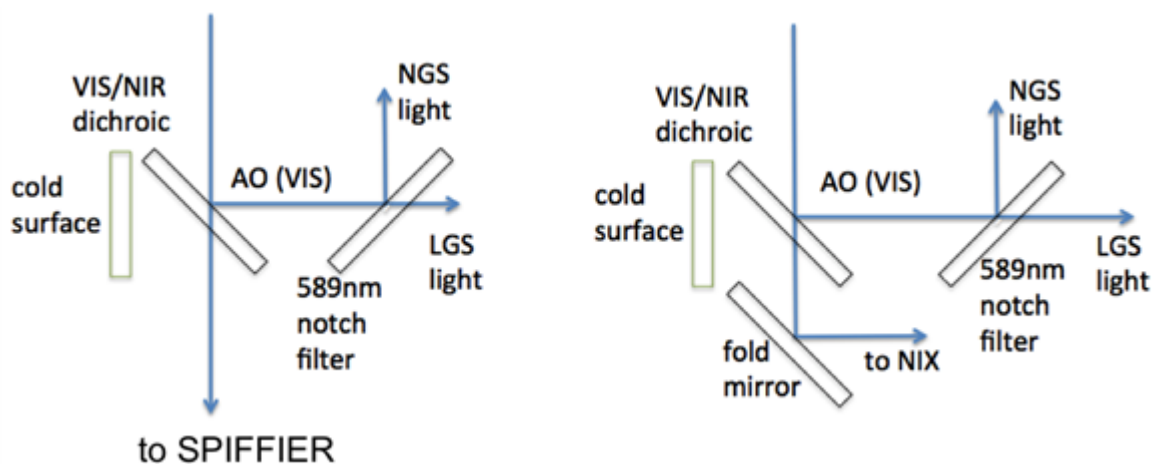


Figure 2: A sketch of the optical path and elements of the warm optics (in black) used to provide IR and VIS light to scientific instruments (NIX, SPIFFIER) and to the AO module. Left: configuration for SPIFFIER operation, right: configuration for NIX operation.

The warm optics feeds the light from the telescope to the AO WFSs. A sketch of the warm optics arrangement and components is shown in Figure 2 where the optical relay configuration for NIX and SPIFFIER observations are reported. The main optical components of the relay include: (a) a 45 degree tilted dichroic separating VIS and NIR light, sending the first to the WFS and the second towards the science instruments; (b) a retractable mirror that is deployed to feed the NIR light to the camera NIX; (c) a notch filter transmitting Sodium Laser light to the LGS WFS and reflecting other visible wavelengths to NGS WFS. In addition a cold window facing part (a) is introduced to reduce background light injected in the science instruments. A detailed picture of the warm optics showing all optomechanical components is reported in Figure 3.

### 2.2.2 NGS WFS

The NGS WFS is a configurable Shack-Hartmann sensor with  $40 \times 40$  subapertures for high-order correction, and  $5 \times 5$  subapertures for low-order & truth sensing for LGS operation. The two configurations respectively referred as HO WFS and LO WFS and are achieved by exchanging two lenslets arrays using a translation stage. The main characteristics of the two SH configurations are reported in the following table.

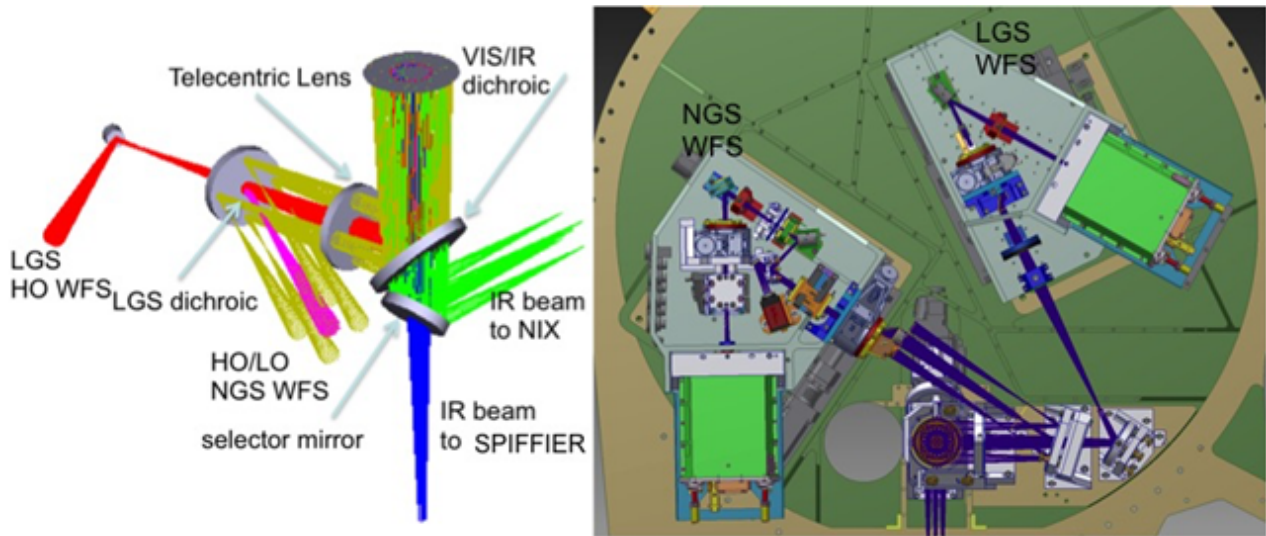


Figure 3: The arrangement of the AO module warm optics. Left: the optical components, right: the optomechanical arrangement as mounted on the ERIS optical plate. The figure shows the two ERIS WFSs, the NGS WFS (left) and the LGS WFS (right).

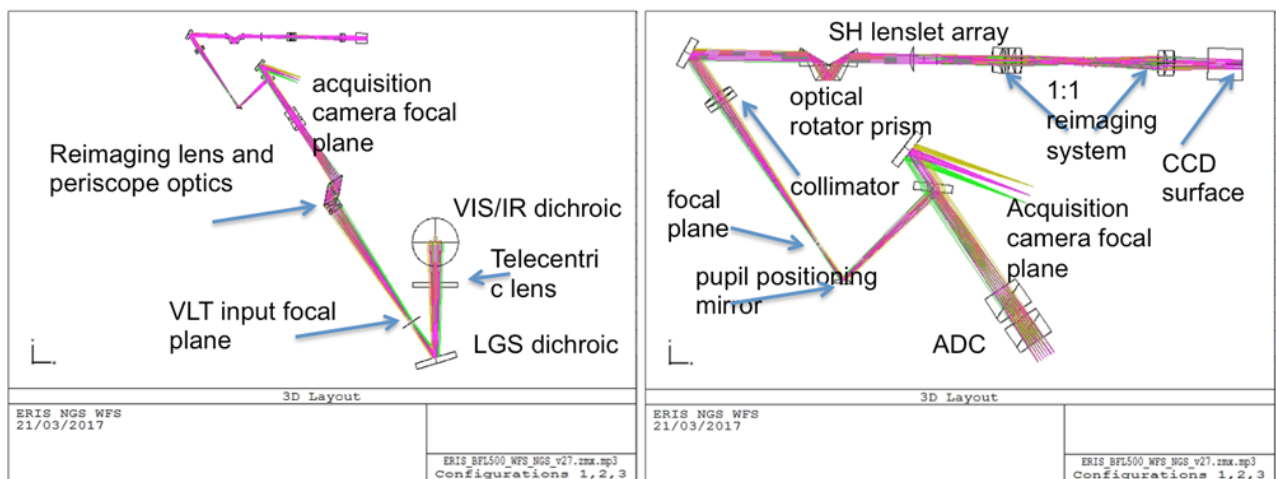


Figure 4: The optical layout of the NGS WFS. Left: optical path from VIS/NIR dichroic, right: zooming into the upper part of the left figure illustrating the optical path from the pupil image to the final spots pattern.

NGS SH sensor main parameters	FoV (arcsec)	Pixel scale (arcsec/pixel)	Pixel per subaperture
HO conf.	2.5	0.41	6x6
LO conf.	2.5	0.21	12x12

The optical layout of the SH WFS path is reported in the Figure 4. In addition, the NGS WFS features an acquisition camera that uses light below 600 nm reflected off-plane by the first folding mirror located after the optical rotator prism. The acquisition camera has a FoV of 15 arcsec and a pixel scale of 0.19 arcsec (when binned by 20 pixels). As labeled in the optical layout the NGS WFS is equipped with:

1. a reimaging lens and periscopic optics that allows to search the 2 arcmin FoV by rotating the periscope and translating the WFS stages.
2. a derotator used in field tracking mode. It is an optical prism derotator which keeps the pupil image fixed on the CCD.
3. a pupil positioning mirror which keeps the pupil aligned on the SH. It can move the pupil by  $\pm 8$  subapertures on the array.

4. an atmospheric dispersion corrector made up of two equal double prisms that compensate for atmospheric dispersion in the range 0-70 deg.
5. a 1:1 reimaging system made up of two equal lenses that create the final image of the spot pattern onto the CCD.

### 2.2.3 LGS WFS

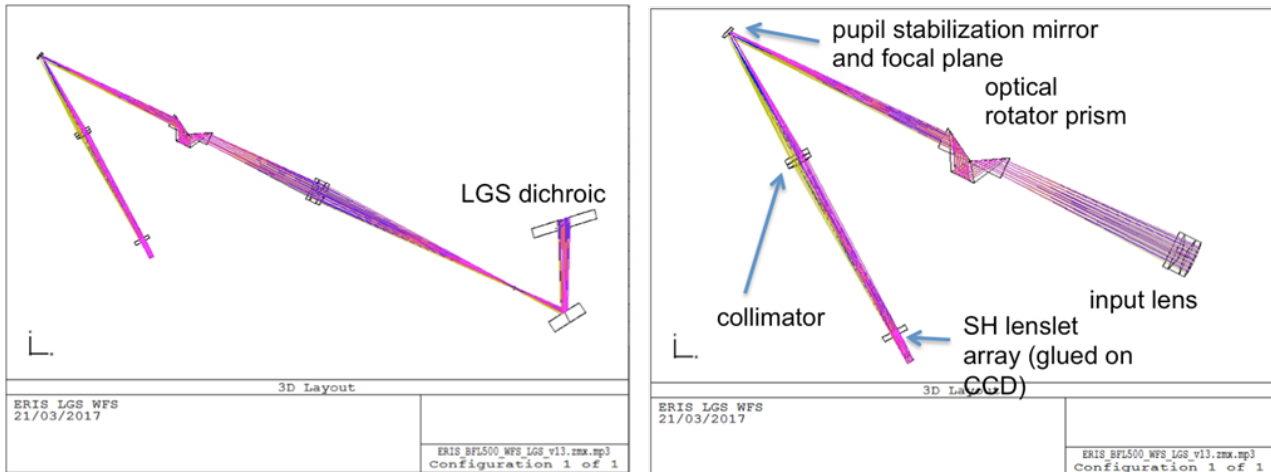


Figure 5: The optical layout of the LGS WFS.

The LGS WFS is a SH sensor with 40x40 subapertures. The main characteristics of the SH configuration are reported in the following table.

LGS SH sensor main parameters	FoV (arcsec)	Pixel scale (arcsec/pixel)	Pixel per subaperture
	5.0	0.83	6x6

The optical layout of the LGS SH sensor is reported in Figure 5. The LGS WFS does not have an acquisition camera so the reference spot is placed in the center of the FoV by using the 4LGSF acquisition camera.

As labeled in the optical layout the LGS WFS is equipped with: (1) an optical prism rotator to keep the pupil image fixed on the CCD pixel grid while the Cassegrain rotator is moving for field derotation (2) a pupil positioning mirror located close to the focal plane to adjust the pupil image on the SH lenslet array in the range of  $\pm 8$  subapertures.

## 2.3 Calibration Unit

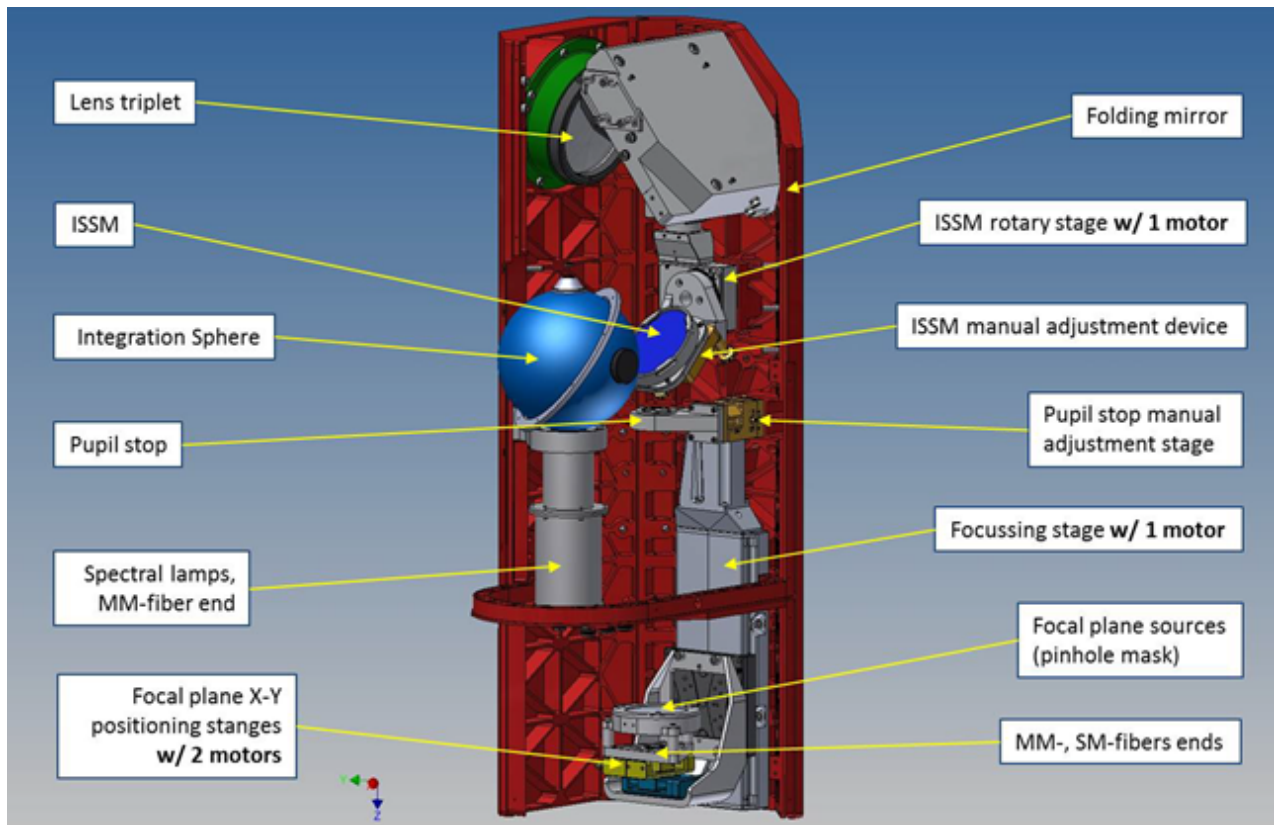


Figure 6: CUMB main components and devices.

The Calibration Unit (CU) is a subsystem of ERIS that provides calibration capabilities for the ERIS instruments (NIX, SPIFFI and AO WFS). It is composed of two separate units.

The first unit, the Calibration Unit Main Bench (CUMB), is optically and mechanically interfaced with ERIS optical plate, the main components can be seen in Figure 6. It is equipped with an objective transmitting from visible to  $2.5 \mu\text{m}$  that operates with a magnification of 1:1.296 in order to project point sources of various sizes onto the Cassegrain focal plane and to deliver a projected virtual position of the pupil that coincides with the telescope secondary mirror. Alternatively, the integrating sphere selector mirror (ISSM) is inserted in the beam to deliver spatially uniform illumination. The second unit, the Calibration Unit Fiber Switchyard (CUFS), is hosted inside one of the ERIS cabinets and interfaced to the CU only. It hosts light sources for flat field capabilities and pinhole mask sources.

The CU includes a selection of light sources: (1) a Quartz-Tungsten Halogen lamp (QTH), (2) four pencil-ray lamps (Ne, Xe, Kr, Ar), (3) a Laser Driven Light Source (LDLS). The QTH lamp provides flatfielding capabilities during day-time, and covers all possible configurations of SPIFFIER, as well as standard narrow/broad imaging with NIX from J to K bands. In L and M bands, flatfielding is performed during night-time and on-sky as part of the standard calibration plan. Pre-defined combinations of pencil-ray lamps are used for SPIFFIER wavelength calibrations depending on the instrument configuration. These lamps are all used with the integrating sphere.

The LDLS serves different purposes with a selected pattern of masks placed onto the back focal plane of the objective, which is used to generate artificial optical/infrared point and extended sources and the backlit three-slit. There are two mechanisms associated with the configuration: one allowing adjustment along the beam for focusing purposes and other lateral adjustment, i.e. position on the NIX/SPIFFIER detector. The three-slit configuration is exclusively used for distortion correction with SPIFFIER. Other options are only available for technical day-time activities.

This is the only configuration of the CU in which the beam passes through a fixed pupil which imitates the secondary mirror of the telescope and the spiders. An artificial point source is used, in this case, for the internal alignment of ERIS subsystems. Positioning of a variable neutral density (ND) filter allows adjusting light levels in the instrument software within the range of 12 magnitudes.

## 2.4 NIX

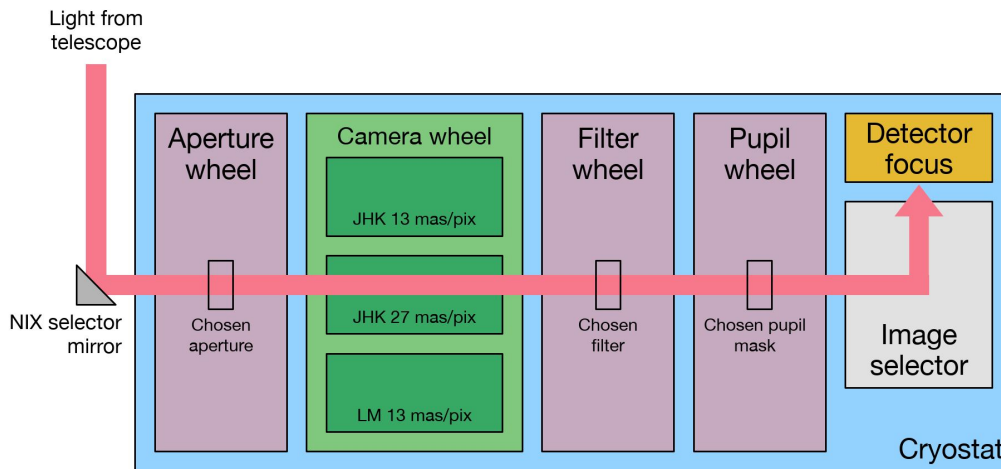


Figure 7: NIX mechanism layout.

The NIX imager provides diffraction-limited observing capabilities from 1-5 microns, with a range of high contrast observing modes. Full details of the ERIS observing modes are given in Section 3 of the document. This section provides a brief overview of the optical layout to explain the aspects of the design that are relevant to the astronomer.

The primary elements of NIX are indicated in Figure 7. As is described in Section 2.2.1 light from the ERIS warm optics is directed into NIX by the NIX selector mirror. The light passes through the aperture window into the cryostat of NIX, indicated by the blue region in the figure. Nearly all components and mechanisms inside the cryostat are cooled to 75K to limit thermal background radiation; the detector is the only item cooled further to  $\sim 35\text{K}$ .

The aperture wheel houses various field masks that are used depending on the observing mode. The aperture wheel has eight possible slots, including a blank position, and is driven by stepper motors providing high positional repeatability of order 50 microns. The design and performance of the other wheels is very similar. Its position will be set automatically for a given observing mode.

The next mechanism is the camera wheel, which contains three different camera barrels. Two are optimised for the shorter wavelengths (J, H and K), providing spatial scales of 13 mas/pix or 27 mas/pix. The third camera barrel is for the longer wavelengths (L and M) delivering 13 mas/pix.

The filter wheel and the pupil wheel are identical mechanisms housed within a single unit. Both wheels can house up to 20 elements that can be combined in various ways for the different science cases. As its name suggests the filter wheel houses all the optical filters – more details of which are given in Section 3.5. The pupil wheel contains a mixture of different elements that include pupil masks, but also a grism and additional filters.

The image selector has four positions one for each of the two field sizes, and one to allow the pupil to be imaged. There are also several blocking positions for this mechanism to fully prevent light reaching to detector. This configuration is either used to instrumental dark frames for calibration or to minimize persistence issues during instrument setup.

Finally, the detector focus stage is used to adjust internal focus of NIX detector. It is left in a static configuration for all observing modes (only for technical pupil imaging is a different internal focus position used). In noAO modes, pre-defined best focus offsets are sent to DSM.

### 2.4.1 Detector

**2.4.1.1 Characteristics** NIX is equipped with a science grade Teledyne Hawaii 2RG detector (2Kx2K). The characteristics of detector are summarized in Table 3. Two readout modes are supported:

- In slow mode, up the ramp (UTR) readout scheme is used as in SPIFFIER. The readnoise as a function of DIT is shown in Figure 8.
- In fast mode, an uncorrelated readout scheme is used. The purpose of this mode is either high background observations in L and M bands or special observing modes requiring fast data acquisition (without special

timing requirements).

In fast mode, raw images have  $\sim 10\text{-}11\text{k}$  ADU bias level which varies depending on the channels for the most part. This subtracts out well, and is only noted here to avoid confusion.

Operating Temperature	$\sim 35\text{K}$
Pixel size	18 microns
Dark Current	$\sim 0.1\text{ e-}/\text{s}$
Well Depth	$\sim 85\text{k e-}$
<i>Slow Mode SLOW_GR_UTR</i>	
Detector Gain	5.2 e-/ADU
Readout Noise	$\sim 17\text{ e-}$ (2s) $\sim 9\text{ e-}$ (60s) $\sim 12\text{ e-}$ (600s)
Minimum DIT	1.6 secs
Readout Speed	0.63 Hz
Non-linearity	$\sim 3\%$ (@ 5k ADU)
<i>Fast Mode FAST_UNCORR</i>	
Detector Gain	2.6 e-/ADU
Readout Noise	50 e-
Minimum DIT	0.034 secs
Readout Speed	30 Hz (Full Frame)
Non-linearity	$\sim 4\%$ (@ 20k ADU)

Table 3: NIX detector parameters

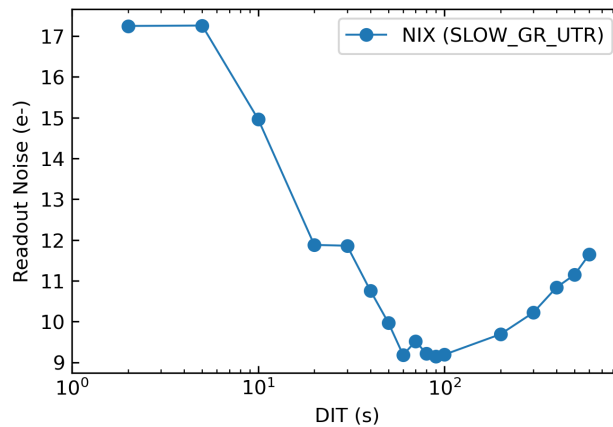


Figure 8: Detector readout noise as a function of detector integration time (DIT) for the the slow readout mode (SLOW\_GR\_UTR) of NIX. This curve is used by the ERIS ETC to estimate S/N of observations.

**2.4.1.2 Subarray Size** NIX detector offers capabilities to increase the readout speed (with respect to that reported in Table 3) by restricting the readout to be done only between two selected rows. This applies only in the vertical direction (i.e. along the read channels); the horizontal width (i.e. across the read channels) is always kept full.

In NIX templates, this feature is introduced via a set of pre-defined options controlled by the `SEQ.NIX.DET.WINDOWING` parameter. The options are given in Table 4.

Note that while the `windowF` option is nominally full frame, with the `FAST_UNCORR` readout mode provides frames with size of 2046 starting from row 3. There is no loss in scientific pixels in this case, only two rows of reference pixels are removed in order to reduce detector glow.

**2.4.1.3 Bad Pixels** Some regions on the NIX detector are densely populated by bad pixels, without any distinction on their type. These regions are represented in Figure 9 in terms of number of identified bad pixels

SEQ.NIX.DET.WINDOWING		First Row	Row size
windowF	slow	1	2048
	fast	3	2046
window1		510	1536
window2		1022	1024
window3		512	1024
window4		1024	512

Table 4: Pre-defined row selections for NIX readouts.

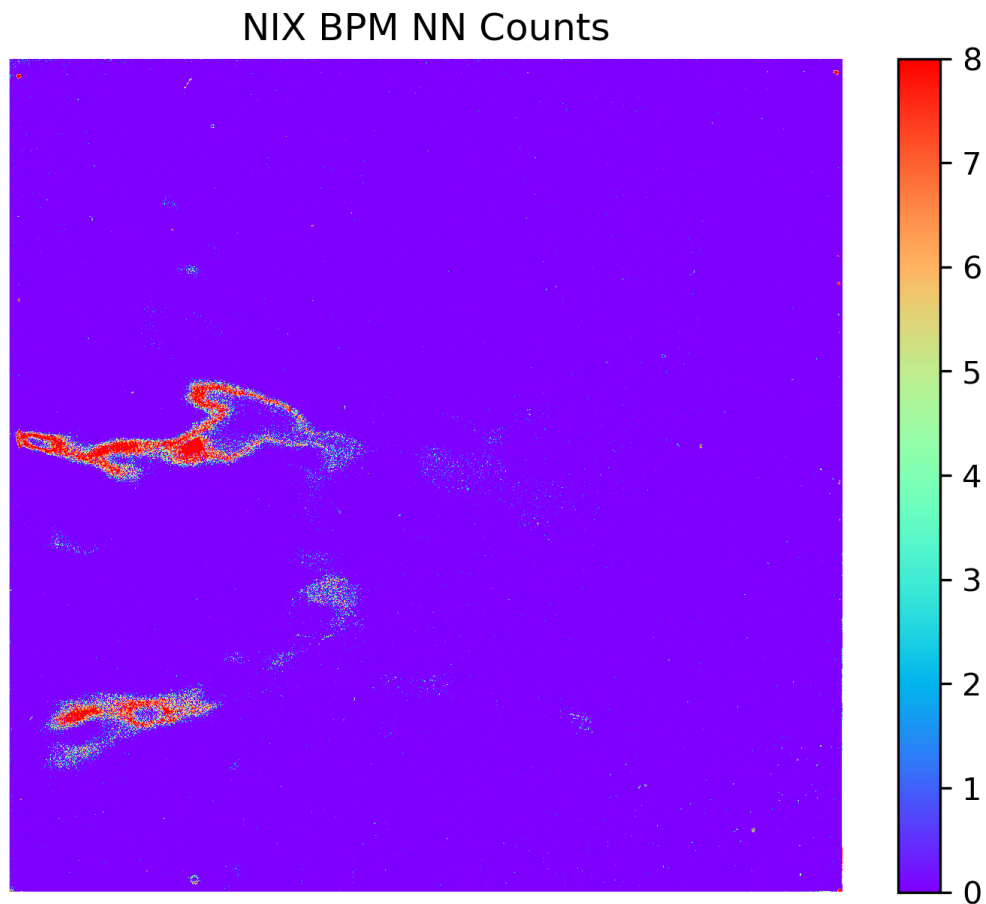


Figure 9: Number of identified bad pixels neighboring each pixel in NIX detector. Pixels which are not identified as bad pixels have a value of 0.

neighboring each pixel. In other words, for pixels marked in red in this figure, there will be very limited local information to recover their true values via simple interpolation methods within a single image. Therefore, high priority targets should avoid these regions. For field observations, dithering is strongly recommended as bad pixels can be replaced using the information from offset frames during aligning and stacking. For observations using the `nixIMG_obs_AutoJitter` template, a jitter width of more than  $5''$  ( $10''$ ) for the 13mas ( $27\text{mas}$ ) camera is recommended. A representative bad pixel map can be found on the ERIS website<sup>1</sup> to help prepare observations with dither patterns.

<sup>1</sup><https://www.eso.org/sci/facilities/paranal/instruments/eris/inst.html>

## 2.5 SPIFFIER

The integral field spectrometer SPIFFIER is an upgraded/refurbished version of SPIFFI (SPectrometer for Infrared Faint Field Imaging) featuring a new HAWAII 2RG detector and four new gratings providing better spectral resolution. Figure 10 shows a view inside the cryostat. The light enters from the top, and passes through the sky-spider. The pre-optics with a filter wheel and interchangeable lenses provides three different image scales. The image slicer re-arranges the two-dimensional field into a pseudo-long slit, which is perpendicular to the base plate. Three diamond turned mirrors collimate the light onto the gratings. In total, four gratings are implemented on the grating drive. A multiple-lens system then focuses the spectra on the detector. All components are cooled in a bath cryostat to the temperature of liquid nitrogen ( $\sim 77$  K). The liquid nitrogen reservoir sits below the instrument plate.

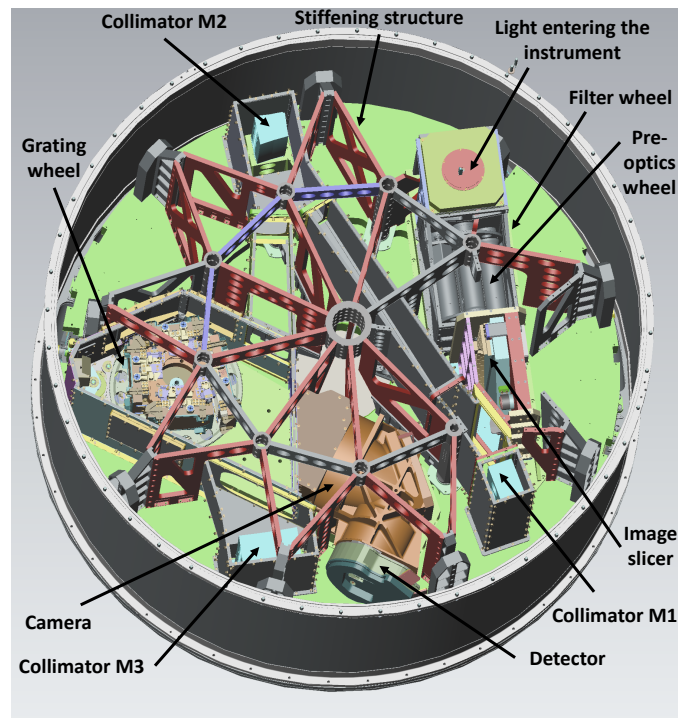


Figure 10: An inside view of the SPIFFIER cryostat with indications for the locations of various opto-mechanical elements. Some housing covers and parts of the stiffening structure are not shown for better illustration. The diameter of the instrument is 1.3m.

SPIFFIER provides simultaneous spectroscopy of  $32 \times 64$  spatial pixels (spaxels) with a spectral resolution of either  $\sim 5000$  or  $\sim 10000$ . Three pixel scales are available by rotating the optics wheel; 25, 100, 250 mas/pixel. A spaxel corresponds to a rectangular area on the sky, for example,  $12.5 \times 25 \text{ mas}^2$  in the 25mas pixel scale. The 25 mas configuration is suited for use with adaptive optics since the angular resolution at  $2.2 \mu\text{m}$  is 56 mas. To make optimal use of the spatial elements in seeing limited observations and at partial correction of the atmospheric turbulence with faint reference stars, SPIFFIER also provides image scales of 100 mas/pixel and 250 mas/pixel. These are associated with correspondingly larger fields of view.

Each of the atmospheric transmission bands J (1.1-1.4  $\mu\text{m}$ ), H (1.45-1.85  $\mu\text{m}$ ), and K (1.95-2.45  $\mu\text{m}$ ) is covered with single exposures at a resolution of  $\sim 5000$  as in SINFONI. With the addition of a new high resolution grating, only half wavelength range of the J, H, and K bands can be measured in a single exposure at a resolution of  $\sim 10000$  - refer to Table 9 for the full set of configurations.

A detailed description of the SPIFFI instrument design can be found in Eisenhauer et al. 2003 (Proc. SPIE 4841, 1686), with part of the upgrades to SPIFFIER described in George et al. 2017 (JATIS, 3, 1).

### 2.5.1 Pre-Optics

Below the entrance focal plane baffle, a triplet lens unit collimates the light onto a cold stop for the suppression of the thermal background. The stop has a diameter of  $\sim 6$  mm, and is equipped with a central obscuration with the equivalent size of the telescope secondary mirror. Just in front of the cold stop is the motorized filter wheel, housing the band-pass filters, which are required to suppress the unwanted diffraction orders of the



gratings. After the cold stop, the motorized optics wheel provides the interchangeable lens systems for the three different image scales, and a pupil-imaging lens for alignment purposes. Each objective consists of two or three lenses. All moving functions are driven by two-phase stepper motors, which have been modified for use at cryogenic temperatures.

### 2.5.2 Image Slicer

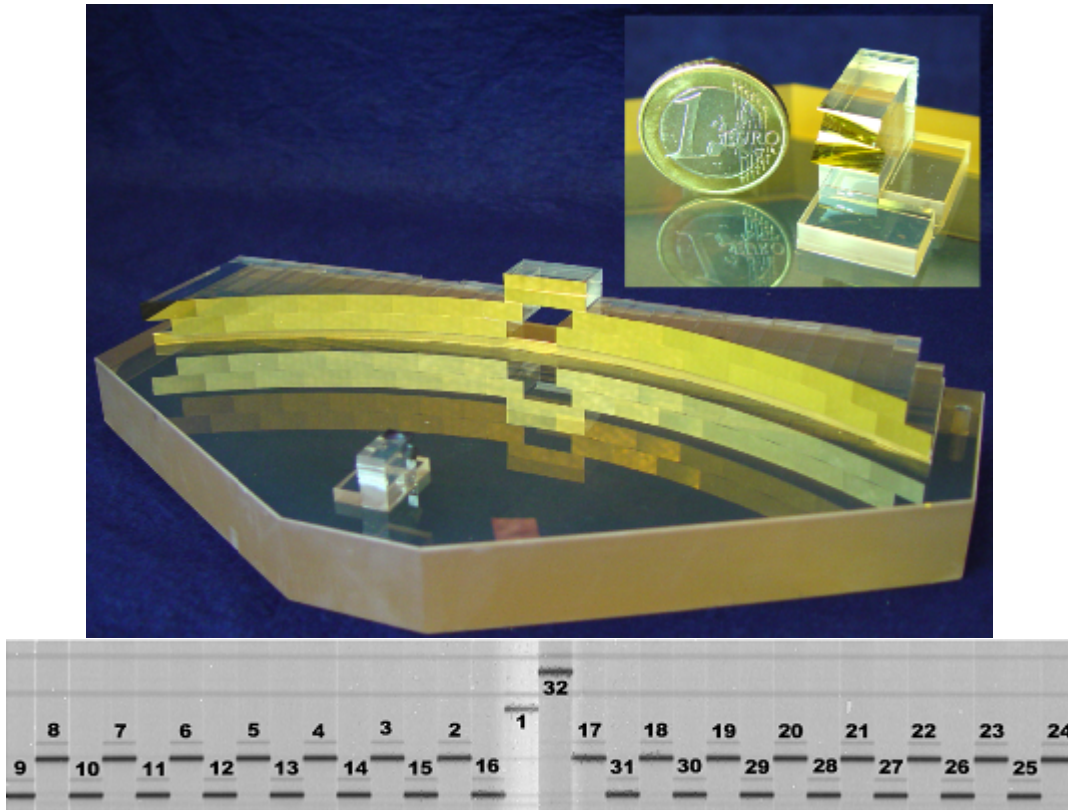


Figure 11: Top: SPIFFIER image slicer (a): The light enters through the hole in the big slicer. A stack of 32 small mirrors, the small slicer (also shown in the sub-panel), slices the image and redirects the light to-wards the 32 mirrors of the big slicer, which re-arranges the slitlets into a 31 cm long pseudo-slit. Bottom: Illustration of the slitlet layout in raw SPIFFIER images, light is dispersed vertically on the science detector.

The focus of the pre-optics is located at the small slicer. This part of the image slicer consists of a stack of 32 plane mirrors, which slices the image into slitlets, and separates the light from each slitlet in different directions. A second set of 32 mirrors, the big slicer, collects the light and forms the pseudo-slit, which appears as a *brick-wall pattern* on the detector. To avoid differential thermal contraction, the unit is completely made from a zero expansion glass, and all parts are optically contacted.

Figure 11 shows the image slicer and the positions of the slitlets on a raw SPIFFIER frame. The slitlets run horizontally across the imaging field-of-view and are numbered from top to bottom on the small slicer.

### 2.5.3 Spectrometer Collimator

After the image has been sliced and re-arranged into a pseudo-slit, three diamond turned mirrors collimate the light onto the gratings. The first mirror is spherical, and the other two mirrors have an oblate elliptical shape. All mirrors are made from Aluminum. The mirrors are gold-coated for higher reflectivity.

### 2.5.4 Grating Wheel

In total, SPIFFIER has four gratings. Three of the gratings cover the J, H, and K atmospheric windows at a resolution of  $R \sim 5000$  similar to SINFONI. The fourth grating is the high-resolution grating and replaces the H+K grating slot in SINFONI. This grating doubles the spectral resolution in a given band but reduces the

wavelength range by a factor of two. For each band, the instrument is pre-configured option to observe either short, middle or long wavelength regime. The options are detailed in Table 9.

Each low resolution grating is blazed to the center of its bandpass, while the high resolution grating is blazed to optimize efficiency in all bands. In order to be able to move the spectrum on the detector with an accuracy of 1/5 of a pixel, the grating wheel is driven with a 1:647 gear, and controlled via an inductive encoder directly attached to the grating wheel.

**2.5.5 Spectrometer Camera**

The camera is a five-lens + 1 folding mirror f/D~1/2.8 design. The diameter of the three big lenses is 170 mm. All lenses have a multi-layer anti-reflection coating optimized for the wavelength range from 1.05-2.45  $\mu\text{m}$ .

**2.5.6 Detector**

SPIFFIER is operated with a science grade Teledyne HAWAII 2RG detector (2k x 2k).

**2.5.6.1 Characteristics** The characteristics of the new detector are summarized in Table 5, and the readout noise is plotted as a function of the detector integration time in Figure 12.

Operating Temperature	77K
Pixel size	18 microns
Dark Current	0.19 e-/s
Well Depth	>80k e-
Detector Gain	2.0 e-/ADU
Readout Noise	12 e- (2s)
	7 e- (60s)
	11 e- (600s)
Minimum DIT	1.6 secs
Non-linearity	~ 3% (@ 20k ADU)

Table 5: SPIFFIER detector parameters

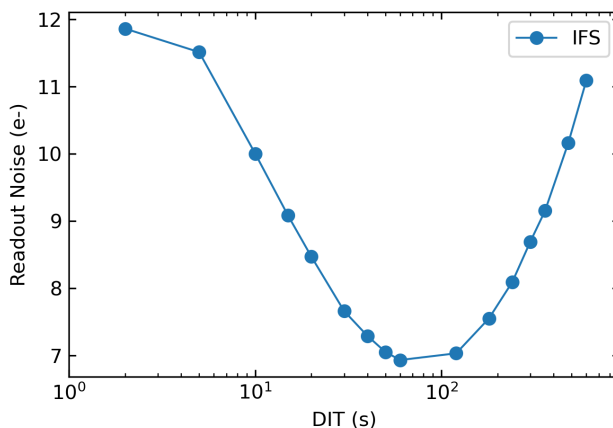


Figure 12: Detector readout noise as a function of detector integration time (DIT) for SPIFFIER. This curve is used by the ERIS ETC to estimate S/N of observations.

**2.5.6.2 Bad Pixels** As commonly seen in infrared arrays, the SPIFFIER detector also has randomly distributed bad pixels. These can be easily interpolated over during data reduction. The only defect worth noting is a clump of cold pixels (not sensitive to light) about 10 pixels in diameter, marked with a dark blue circle in Figure 13. This spot falls into slitlet 16 in all configurations, i.e. in the middle of the reconstructed image.

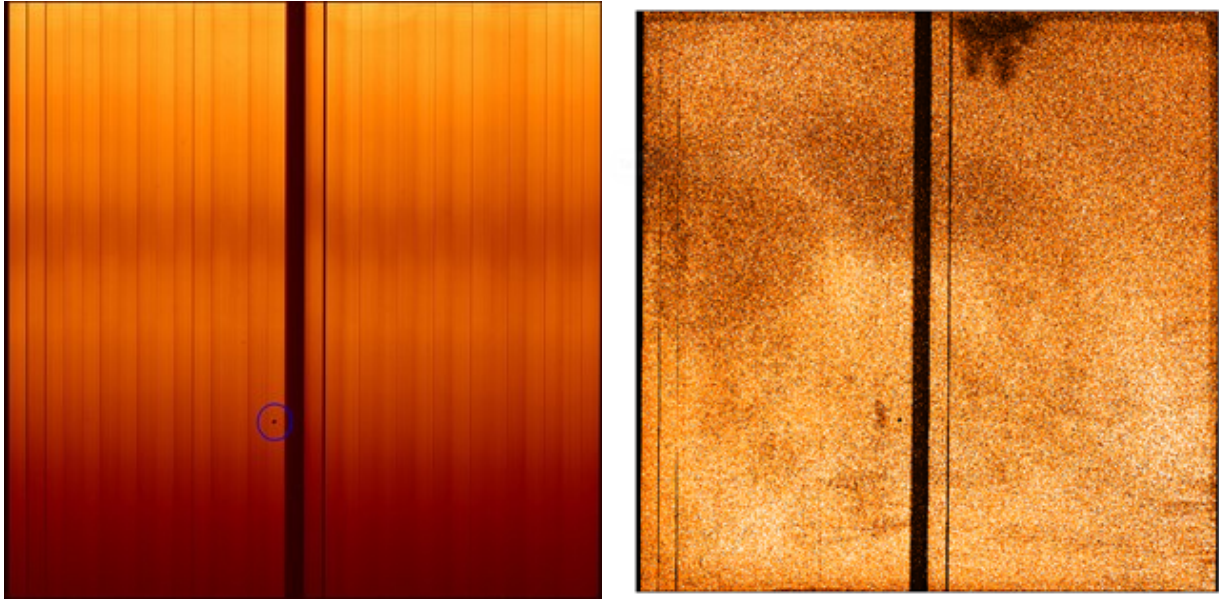


Figure 13: Left: SPIFFIER K<sub>low</sub> flat at 25 mas pixel scale. A clump of cold pixels is marked with circle in the left panel. Right: 2D persistence map after a 5-minute long flat exposure.

**2.5.6.3 Persistence** In contrast to the old SINFONI detector, the new detector of SPIFFIER is less prone to persistence events -- in the worst cases, the duration is reduced from days to hours. However, the instrument still needs to be operated in a way that minimizes persistence. Operationally, when not observing, the filter wheel always remains in the blocked configuration to avoid excessive flux reaching the detector and so-called persistence frames are continuously recorded during instrument setup. On the observational side, however, it is responsibility of users to follow persistence limits to avoid disturbing subsequent exposures.

Figure 13 shows a 2D persistence map after a long (5-minute) flat exposure near full well. As seen in the image, illuminated parts of the detector have almost uniform persistence background with the exception of low persistence anomaly - a thumb-like feature between slits 17 and 19 at the longest wavelengths. However, note that bright point-like sources or OH sky lines will still leave distinct persistence footprint on the detector.

In Figure 14, we report the persistence decay timescale with respect to peak illumination flux. In simple terms, exposures on the order of a minute reaching near 80% well-depth would require about an hour recovery time before the start of upcoming science OBs.

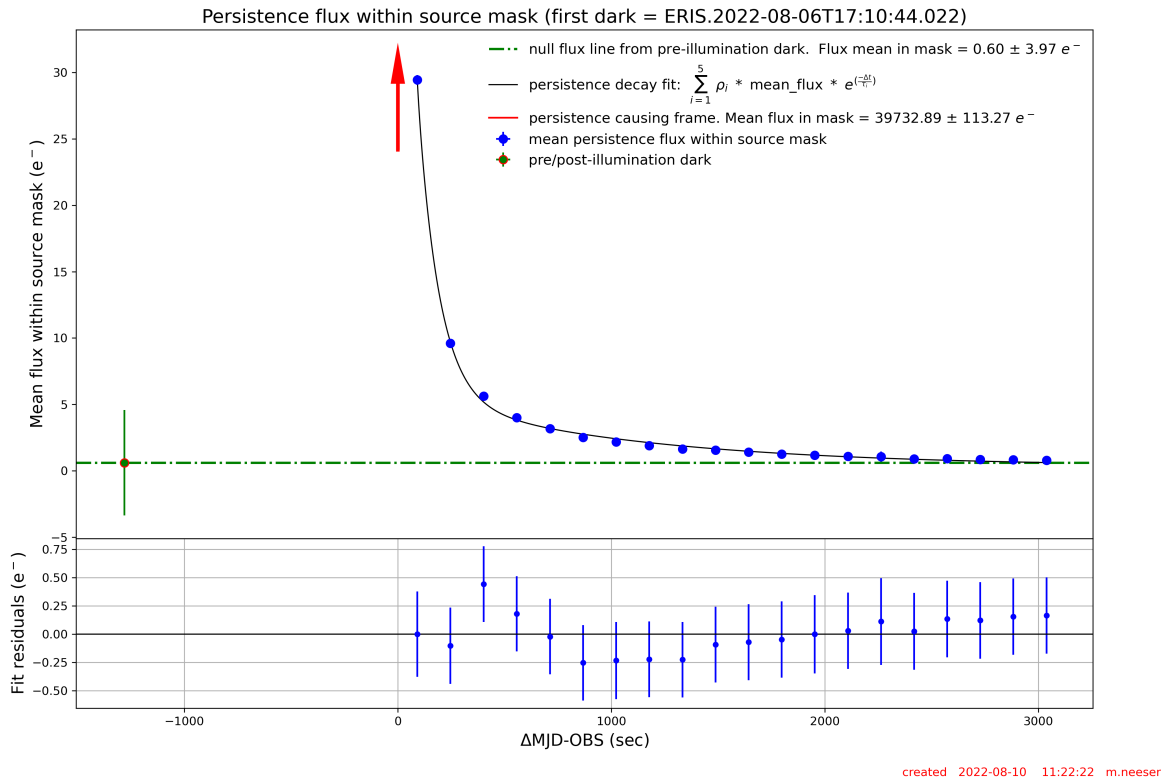


Figure 14: Persistence recovery time of SPIFFIER detector with respect to peak flux.

### 3 Observing Modes and Instrument Configuration

Table 6 below summarizes the different modes and configurations offered by ERIS. Observations with ERIS can only be carried out in combinations of these. But not all combinations are possible. For example, pupil tracking is associated with some instrument related restrictions, which are described in Section 3.1; and the seeing limited AO mode does not make sense to use with the high contrast imaging observing mode. So the possible combinations are limited by the available templates. The various tracking, AO, and observing modes are explained in more detail in the following subsections.

#### 3.1 Focal Plane Rotation Modes

This defines whether the orientation of the field or pupil in ERIS is fixed with respect to the detector focal plane.

Field tracking is the standard mode, and means that the orientation of the sky on the focal plane remains constant (so that ERIS rotates at a speed that depends on declination and hour angle). Pupil tracking means that the orientation of the pupil on the focal plane remains constant (i.e. ERIS is set at some predefined angle and then does not rotate). This is an important capability for high contrast imaging, in order to remove speckles in the PSF of the primary star. With pupil tracking, ERIS rotates to a pre-configured angle so that the pupil mask is aligned with the telescope spider arms. How this corresponds to the orientation on-sky depends on the declination and hour angle of the pointing.

Note that the use of off-axis guide stars with pupil tracking mode is not supported.

#### 3.2 Differential Tracking Modes

This defines the rate at which the telescope, instrument, and AO system move across the sky in order to keep an object centered in the field of view.

Sidereal tracking is the standard mode. This applies to most science targets, which remain at a fixed right ascension and declination for the duration of an OB (although in some cases an object's proper motion may

<i>Focal Plane Rotation Modes</i>	
Field tracking	The standard focal plane rotation mode, in which the orientation of the field on the instrument focal plane remains constant.
Pupil tracking	In ERIS, this is used exclusively for Angular Differential Imaging (ADI), and means that the orientation of the pupil on the instrument focal plane remains constant. Its primary application is for high contrast imaging with NIX.
<i>Differential Tracking Modes</i>	
Sidereal tracking	The standard sky tracking mode, in which the telescope (+instrument) and AO system follow targets at a fixed right ascension and declination.
<i>Adaptive Optics modes</i>	
NGS-AO	On-axis or off-axis
LGS-AO	With an on-axis or off-axis tip-tilt star
Seeing Limited	No AO guide star
<i>SPIFFIER Observing Modes</i>	
Integral field spectroscopy	FOV: 0.8", 3.2", 8"; R ~5k or 10k; 1-2.5 $\mu$ m
<i>NIX Observing Modes</i>	
Short Imaging	13/27 mas/pix (26"/55" FOV); J-K narrow/broad bands
Long Imaging	13 mas/pix (26" FOV); L-M narrow/broad bands
Apodizing Phase Plate (APP)	K-M narrow bands; 13 mas/pix

Table 6: Short summary of ERIS modes available in P111.

mean that it has moved between epochs of observations).

### 3.3 Adaptive Optics Modes

There are four AO modes, summarized in Table 6. Their combination with respective observing modes is limited by the available templates to only those that make sense.

- **NGS-AO**, a natural guide star (specified already in Phase 1 proposal preparation) is sensed at visible wavelengths to provide the AO correction. The guide star can be on axis or up to 1 arcmin off axis. Because ERIS uses only a single DM (the DSM of the AOF), the field of view over which there is a good AO correction is finite. This also means that in the off-axis configuration, anisoplanatism can significantly reduce the AO performance at the location of the science target.
- **LGS-AO**, any one of the lasers from the 4LGSF is used to generate an on-axis LGS that is used to correct high order aberrations. A second WFS senses a tip-tilt star at visible wavelengths simultaneously. The tip-tilt star can be on axis or up to 1 arcmin off axis. Note that, when dithering, the LGS will always point to the centre of the observed field, while the science target will move to different positions in the field. The impact of the resulting high order anisoplanatism will usually be small (note that tilt anisoplanatism, which dominates the off-axis PSF shape, is unaffected by the location of the LGS). This mode of operation has advantages in improving the overall PSF for extended targets and fields.
- **Seeing limited**, in this ‘no AO’ mode, the AO system is off (loops open) and so no guide star is specified. Instead VLT field stabilization is used.

### 3.4 SPIFFIER modes

From an operational perspective, the use of SPIFFIER in ERIS is similar to SINFONI. There is only one mode: integral field spectroscopy. But this mode has a variety of fixed configuration options for the pixel scale (see Table 7 and Fig. 15) and the spectral setting (band/wavelength and resolution), see Table 9. An important difference to SINFONI is that during acquisition, the AO system goes first, after which one can expect that the SPIFFIER pointing should be reasonably precise. The offset between the centers of the three fields of view are given in Table 8. For observations at a non-zero position angle (i.e. `TEL.ROT.OFFANGLE`  $\neq$  0 deg), it is strongly recommended to use `DETECTOR` offsets to move the telescope to recenter an object if the plate scale is changed, otherwise you must apply the appropriate rotation to the `SKY` offsets to account for the instrument rotation.

Field of view	Spaxel size on-sky	Tag
0.8"x0.8"	12.5x25mas	25mas
3.2"x3.2"	50x100mas	100mas
8"x8"	125x250mas	250mas

Table 7: FOV and spaxel size for each pixel scale options of SPIFFIER.

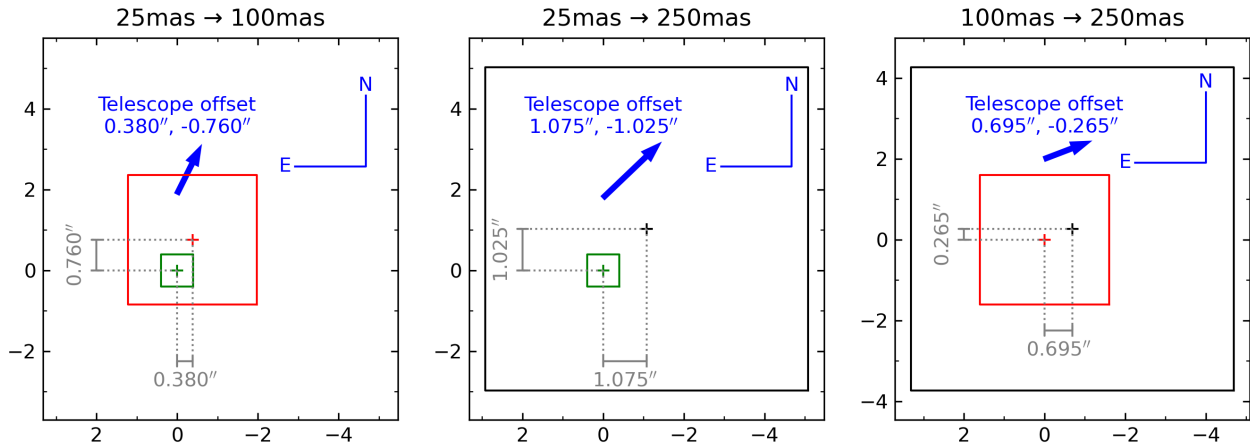


Figure 15: Relative centering of the SPIFFIER FoVs for the three allowed changes within a single OB; the pixel scale cannot be decreased between subsequent science templates. The telescope offset assuming `TEL.ROT.OFFANGLE=0` deg required to move an object from the center of the smaller field of view to the center of the larger field of view is shown.

Tag	25mas		100mas		250mas	
25mas	(32.0, 32.0) px	(0, 0)''	...	...	...	...
100mas	(28.2, 24.4) px	(+0.380, -0.760)''	(32.0, 32.0) px	(0, 0)''	...	...
250mas	(27.7, 27.9) px	(+1.075, -1.025)''	(29.2, 30.9) px	(+0.695, -0.265)''	(32.0, 32.0) px	(0, 0)''

Table 8: Pixel coordinates for the center of each pixel scale (columns) within the other pixel scales (row), and the telescope offset to move an object from the center of one field of view to the center of the other, assuming `TEL.ROT.OFFANGLE=0` deg. As an example, the center of the 25mas field of view is at pixel coordinate (28.2, 24.4) in the 100mas field of view, and a telescope offset of (+0.380, -0.760)'' would be required to move an object from the center of the 25mas field of view to the center of the 100mas field of view.

There is no restriction between AO mode and the choice of pixel scale. Since the field of view of 25mas pixel scale configuration is  $<1$  arcsec, the 100mas pixel scale configuration can be used during acquisition if the object coordinates are not precisely known. If this is done the target will be centered using the 100mas pixel scale configuration and an offset must be applied within the first science template at the 25mas pixel scale configuration if precise centering for the science exposures is required (see Table 8, and the schematic in Figure 15). If the object coordinates are precisely known then it is highly recommended to use the desired pixel scale configuration for the science for the acquisition.

There are twelve options for the spectral configuration and these are detail in Table 9. Low resolution configurations roughly cover a full single broad band. Alternatively, short and long variants can be used in conjunction to observe a full band doubling spectral resolution at the expense of longer observing time. The middle configurations are useful if there is a spectral feature of interest in the middle of a given band and higher resolution is required.

SPIFFIER is only offered with field tracking, but the position angle of the instrument can be set freely.

### 3.5 NIX modes

NIX has 5 different observing modes; 1 associated with imaging, 3 with high contrast modes, and 1 with spectroscopy.

The imaging mode has two pixel scales: 13 mas/pix and 27 mas/pixel, which provide respectively  $\sim 26 \times 26$  and  $55 \times 55$  arcsec fields of view. The smaller pixel scale is designed to fully sample the PSF in the J, H and

Configuration	Band	$\lambda_c$ [ $\mu\text{m}$ ]	$\lambda$ range [ $\mu\text{m}$ ]	Resolution
Low Resolution	J_low	1.25	1.09-1.42	$\sim 5000$
	H_low	1.66	1.45-1.87	$\sim 5200$
	K_low	2.21	1.93-2.48	$\sim 5600$
High Resolution	J_short	1.18	1.10-1.27	$\sim 10000$
	J_middle	1.26	1.18-1.35	$\sim 10000$
	J_long	1.34	1.26-1.43	$\sim 10000$
	H_short	1.56	1.46-1.67	$\sim 10400$
	H_middle	1.67	1.56-1.77	$\sim 10400$
	H_long	1.76	1.66-1.87	$\sim 10400$
	K_short	2.07	1.93-2.22	$\sim 11200$
	K_middle	2.20	2.06-2.34	$\sim 11200$
K_long	2.33	2.19-2.47	$\sim 11200$	

Table 9: SPIFFIER grating parameters. Resolution values correspond to the 1.6 pixel line FWHM. For simplicity, throughout the document high resolution configurations are referred to as R $\sim 10000$  and low resolution configurations as R $\sim 5000$ .

K filters (1 to 2.5  $\mu\text{m}$ ), while the large field of view is a balance between reasonable sampling and as large a field of view as possible. In long wavelength imaging ( $>2.5$   $\mu\text{m}$ ), only a 13 mas/pix configuration is available. The fine pixel sampling choice in this configuration is due to the high sky background in these wavelengths.

The optical design of the instrument means that a small border of  $\sim 10$  pixels will be vignetted around the outside edge of the detector for both aperture settings. This will help with alignment of the components and will reduce the amount of scattered light reaching the detector. It is possible this area of unexposed could provide additional input to the data reduction.

*We note that NIX pipeline includes only basic (single exposure) image reduction steps for high contrast modes: dark subtraction, linearity correction, flat-fielding, and bad pixel interpolation. It does not provide further support for scientific analysis beyond that point. For the high contrast modes, observers are responsible for requesting all the necessary calibrations beyond those given above.*

### 3.5.1 Filter Wheel

Filter	$\lambda_c$ [ $\mu\text{m}$ ]	FWHM $_{\lambda}$ [ $\mu\text{m}$ ]	Average(Peak) Transmission [%]
J	1.28	0.20	82
H	1.66	0.31	93
Ks	2.18	0.39	87
Short-Lp	3.32	0.43	80
Lp	3.79	0.60	78
L-Broad	3.57	1.04	83
Mp	4.78	0.58	80
Pa-b	1.282	0.021	75(83)
Fe-II	1.644	0.020	86(94)
H2-cont	2.068	0.064	80(90)
H2-1-0S	2.120	0.020	67(77)
Br-g	2.172	0.020	65(75)
K-peak	2.198	0.099	83(89)
IB-2.42	2.420	0.049	71(82)
IB-2.48	2.479	0.051	65(78)
Br-a-cont	3.965	0.108	82(91)
Br-a	4.051	0.023	69(80)

Table 10: The table lists NIX filter wheel contents. FWHM $_{\lambda}$  is the width at half transmission.  $\lambda_c$  is the middle of this range. The average transmission is calculated within the half transmission limits. For narrow band filters, we also include the peak transmission inside parentheses.

There is a wide range of filters to choose from, most of which are mounted in the filter wheel. When the user selects a ‘short’ wavelength filter (i.e.  $\lambda < 2.5$   $\mu\text{m}$ ) or a ‘long’ wavelength filter, the associated pupil wheel mask is automatically selected for the pupil wheel. Two additional filters are mounted in the pupil wheel: the

neutral density (ND) filter and the blocking filter. The blocking filter provides additional blocking of the long wavelength thermal background. The full list of filters is given in Table 10; note that the L-Broad filter is designed solely for use with the LSS mode.

Additionally, there is **Blocking** filter in the pupil wheel, see Section 3.5.2. Since the NIX detector is sensitive beyond  $2.5 \mu\text{m}$ , this filter is included to block a potential long-wavelength leak in  $< 2.5 \mu\text{m}$  observations at the cost of throughput (from 5% in J to 10-15% in K). During the commissioning, no problematic cases were observed which requires the use of this filter.

Filter transmission profiles are available on the ERIS website<sup>2</sup>, and are used to compute the total instrument throughput reported in the ERIS ETC<sup>3</sup> which can be displayed if selected on the “Select Output” tab.

### 3.5.2 Pupil Wheel

The pupil wheel of NIX contents a range of different elements that are relevant to the sections that follow, these are detailed in Table 11. For all settings, there is a tradeoff to be considered between maximizing throughput, while reducing the thermal background. For longer wavelength observations, more care has to be taken to limit the emission from the sky and structures surrounding the pupil. So, to optimize the observations two ‘reduced stops’ are available, a larger one for JHK to maximize throughput and a smaller one for LM that limits the background.

No.	Item	Obs. Mode	Description
1	JHK-pupil	imaging	The JHK reduced pupil stop is a metal plate with a circular aperture.
2	Blocking	imaging	A copy of the JHK reduced pupil stop with a filter that enhances blocking of out of band thermal background.
3	LM-pupil	imaging	The LM reduced pupil stop is a metal plate with a smaller circular aperture than the JHK stop, to reduce thermal background.
4	Spider	imaging	The spider mask blocks out thermal emission from the secondary mirror and the spiders at the expense of throughput ( $\sim 15\%$ reduction); only for pupil tracking.
5	ND	imaging	A copy of the LM reduced pupil stop with a neutral density filter.
6	APP	high contrast	An apodizing phase plate that produces a pair of offset images in which opposite halves of the PSF are suppressed, and a fainter central image as a photometric and astrometric reference.
7	SAM-23	high contrast	Sparse aperture masks with the specified number of mini-apertures for non-redundant and partially redundant interferometric imaging.
8	SAM-9		
9	SAM-7		
10	Lyot	high contrast	The Lyot stop is a spider mask with an undersized circular aperture, to be used in conjunction with AGPMs in the aperture wheel.
11	Lyot-ND	high contrast	A copy of the Lyot stop with a neutral density filter, useful when observing very bright objects.
12	Grism	spectroscopy	A grism for L-band spectroscopy with a copy of the LM reduced pupil stop, used with the slit mask in the aperture wheel
13	Open	–	An empty aperture; not user-selectable.
14	Block	–	A blocked aperture to stop any light reaching the detector; not user-selectable.

Table 11: NIX pupil wheel contents

### 3.5.3 Possible Modes and Settings

The possible observing modes and the possible cross matches between the observations are shown in Table 12 and Table 13.

<sup>2</sup>(<https://www.eso.org/sci/facilities/paranal/instruments/eris/inst.html>)

<sup>3</sup><https://etc.eso.org/observing/etc/eris>



	Aperture Wheel	Camera	Filter wheel	Pupil wheel	Tracking
Short imaging	Large field	27mas-JHK	< 2.5 $\mu\text{m}$ filter	JHK-pupil, Blocking, ND	Field
	Small field	13mas-JHK			
Long Imaging	Small field	13mas-LM	> 2.5 $\mu\text{m}$ filter	LM-pupil,ND	Field
APP	Small field	13mas-LM	> 2.5 $\mu\text{m}$ filter	APP	Pupil

Table 12: Configuration combinations for observing modes with NIX.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
		J	H	Ks	Short-Lp	Lp	L-Broad	Mp	Pa-b	Fe-II	H2-cont	H2-1-OS	Br-g	K-peak	IB-2.42	IB-2.48	Br-a-cont	Br-a
1	JHK-pupil	X	X	X					X	X	X	X	X	X	X	X		
2	Blocking	X	X	X					X	X	X	X	X	X	X	X		
3	LM-pupil				X	X		X									X	X
5	ND	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X
6	APP										X	X	X	X	X	X	X	X

Table 13: All possible combinations for the filter and the pupil wheel.

## 4 ERIS Performance Overview

The following section is intended to give the user a rough idea of the expected ERIS performance. It provides an overview only, and the Exposure Time Calculator (ETC) should be used to estimate the feasibility of science observations. The ERIS ETC can be found at <http://www.eso.org/observing/etc/>.

### 4.1 Adaptive Optics System Performance

As already discussed, the ERIS provides two main observing AO modes namely NGS mode and LGS mode. Both require using a NGS, as a high order and tip tilt reference respectively. The following subsections detail the performances provided by these 2 modes. The performance for the seeing enhancer depends only on the seeing and airmass at the time of the observations, and not on the user's choice of NGS. The expected resolution is typically in the range 0.1–0.3 $\prime$ . For the LGS and NGS modes, the Strehl ratio (SR) achieved in nominal seeing of 0.87 arcsec along the line of sight, is given as a function of magnitude and distance of the NGS. Then, in order to give an idea of how the system performance changes, the on-axis performance is shown for each of 3 line-of-sight seeing values (0.7, 0.87 and 1.1 arcsec). The ETC provides more complete information.

#### 4.1.1 AO System Reference Star

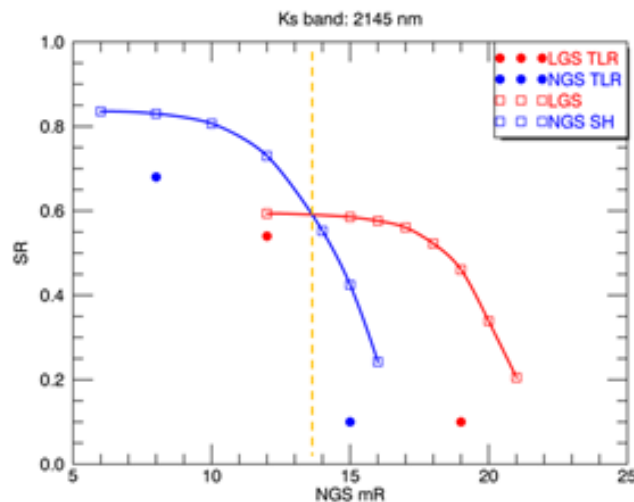


Figure 16: The SR in K band as a function of the reference star magnitude in R band for NGS and LGS case. SR values are given on the y-axis in this plot.

The ERIS AO module has a reference star acquisition FoV of circular shape with a diameter of 120 arcsec. The AO performances are reported in terms of SR as a function of reference star magnitude in R band. The star type is assumed G2V. Note that the NGS WFSs (both HO and LO) wavelength range is 600-1000 nm, so the user is encouraged to search for redder type star in the observation planning. The atmospheric parameters used in the simulations assume standard atmospheric conditions at Paranal and consider a seeing value of 0.87 arcsec, which is taken as the seeing along the line of sight at 30 deg of Zenith distance. Figure 16 summarises the AO performance on-axis for NGS and LGS versus reference star magnitudes (blue and red curves respectively) and the requirements (blue and red dots). These data show the interesting condition that when the NGS is fainter than a R $\sim$ 13.5 mag, the LGS option should be used all the time.

#### 4.1.2 NGS mode performance

The general plot of SR vs. reference star magnitudes and off axis distances is reported in Figure 17. Since the simulations have been done with a given wind profile the SR pattern is not centro-symmetrical. The reported values are an average for off-axis targets located at 0, 90, 180 and 270 degrees with respect to the reference coordinate system of the simulations.

With the help of this figure, the case of multiple reference star availability can be solved by comparing SR(mag, r) for the given reference stars. In the plot, NGS magnitudes below 14 mag has not been considered

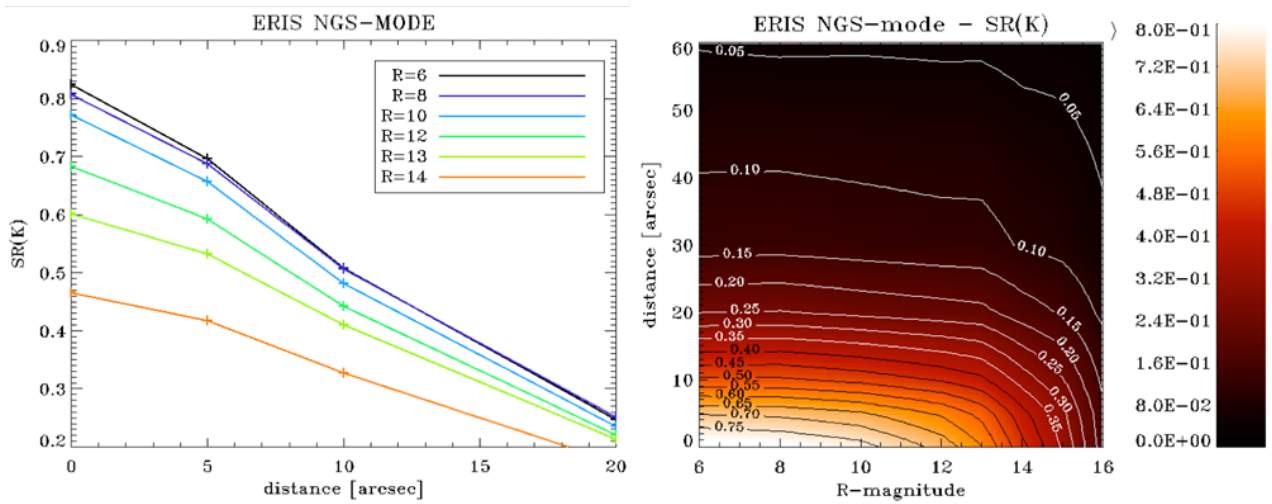


Figure 17: The NGS mode performance as a function of reference star magnitude and off-axis distance from scientific target.

because for mag > 13 better performances are achieved by using the ERIS LGS mode irrespective of the off-axis distance.

4.1.3 LGS mode performance

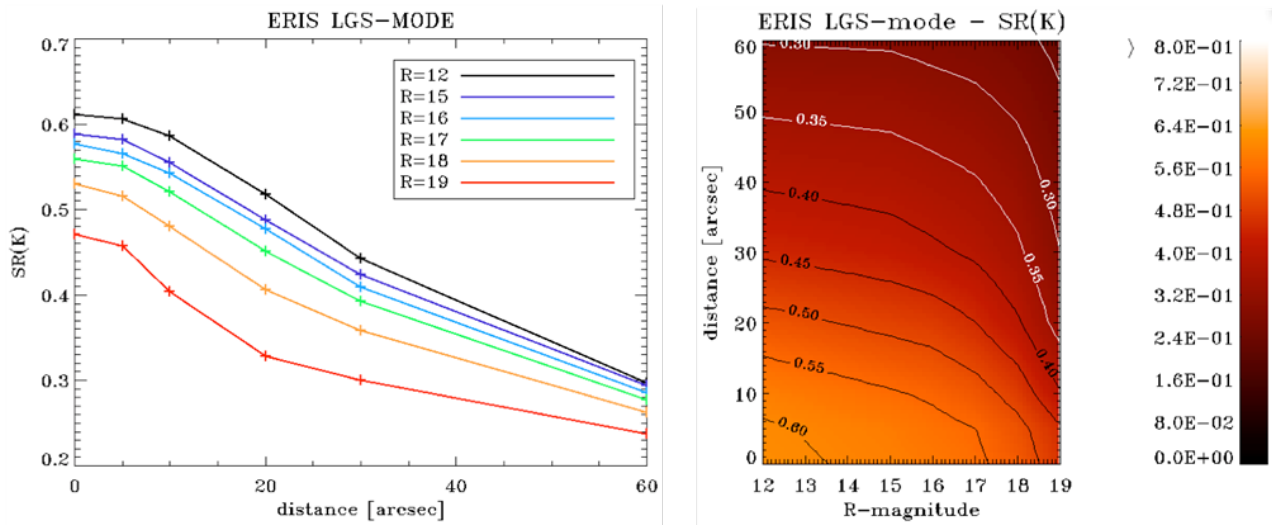


Figure 18: The LGS mode performance as a function of reference star magnitude and off-axis distance from scientific target.

The general plot of SR vs. reference star magnitudes and off-axis distance is reported in Figure 18. The simulations have been done with a given wind profile, so the SR pattern is not centro-symmetrical. The reported values are an average for off-axis target located at 0, 90, 180 and 270 degrees with respect to the reference coordinate system of the simulations.

With the help of this figure, the case of multiple reference star availability can be solved by comparing SR(mag,r) for the given reference stars.

4.1.4 NGS mode and LGS mode performance versus reference star spectral type

When a single reference star is found within 1 arcmin of the science target (i.e. within the AO module’s FoV), the NGS vs LGS mode performances can be compared easily. With the atmospheric parameters considered for ERIS, this comparison is reported in Figure 19.

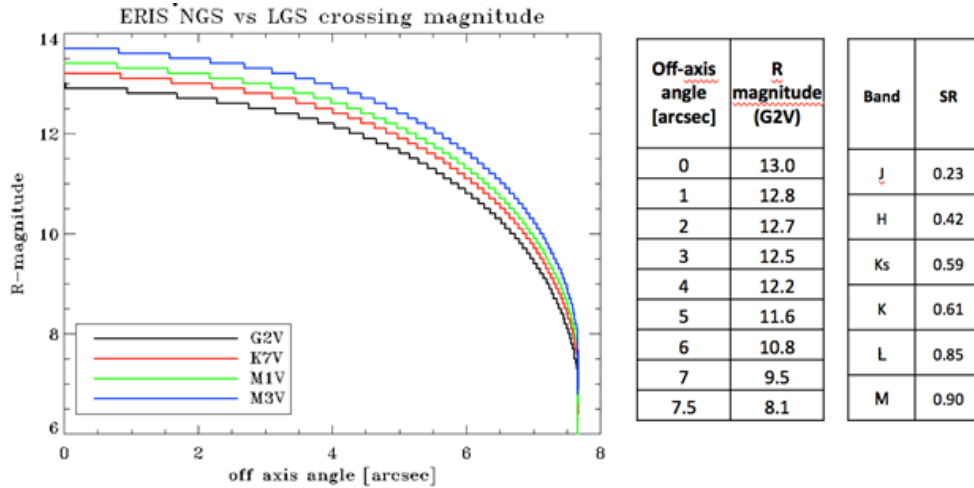


Figure 19: Identification of maximum off axis angle for the NGS WFS reference star for NGS and LGS mode equal performances. The table on the right side shows the limiting magnitude value for equal performances and the achieved SR in various bands. The magnitude is given for different star types. The ERIS specifications refer to the G2V type star.

The Figure shows the maximum off-axis angle at which one gets better performance with the NGS mode with respect to the LGS mode. If a reference star with a given (Rmag,r) values lies above (or to the right of) the line for its spectral type, then LGS mode provides better performance than the NGS mode. The plot shows that for redder spectral types, there is a slight gain in the NGS performance, as expected for the WFS bandpass. But the important conclusion is that the LGS mode always leads to a better SR for stars fainter than 14 mag in R band.

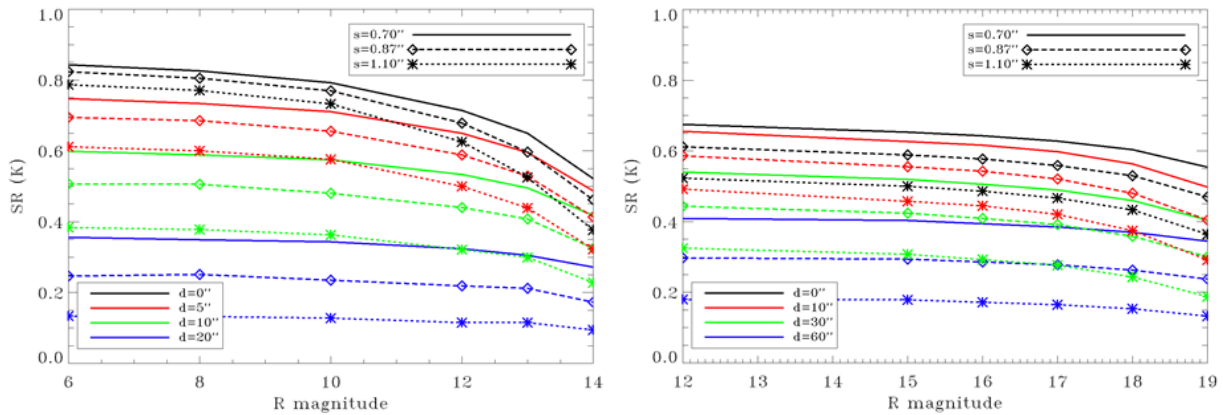


Figure 20: K band SR for 3 different seeing values for NGS (left) and LGS (right) respectively.

#### 4.1.5 AO performance versus seeing value

Figure 20 shows the on-axis system performances for two additional seeing values (0.7 and 1.1 arcsec) to allow estimate the performances as a function of seeing. The different colour lines correspond to different off-axis distances for the star (i.e. indicating anisoplanatism). Performance values can be interpolated within the given ranges.

#### 4.1.6 Performance vs average wind speed

The variation of the AO system performance (NGS and LGS modes) can be considered negligible within the 9.6-14.3 m/s range of wind speeds covered in the simulations.

#### 4.1.7 Sky background from the Moon

The sky background in the LGS low-order wavefront sensor was measured at several angular separations from a half-Moon (FLI  $\sim 0.57$ ) on the night of 2022-08-05. Simulations of the sky emission spectrum at each pointing were made using the ESO SkyCalc Model Calculator<sup>4</sup>, which were converted into Gaia RP fluxes using the filter response curve. These were scaled to the counts measured in the low-order wavefront sensor, accounting for a bias level expected in the measured counts. Using this scaling factor and a large number of SkyCalc simulations, the sky background was predicted for a range of values of the Moon distance and fractional lunar illumination, as well as target altitude (Figure 21). An acceptable background level for a range of guide star magnitudes is shown, and these should be used to place constraints on both service and visitor-mode observations. The system has been tested in LGS mode with a 15th magnitude tip-tilt star at a distance of 15 deg from the full moon, however the telescope guide star was approximately 12th magnitude.

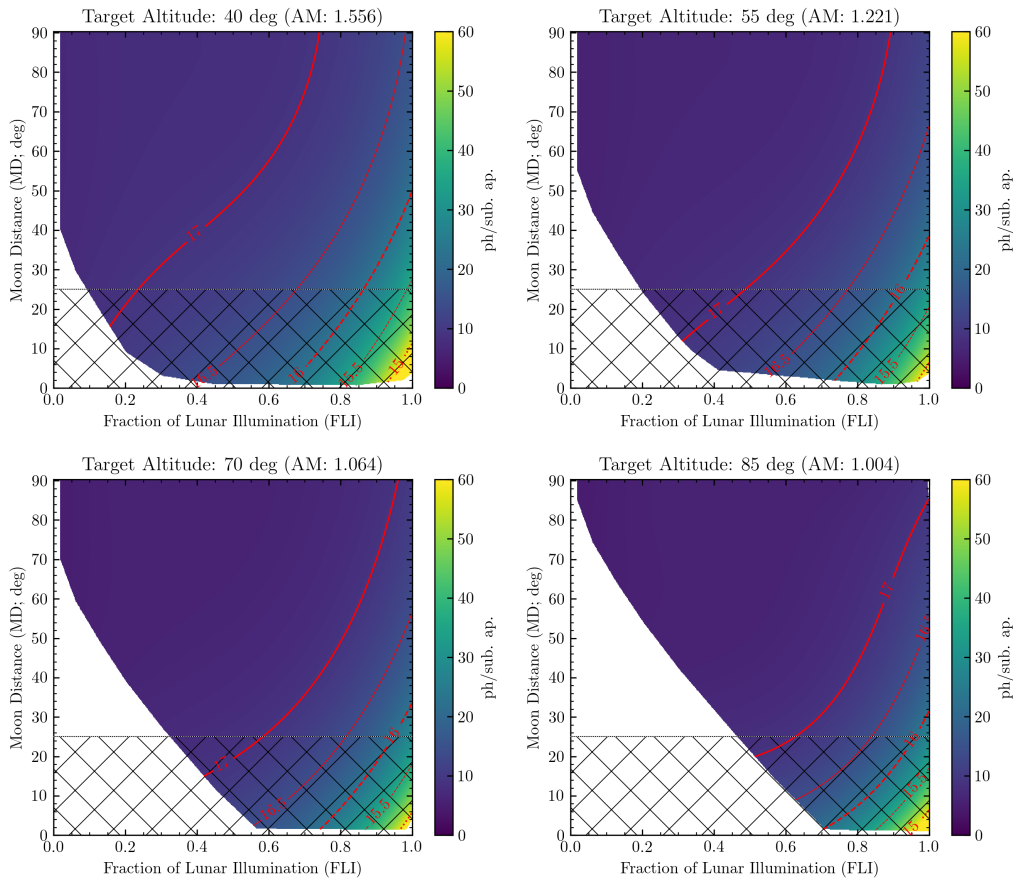


Figure 21: Estimated sky background in photons per sub-aperture in the LGS low-order wavefront sensor at 250Hz as a function of fraction of lunar illumination (FLI) and Moon distance (MD) for four different target elevations. Red contours denote recommended maximum Moon background levels for guide stars between 17th and 15th magnitude. The hatched region denotes Moon distances that are not permitted due to issues with telescope guiding. Due to geometry it is not possible for a Moon with FLI $\sim 0$  to be close to the zenith at night.

The increased sky background from the Moon may also affect the quality of the adaptive optics correction. In particular, the numerical simulations of AO performances assume that the Moon on sky position is 90 degrees from the meridian where observations take place. In different conditions (Moon closer to the line of sight) some degradation of the AO performance may occur, especially in LGS mode with faint tip-tilt stars. Even here, it is important not to over-specify the constraints, as this reduces the chances for the OB to be executed successfully.

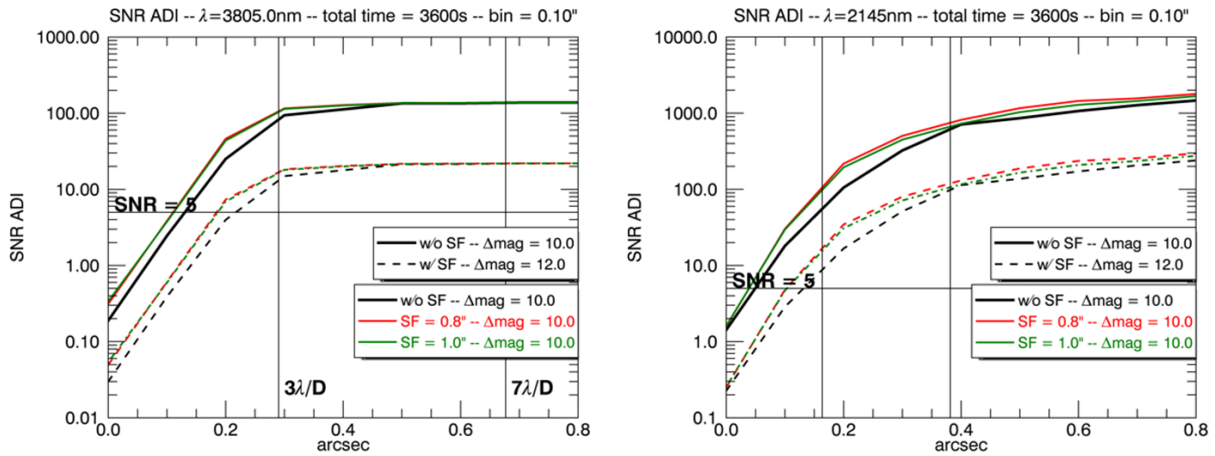


Figure 22: The SNR for L' (left) and K band (right) computed with numerical simulations when AO corrected images are combined by using ADI technique. The SNR saturates quickly in the L' case because of the large contribution from sky background.

#### 4.1.8 PSF and ADI contrast in AO mode

Figure 22 plots the contrast achieved using the ADI technique in NGS AO mode in K and L' bands. The total exposure time in this simulations is 3600s, made by combining 100 image pairs. The baseline mode results are shown with the black line while enhanced performance, using the focal plane Spatial Filter (SF) option in the SH sensor are shown as the red and green curves. This adjustable filter improves the high contrast performance. The difference between the two modes is quantified in the figure.

As an additional comparison of the baseline versus filtered SH option, Figure 23 is a plot of the PSF profiles in K and L' bands for both options.

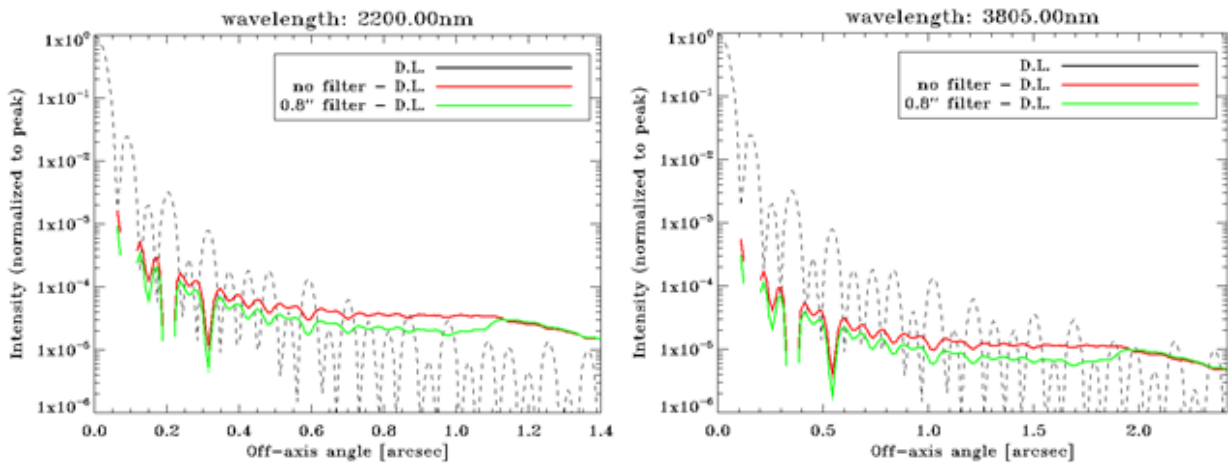


Figure 23: The corrected PSFs profiles at K and L' band for the two options baseline and filtered SH for the NGS WFS. Different behavior is given by red and green line respectively. DL in the figure labels means Diffraction Limit.

## 4.2 NIX performance

The NIX performance for imaging is best assessed through the ETC, because the signal-to-noise that can be achieved depends on a number of details of the configuration – most obviously the filter, the exposure time, and the number of exposures. It also depends on the details of the source distribution, and on how well the background can be inferred either from the dithered science frames or from separate sky frames.

<sup>4</sup><https://www.eso.org/observing/etc/bin/gen/form?INS.MODE=swspectr+INS.NAME=SKYCALC>

This main purpose of this section is to provide additional useful information about the more complex modes.

#### 4.2.1 Detector

**4.2.1.1 Optimal DITs in long wavelength** Observations at longer wavelengths (3–5 $\mu$ m) are strongly affected by the high and variable background due to the thermal emission from the atmosphere. This can be somewhat mitigated by frequently measuring the sky background during your observations. As chopping is not possible with ERIS the background can only be sampled by offsetting the telescope. The overhead associated with this can be reduced if it is possible to keep the science target within the field of view at all times. For isolated regions we recommend using the `ERIS_nixIMG_obs_AutoJitter` template. More complex regions will require a carefully-constructed offset pattern. It is strongly recommended to frequently sample the sky during observations with the broadband long-wavelength filters (`Short-Lp`, `Lp`, `Mp`). Observations with these filters cannot exceed two minutes within a single exposure (i.e.  $DIT \times NDIT \leq 120$  s).

During the commissioning, recorded count levels for Lp filter are 20k, 15k e<sup>-</sup> per 0.2 seconds respectively in April and June; 46k, 36k e<sup>-</sup> per 0.05 seconds for Mp filter. These count levels should be approached conservatively. In particular, there is no data recorded in warmer Chilean summers, where the count rates are expected to be higher with the warmer telescope.

In Mp band, the background is by far the limiting factor even at the fastest full frame readout time. The read noise is about 50 e<sup>-</sup> rms in fast readouts. Hence, the detector can be read at full speed ( $DIT=0.034$ ) to be conservative with the background level. There is no practical advantage for longer DITs (but see Section 4.2.1.2 for cube mode). In Lp band, the situation is similar but there is no need to configure the detector to read at the fastest speeds. 0.1–0.2 DITs should serve well for most observing cases.

**4.2.1.2 NDIT Limits in cube mode** NIX has the potential to generate approximately 330 GB per hour when used at the fastest frame rate in cube mode. For operational reasons when using cube mode the maximum number of NDITs permitted within a single OB is limited to the equivalent of:

- 15,000 NDITs per hour for `windowF`
- 20,000 NDITs per hour for `window1`
- 30,000 NDITs per hour for `window2` and `window3`
- 60,000 NDITs per hour for `window4`

These limits are prorated to the total duration of the OB, including overheads. For example, a 30 minute OB using `windowF` can have at most 7,500 NDITs in cube mode.

The maximum number of NDITs allowed per exposure in cube mode is limited to:

- 500 NDITs per exposure for `windowF`
- 625 NDITs per exposure for `window1`
- 1000 NDITs per exposure for `window2` and `window3`
- 2000 NDITs per exposure for `window4`

**4.2.1.3 Saturation and Persistence Limits** NIX has a variety of modes and some requiring deliberate saturation to work effectively. Hence, the restriction on count levels is more relaxed with respect to SPIFFIER. Detector saturation is currently permitted up to ten times the saturation level of the detector. This corresponds to a limit of 850k e<sup>-</sup> (163k ADU in SLOW mode, 327k ADU in FAST mode). The table below gives the brightest magnitude permitted for each readout mode, camera, and filter combination at the minimum exposure time. These limits were calculated using the ERIS ETC assuming:

- $DIT=1.6$ ,  $NDIT=1$  for SLOW;  $DIT=0.034$ ,  $NDIT=1$  for FAST
- An A0V spectrum
- NGS on-axis, 50% turbulence category
- Airmass of 1.2, FLI of 0.5, and PWV of 2.5mm

	SLOW (DIT=1.6s)		FAST (DIT=0.034s)		Attenuation (mag)	
	13mas	27mas	13mas	27mas	ND	APP
J	$J = 10.4$	$J = 11.6$	$J = 6.6$	$J = 7.9$	6.00	-
H	$H = 9.0$	$H = 10.2$	$H = 5.0$	$H = 6.3$	5.50	-
Ks	$K = 8.7$	$K = 9.9$	$K = 4.6$	$K = 5.9$	5.06	-
Ls	†	-	$L = 3.5$	-	4.64	-
Lp	†	-	$L = 3.5$	-	4.57	-
Mp	†	-	$M = 3.0$	-	4.50	-
Pa-b	$J = 7.3$	$J = 8.6$	$J = 3.2$	$J = 4.6$	5.98	-
Fe-II	$H = 6.0$	$H = 7.2$	$H = 1.7$	$H = 3.0$	5.51	-
H2-cont	$K = 6.5$	$K = 7.7$	$K = 2.2$	$K = 3.5$	5.13	2.3
H2-1-0S	$K = 5.3$	$K = 6.5$	$K = 1.0$	$K = 2.3$	5.10	2.2
Br-g	$K = 5.2$	$K = 6.4$	$K = 0.9$	$K = 2.2$	5.06	2.2
K-peak	$K = 6.9$	$K = 8.1$	$K = 2.7$	$K = 4.0$	5.05	2.5
IB-2.42	$K = 5.7$	$K = 6.9$	$K = 1.5$	$K = 2.8$	4.94	1.3
IB-2.48	$K = 5.3$	$K = 6.5$	$K = 1.0$	$K = 2.3$	4.91	1.1
Br-a-cont	$L = 4.0$	-	$L = 0.0$	-	4.57	1.9
Br-a	$L = 4.0$	-	$L = 0.0$	-	4.56	2.2

† The sky background causes saturation in less than the minimum DIT.

Table 14: Maximum star brightness permitted for each filter, camera, and readout mode. Attenuation of the ND and APP are also given.

These brightness limits assume that either the JHK-pupil or LM-pupil is being used. The attenuation of the ND filter and APP on the peak flux are also given.

The Blocking filter in the pupil that can be used in conjunction with short-wavelength (<2.5um) filters has a small attenuation of between 0.05-0.25 magnitudes, larger at longer wavelengths.

The user should consult the ETC to ensure that their instrument setup does not result in a count rate above the limit. These restrictions are put in to limit the effects of persistence in between consecutive OBs. Within a single OB, users are responsible for designing their observing strategy to minimize the impact in their data.

#### 4.2.2 Optical ghosts

All instruments suffer ghosting due to internal reflection within the filters, for which a faint (almost in focus) ghost image appears slightly offset from the true image. This is more noticeable with narrow band filters because their peak transmission is lower than for broad band filters. This section summarises the ghosting in NIX. The relative position and strength of the ghost for each filter in the centre of the field is indicated in Table 15 and Figure 24. The way in which the position of the ghost shifts across the field is summarised in Figure 25. A more detailed mapping of the ghost in the Br-g filter shows that where  $\delta(x, y)_{ghost}$  is the relative

$$\delta x_{ghost} / \Delta X_{source} = \delta y_{ghost} / \Delta Y_{source} = 0.0258$$

shift of the ghost with respect to the source, and  $\Delta(X, Y)_{source}$  is the shift of the source on the detector. Thus it is possible to calculate the relative position of the ghost for any location in the field using the central offsets given in Table 15.

Ghosts can often be ignored, especially when dithering images of faint objects, because they remain below the noise level in the combined image. But they should be noted especially for high contrast imaging, since a ghost may appear in the dark region around the PSF.

#### 4.2.3 High contrast imaging

High Contrast Imaging (HCI) is used in the imaging of faint circumstellar material or planetary companions, where the diffraction halo of the central star is the dominant noise source in the regions of interest. In nearly all cases the AO system uses the star as the NGS. In the context of NIX, both focal and pupil plane coronagraphy as well as sparse aperture masking, are considered high contrast techniques because they all aim to enable the user to measure characteristics of these targets as close as possible to their primary star.



Filter	$X_{offset}$ (pix)	$Y_{offset}$ (pix)	Peak ratio (%)	Total ratio (%)
J	4	-25	<0.1	0.2
H	3	-26	0.1	0.4
Ks	-1	-46	0.1	0.1
Pa-b	-3	-33	0.2	0.8
Fe-II	12	-20	0.1	0.4
H2-cont	5	-53	0.1	0.2
H2-1-0S	-1	-31	0.3	1.8
Br-g	0	-30	0.7	2.1
K-peak	2	-25	0.1	0.3
IB-2.42	30	-46	0.6	0.8
IB-2.48	7	-35	1.1	2.0

Table 15: Relative positions and strengths of ghosts at the centre of field with the 13mas\_JHK camera in NIX.

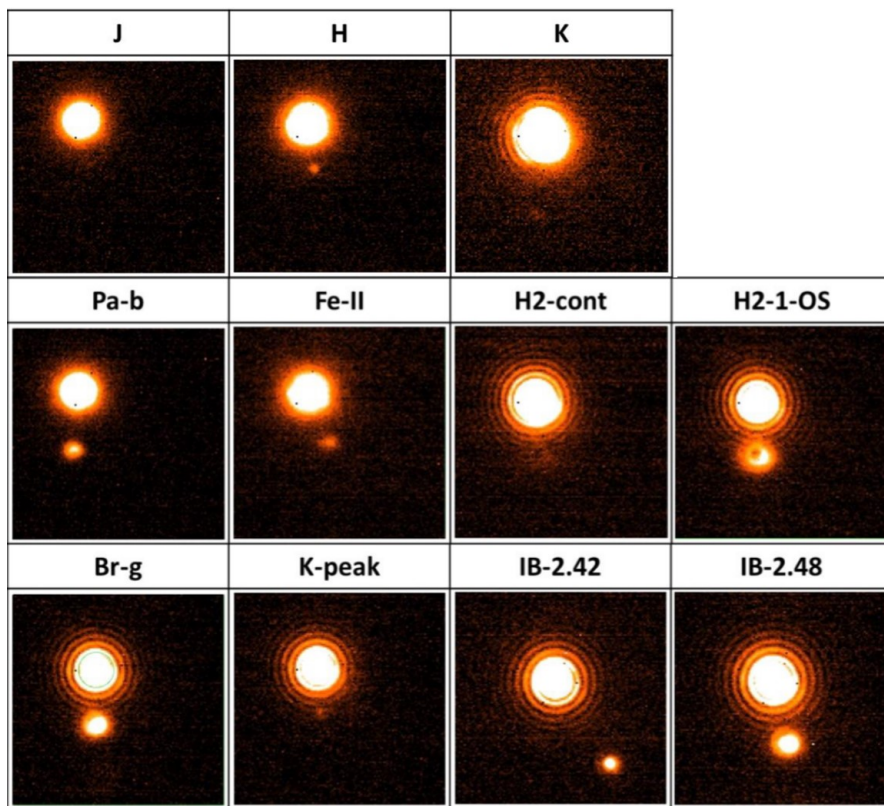


Figure 24: Relative positions and strengths of ghosts in the centre of the field.

All coronagraphs reduce the diffraction halo, and its associated speckle noise after post processing, at the expense of some loss in the throughput of the faint companion. This process is most effective when the target's primary star is bright enough that the AO performance is very good. In this case, the remaining speckles in the PSF halo are quasi-static because they originate from the instrument. As such, they can be separated from the source by tracking the pupil rather than the field, so that the speckle pattern remains fixed on the detector while the astrophysical source (e.g. the exoplanet) moves on the detector from one exposure to the next. The differential rotation can be maximised by observing the source as it crosses the meridian, The data can then be processed to remove the speckles with dedicated ADI techniques, which may differ according to the specific use case.

**4.2.3.1 Pupil Plane Coronagraphy** The pupil plane coronagraph is a grating vector Apodizing Phase Plate (APP, Otten et al. 2014, Optics Express, 22, 30287). The APP is a single optic that goes in the pupil plane. It generates three images of the star. The central image contains about 2% of the total flux from the

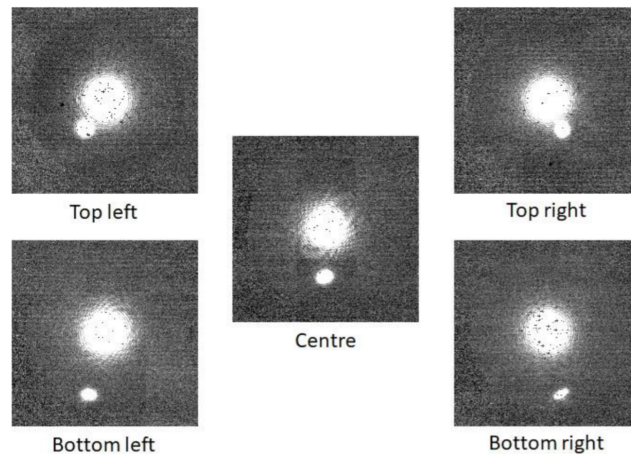


Figure 25: Dependency of relative ghost position on location in field, illustrated with the Pa-b filter.

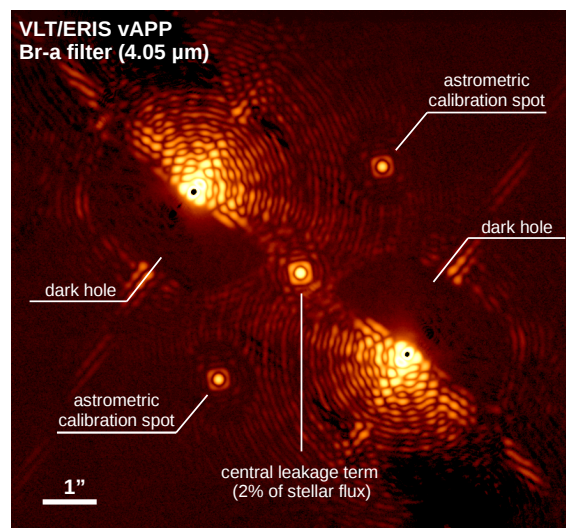


Figure 26: NIX on-sky APP PSF with Br-a filter.

star, and acts as a photometric and astrometric reference. The other two PSFs contain 49% of the transmitted flux each. Each of these two PSFs has a dark D-shaped region of suppression on one side of the star. The two D-shaped regions of both images are on opposite sides of the star, and so provide nearly 360 degrees of suppression when combined. As the orientation of the pupil mask relative to the telescope spiders must be fixed, it is not possible to set the instrument to an arbitrary rotation. For APP observations, which are always taken in pupil-tracking mode, North is at a position angle of  $90 - \text{PUP\_ANGLE} + \text{PARANG}$  degrees. `PUP_ANGLE` is fixed at 36 deg for the APP.

The APP works on all objects in the field of view simultaneously, providing suppression for single and multiple star systems. In these cases, care must be taken when dithering to define positions that will not cause overlapping PSFs in the subtracted image sets. The mode requires no special alignment in the focal plane, and is insensitive to tip-tilt motions and pointing errors in the telescope pointing. It is designed to work with any narrow band filter in K, L or M bands. In principle it can also be used with broad filters, but this will lead to radial smearing of the stellar PSFs.

The APP observations should be designed in a way that the central leakage term is not saturated in a single DIT since this serves as flux calibration. D-shaped components can be saturated to optimize achievable contrast. Table 16 provides guidance for the planning and users should refer to the ERIS ETC for the estimates of peak intensities in nominal PSFs at a given star magnitude, and Table 14 for the (unattenuated) bright limit for each filter, camera, and readout mode. Peak intensities after attenuation by the APP must not exceed ten times the saturation level of the detector (see Section 4.2.1.3).

During the commissioning, APP on-sky contrast curves are derived for Br-g and Br-a representing respectively a below and above  $2.5 \mu\text{m}$  filter. These are shown in Figure 27. For Br-g case,  $\gamma$  Gru (K=3.5 mag)

Filter	North [%]	South [%]	Leakage [%]	Calib Spot [%]
H2-cont	12.4	11.6	4.5	0.2
H2-1-OS	13.6	12.3	4.5	0.2
Br-g	12.7	13.3	4.3	0.2
K-peak	9.6	9.93	3.9	0.2
IB-2.4	24.6	29.5	2.3	0.4
IB-2.48	26.7	35.1	1.6	0.3
Br-a	16.6	15.5	1.5	0.3
Br-a-cont	13.3	12.5	1.7	0.3

Table 16: Relative peak intensities of various components in APP PSFs with respect to the nominal diffraction limited PSF. North/south indicate the peak of the D-shaped components; leakage and calibration spots are shown in Figure 26.

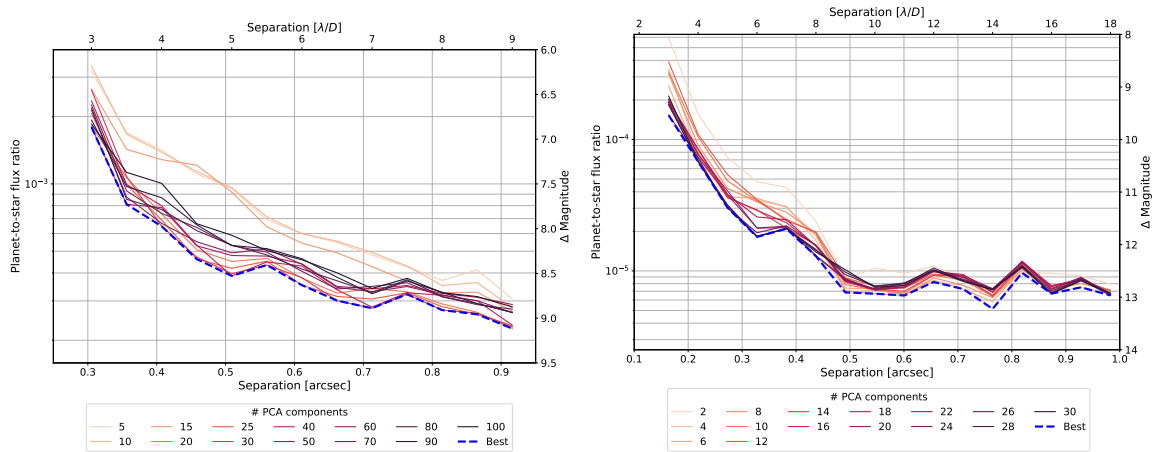


Figure 27: Representative APP on-sky contrast curves corresponding to  $5\sigma$  fake source detection in Br-a (left) and Br-g (right) filters. For details refer to the text.

observed for 45 minutes (net exposure time) with an average seeing of  $0.9''$  and PVW 6.9 mm. For Br-a case,  $\iota$  Cap (L=2.2 mag) observed for 12 minutes with an average seeing of  $0.6''$  and PVW 1.2 mm. The datasets are reduced with ADI-based Principle Component Analysis (PCA) (PYNPOINT; Amara et al., 2012, MNRAS, 427) and the limits are derived from fake planet injections. The resulting contrast will vary based on the post-processing technique used.

### 4.3 SPIFFIER performance

This section provides a brief overview of the important information about SPIFFIER performance needed for planning observations. This should be used in conjunction with the information available in Section 4.1 on the AO performance.

Limiting magnitudes and sky background may differ based on observing conditions, hence we recommend users to use the ERIS ETC for proper estimates (see Section 6.3).

#### 4.3.1 Detector

The detector characteristics (dark current, etc.) are shown in Table 5.

**4.3.1.1 DITs and NDITs** For long exposures on faint targets, we recommend to work with NDIT=1 and a DIT to reach the desired SNR per pointing. If there is a saturation risk, NDIT > 1 with a shorter DIT can be used to lower the counts per integration, but daily calibrations will provide darks with NDIT=1. For exposures longer than 150s, it is mandatory in both service and visitor mode to select the DIT from the recommended values of 150s, 300s, 600s or 900s.

For short exposures, we recommend DIT values of 2s, 5s, 10s, 15s, 20s, 30s, 60s or 100s to reduce the calibration load and to enable sharing of the calibration data with other projects.

**4.3.1.2 Saturation and Persistence Limits** Persistence characteristics are reported in Section 2.5.6. In service mode observations the count level must not exceed 50% of the detector well depth. This corresponds to a limit of 40k e- (20k ADU). The table below gives the brightest magnitude permitted for each grating and plate scale configuration at the minimum exposure time. These limits were calculated using the ERIS ETC assuming:

- DIT=1.6, NDIT=1
- An A0V spectrum
- NGS on-axis, 50% turbulence category
- Airmass of 1.2, FLI of 0.5, and PWV of 2.5

	25mas	100mas	250mas
J_low	$J = 4.3$	$J = 6.9$	$J = 7.1$
H_low	$H = 4.5$	$H = 6.8$	$H = 7.1$
K_low	$K = 4.0$	$K = 6.3$	$K = 6.5$
J_short/_middle/_long	$J = 3.2$	$J = 5.8$	$J = 6.0$
H_short/_middle/_long	$H = 3.4$	$H = 5.8$	$H = 6.1$
K_short/_middle/_long	$K = 3.2$	$K = 5.4$	$K = 5.7$

Table 17: Maximum star brightness permitted for each grating and plate scale configuration.

The user should consult the ETC to ensure that their instrument setup does not result in a count rate above the limit. These restrictions are put in to limit the effects of persistence in between consecutive OBs. Within a single OB, users are responsible for designing their observing strategy to minimize the impact in their data. These limits are relaxed by one magnitude in visitor mode, but the user should consider the effect of persistence when planning their observing run.

### 4.3.2 Spectral Resolution and Wavelength Selection

Figure 28 presents SPIFFIER line profiles for a few selected configurations. For a given configuration, the resolution is stable across the detector, varying only by a few percent. There are small asymmetries in some high resolution configurations at the 250 mas pixel scale, as indicated in the figure with red arrows. In all configurations, line profiles are undersampled: line widths are between 1.3 and 1.6 pixels across different configurations.

For faint objects, there is a tradeoff between spectral resolution and detectability. When observing at higher resolution, the continuum and spectrally resolved line emission are spread over more pixels, so the detector dark current and read noise become more important. Thus less observing time is needed to detect a line at lower resolution.. On the other hand, at lower resolution, especially in the H-band, OH-lines contaminate a larger portion of the spectrum. Spectrally unresolved emission lines and narrow velocity features can be measured more accurately and sensitively at higher resolution, but a single exposure covers a smaller wavelength range at higher resolution so not as many diagnostic lines may be present in the spectrum. It is up to the observer to weigh these tradeoffs and decide whether to observe at  $R \sim 5000$  or  $R \sim 10000$ . The ETC can be used to determine the observing time needed to obtain a certain S/N for emission lines and continuum in the various instrument setups.

### 4.3.3 Object-sky observation pattern

In practice, there are three ways to estimate the sky during SPIFFIER observations. We describe the concepts here using a few templates as a basis – for a definitive listing see Section 7.8.2.

- The template specifically tailored for this task is `ERIS_ifs_obs_FixedSkyOffset`. The template supports two different object-sky patterns: (1) O-S-S-O (2) O-S-O-O-S-O. In the former option, object and sky frames are alternated with 50% of the total time spent on the object. The latter option, in which less time would be spent on the sky, is also commonly used when object exposures are well dithered. In this case, the nearest-in-time sky exposure is used to correct each object exposure.

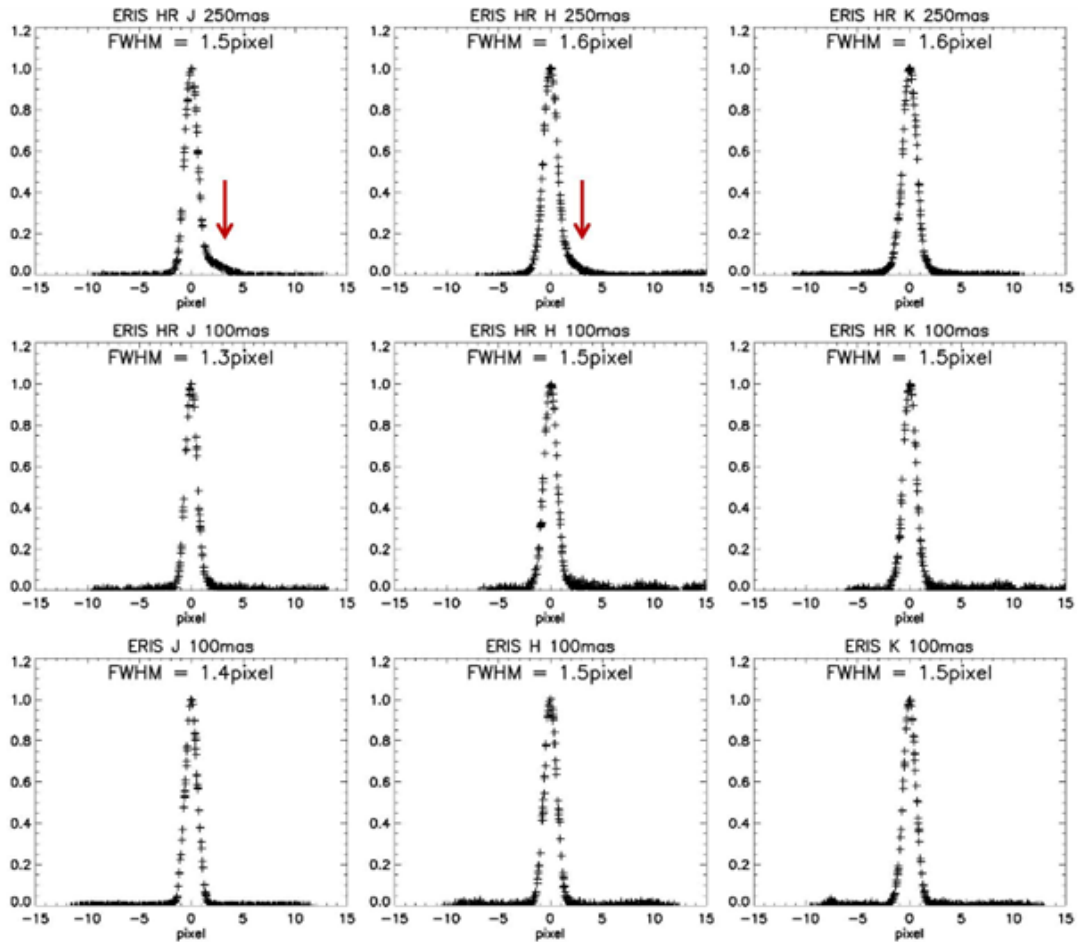


Figure 28: Fine sampled SPIFFIER line profiles at selected pixel scales. Red arrows indicate the asymmetries in line profiles.

- The template `ERIS_ifs_obs_AutoJitter` can be used to estimate the sky background directly from the object frames for isolated sources (it does not inherently support dedicated sky frames). For example, offsets can be applied to place the source successively in the four quadrants of the SPIFFIER field of view. Then the empty quadrants can be used to estimate sky background. The object size should be considerably smaller than the selected field of view for optimal results, and the user should be sure that the rest of the field is suitable for sky background estimation.
- A more generic option is the `ERIS_ifs_obs_GenericOffset` template. This template provides full flexibility to the user. It is possible to assign each dither either an `Object(O)` or `Sky(S)` tag.

Among all three approaches the first one is a safer choice to obtain sky frames with SPIFFIER for less experienced users.

## 5 Observing with ERIS – Overview

### 5.1 Modes offered in Period 111

Only a subset of the capabilities of ERIS described in this manual are offered in P111. Additional modes may be offered in subsequent periods contingent on successful commissioning. The following modes are offered in P111:

- AO modes: noAO, NGS, LGS (seeing enhancer is not offered)
- Sidereal targets only
- Field tracking only, except for NIX APP observations
- SPIFFIER – all gratings and plate scales
- NIX imaging – 13mas and 27mas cameras, all filters
- NIX APP – 13mas camera, narrow-band K and L-band filters only, pupil tracking only.
- NIX – Fast and slow readout modes

### 5.2 Modes not offered

The following modes are not offered. Some of these modes may be offered in future periods contingent on successful commissioning.

- AO modes: seeing enhancer
- AO spatial filtering, the mechanism is fixed at the largest diameter aperture
- Observations of non-sidereal targets, any form of differential tracking
- Pupil tracking, except for NIX APP observations
- NIX sparse aperture mask observations
- NIX focal plane coronagraphic observations
- NIX long slit spectroscopic observations
- NIX windowed (subarray) mode

### 5.3 Service Mode

The majority of ERIS observations will be conducted in service mode (SM). It is important to carefully review the materials in this manual, as well as the information presented on the ESO website<sup>5</sup>, when preparing ERIS observing blocks to ensure that they are feasible.

### 5.4 Visitor Mode

Observations with ERIS can also be performed in visitor mode (VM) or delegated visitor mode (dVM). Information regarding visitor mode operations can be found on the ESO website<sup>6</sup>. Visitors are required to prepare backup targets in the event of poor conditions. Pointing restrictions can occur due to high winds from the north, so users are strongly encouraged to have backup targets in the south. Visitors should be aware that twilight time may be used by the observatory, and is not necessarily available for the visitor.

For more information, please refer to [https://www.eso.org/sci/facilities/paranal/sciops/vm\\_backup.html](https://www.eso.org/sci/facilities/paranal/sciops/vm_backup.html)

<sup>5</sup><https://www.eso.org/sci/observing/phase2/SMGuidelines/SMRules.ERIS.html#InsSpec>

<sup>6</sup><https://www.eso.org/sci/observing/phase2/VMGuidelines.ERIS.html>, <http://www.eso.org/sci/facilities/paranal/sciops/>

## 5.5 AO Limits for Service and Visitor Mode

The table below summarises the key limits and observing constraints that apply to either or both of service and visitor mode observations with ERIS. Particularly important are the Gaia BP and RP magnitude limits for the natural guide star (NGS mode) and tip/tilt star (LGS mode). Several of these parameters are automatically checked at Phase 1, and all are automatically checked at Phase 2. Observations exceeding these constraints/limits will not be accepted.

Constraint	Run Type	NGS	LGS	LGS-SE	noAO
Gaia BP	SM/VM	$\leq 19$	$\leq 19$	N/A	N/A
Gaia RP	SM/VM	1-11	7-17	N/A	N/A
Off-axis radius	SM/VM	0''-60'' (< 30'' rec.)	0''-60''	N/A	N/A
Airmass	SM/VM	< 1.9	< 1.9	< 1.9	< 2.9
TCAT	SM	$\leq 85\%$	$\leq 85\%$	$\leq 30\%$	Any
DIMM seeing	SM	$\leq 1.4''$	$\leq 1.4''$	$\leq 0.8''$	Any
FLI	SM	N/A	$\leq 0.5$ for RP > 16	N/A	N/A

## 5.6 Observing Constraints for Service Mode

All of the following constraints apply to service mode observations. Visitor mode observations must still respect the airmass constraint as this is a fundamental limitation of the instrument.

### 5.6.1 Image Quality and Turbulence Category (TCAT)

The constraints and classification for ERIS OBs depends on what AO mode is being used.

For NGS, LGS, and LGS-SE observations:

- The TCAT specified at P1 corresponds to a specific threshold of the V-band seeing at zenith and coherence time.
- The same TCAT is used at P2 (with the image quality left at the default value).
- The OB is graded by comparing the DIMM-measured seeing and coherence time to the thresholds of the requested TCAT.

For no-AO observations:

- The TCAT specified at P1 corresponds to a specific V-band seeing at zenith threshold.
- The image quality specified at P2 is the predicted image quality (FWHM) given the requested TCAT, airmass, and central wavelength. The ETC calculates this value for all no-AO simulations.
- The OB is graded by comparing the requested image quality to the realized FWHM in the IFS/NIX images at the requested wavelength (or approximated from the DIMM if no obvious point source is present) over the course of the OB.

The maximum permissible turbulence category for each AO mode are:

- NGS, LGS: 85%
- LGS-SE: 30%
- noAO: Any

### 5.6.2 Sky Transparency

The permissible sky transparency categories for each AO mode are:

- NGS, LGS, LGS-SE: photometric, clear, thin cirrus
- noAO: photometric, clear, thin cirrus, thick cirrus

Observations using faint NGS (>10th magnitude) or TT stars (>16th magnitude) are not recommended under thin cirrus conditions.

### 5.6.3 Airmass

Observations utilising NGS must be performed at airmass less than 1.9. Observations utilising LGS or LGS-SE must be performed at airmass less than 1.9. You should use the ETC to select an appropriate airmass constraint for your observations, considering the airmass of your target at culmination.

### 5.6.4 Lunar Constraints

You should not over-specify the Moon constraints (MD: moon distance, FLI: fraction of lunar illumination) as this reduces the chances of the observation being executed. While the Moon does not directly affect infrared observations, it can cause issues when using faint NGS/TT stars (see Section 4.1.7). LGS observations using a tip-tilt star with a Gaia RP magnitude fainter than 16th magnitude are particularly affected. These OBs must have a moon illumination (FLI) constraint of 0.5 or less to ensure the background in the low-order wavefront sensor from scattered moonlight does not overwhelm the faint guide star.

For most other ERIS observations the moon illumination constraint can be entirely relaxed by selecting FLI=1. Only for the shortest wavelength filters (<1.2 $\mu$ m) there is an increased contribution from the sky background, potentially degrading the sensitivity of your observations. The minimum moon distance permitted is 25 degrees. It is recommended to use a more stringent constraint of 40 degrees when using TT stars close to the faint limit.

### 5.6.5 Twilight Constraints

Observations of bright objects can be carried out in twilight, up to 45 minutes before the end of astronomical twilight. You should use the twilight constraint in the p2 tool to specify the number of minutes before the end of astronomical twilight that an OB can be started (e.g., -30 means the OB can be started at the earliest 30 minutes before the end of astronomical twilight).

### 5.6.6 PWV Constraints

The sky transmission and emission in the L and M-band vary strongly as a function of precipitable water vapour (PWV). You should use the ETC to select an appropriate PWV constraint for OBs with observations at these wavelengths.

### 5.6.7 LST Constraints

Specifying a local sidereal time (LST) constraint may be desirable for observations using pupil tracking. The length of the LST interval must at the very least exceed the duration of the OB. Relaxing the interval further will make scheduling your observation easier. You should use at least the duration of the OB plus an additional 30 minutes. There are no limits on the maximum duration of the LST interval.

### 5.6.8 Wind Speed

There are no specifications for maximum wind speed beyond those set by the observatory. Section 4.1.6 states that AO performance is not strongly affected by wind speed within the range 9.6-14.3 m/s. For service mode observations, the instrument operator will decide on whether the conditions are suitable for AO. For visitor mode observations, you are strongly encouraged to prepare backup OBs with targets in the south (as the wind is preferentially from the north) or with noAO in case the conditions are poor.



## 6 Observing with ERIS – Phase 1: Proposal Preparation

This section will help you to decide whether ERIS is the right instrument for your scientific project, take you through a quick evaluation of the observing time needed, and guide you through the particularities of ERIS in the proposal form.

### 6.1 Is ERIS the right instrument for your project?

ERIS is, above, all, an adaptive optics instrument that is designed to provide diffraction limited observations at near infrared wavelengths. It has a variety of different observing modes and configurations that make it a very flexible single source instrument. These include with SPIFFIER:

- Integral field spectroscopy in J, H, and Ks bands. The field of view is between 0.8" and 8" depending on the pixel scale selected, and the spectral resolution is either  $R \sim 5k$  (covering a full single band in one setting) or  $R \sim 10k$  (with half the coverage).

and with NIX:

- Imaging in J, H, and Ks bands with broad and narrow filters over a field of 26" or 55" according to the pixel scale selected; and in L', and M' bands over a 26" field.
- High contrast imaging in L' and M' bands using focal plane coronagraphs, pupil plane coronagraphs, or sparse aperture masks.
- Long slit spectroscopy at low ( $R \sim 900$ ) resolution in a broad L band.

The AO system achieves excellent performance using a laser guide star and the adaptive secondary mirror of the Adaptive Optics Facility. It can still achieve some correction with tip-tilt stars that are as faint as  $R \sim 19$ mag or up to 60" off-axis. And if no tip-tilt stars are available, the AO system can provide improved resolution with its 'seeing enhancer' mode; and seeing-limited observing is always possible although this is not the primary purpose of the instrument.

### 6.2 Targets and Reference Stars

Proposals requesting either NGS or LGS observations must specify the AO reference stars associated with each target (even if they are the same) in the "Observations" part of the proposal form. When the targets are too faint to act as AO reference stars it is recommended to query the Gaia DR3 catalogue via Vizier<sup>7</sup> to find suitable stars. The magnitude range should be limited appropriately using the constraint fields:

- BPmag: < 19, RPmag: 1..11 for NGS,
- BPmag: < 19, RPmag: 7..17 for LGS,

and the target dimension should be limited to one arcminute. Checking compute distance, and "sort by distance" on the preference panel on the left can help you find a reference star not too close to the edge of the AO patrol radius. If a suitable reference star cannot be found using this query the observation of this target in this AO mode is not feasible.

Add the selected reference star to your target list. The p1 tool will resolve the coordinates of stars with Gaia identifiers (e.g., Gaia DR3 528971921686611200), but it will only add magnitudes for stars in SIMBAD. Please manually add the Gaia BP and RP magnitude of the reference star (the form only accepts the name "B" and "R" in the "Band" field for now). These magnitudes will be used to confirm the feasibility of the observations. The reference star can then be associated with the observation of the target star in the "Observations" page of the p1 tool.

It is not necessary to select a telescope guide star at this stage. A check will be made at Phase 2 to confirm that there is a suitable telescope guide star in the vicinity of the target.

<sup>7</sup><https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/355/gaiadr3>

### 6.3 The Exposure Time Calculator (ETC)

The ERIS ETC is available in <https://etc.eso.org/observing/etc/eris>. Users should plan their observing strategy based on the calculations in this webpage. Particular attention should be made to the saturation limits described in this manual.

Describing the parameters used in the ETC to estimate the SNR of the observation in the “Time Justification” part of the proposal form would greatly help in assessing the feasibility of the proposed observations.

### 6.4 Instrument and Telescope Overheads

In addition to the required exposure time calculated using the ETC to achieve the desired SNR, estimates for the telescope and instrument overheads are required as a part of the proposal form. Table 18 gives estimates for the different overheads. These should be used to estimate the total telescope and instrument overhead for each observation. Make sure that the integration time and overheads for sky frames are accounted for, if these are required.

Action	Time (sec)
Telescope	
Telescope preset (first)	360
Telescope preset (subsequent in concatenation)	100 + target_separation [deg]
Telescope offset ( $\leq 0.5''$ )	5
Telescope offset ( $> 0.5''$ )	15
AO	
Acquisition NoAO	60
Acquisition AO (NGS)	300
Acquisition AO (LGS)	360
IFS	
Acquisition (no interactive centering)	$\sim 45$
Acquisition (interactive centering)	$\sim 90$
Detector overhead per NEXP	$2.14 \times \text{NDIT} - 1.14$
Persistence recording overhead per NOFF	12
Change of grating (between high-res gratings)	5
Change of grating (all other)	160
NIX (nixIMG, nixAPP)	
Acquisition (no interactive centering)	$\sim 45$
Acquisition (interactive centering)	$\sim 90$
Detector overhead per NEXP (SLOW, windowF)	$1.92 \times \text{NDIT} - 1.07$
Detector overhead per NEXP (SLOW, windowF, cube)	$1.92 \times \text{NDIT} - 1.07$
Detector overhead per NEXP (FAST, windowF)	$10 \times \text{DIT} + 0.5$
Detector overhead per NEXP (FAST, windowF, cube, $\text{DIT} > 0.154 \text{ s}$ )	$10 \times \text{DIT} + 0.5$
Detector overhead per NEXP (FAST, windowF, cube, $\text{DIT} \leq 0.154 \text{ s}$ )	$10 \times \text{DIT} + 0.5 + \text{NDIT} \times (0.154 - \text{DIT})$
Persistence recording overhead per NOFF	7
Change of camera (parallel with change of filter)	30
Change of filter (parallel with change of camera)	15

Table 18: Table of instrument overheads. In a single OB, the user will have overheads for either SPIFFIER or NIX. Note: Target centering takes variable amounts of time depending on the acquisition exposure times and instrument mode.

A more precise estimate of the total execution time can be made with the p2 demo environment<sup>8</sup>, but this is not necessary for the proposal submission. The p2 tool takes into account the actual integration time for acquisition images, as well as the time taken to move the various mechanisms if multiple science templates are used.

### 6.5 Night-time Calibrations

Some observing modes require additional night-time calibrations. The time used to take these night time calibrations is charged to the user. Section 7.9 lists options and recommendations for night-time calibrations for the available observing modes. The user should ensure that their proposal includes adequate time for all required night-time calibrations that are not part of the standard calibration plan.

<sup>8</sup><https://www.eso.org/p2demo/>

### 6.5.1 Telluric Standards - IFS

Telluric standard stars for IFS observations **must be requested by the user if required** as these will not be obtained automatically as a part of the observatory's calibration plan. If a telluric standard star is required then the time taken must be included in the total time request in the proposal. Finding a suitable telluric star is not required at Phase 1. Instead, it can be assumed that each observation of a telluric standard will take twelve minutes: six minutes for the telescope preset, one minute for the noAO acquisition, and five minutes for integration and associated overheads. This estimate should be appropriately increased if the standard has to be observed with multiple grating settings. At Phase 2 the telluric standard should be identified and included in a concatenation with the science target using the `ERIS_ifs_cal_StandardStar` template.

Additional details regarding the selection of suitable telluric standards can be found in Section 7.7.1.

### 6.5.2 Photometric Standards - NIX imaging

At the start of the night (or operations with ERIS) a photometric standard will be observed at a low and high airmass in five of the broadband imaging filters ( $J$ ,  $H$ ,  $K_s$ ,  $L'$ , and  $M'$ ) to measure the atmospheric transparency by comparing the measured zero point to a reference value. If the conditions are either "clear" (CLR) or "photometric" (PHO), a standard will be observed every two or three hours during the night to monitor the atmospheric transparency.

NIX broadband imaging OBs requesting PHO conditions must have a photometric standard observed within three hours before and after the OB is executed to confirm stability of the atmospheric transparency. If this condition is not met, the OB will be repeated. These standards will be observed as a part of the observatory's calibration plan, so it is not necessary for them to be requested by the user at either Phase 1 or Phase 2.

Dedicated photometric standards can be requested by the user. This may be desirable for an observation requesting PHO conditions if the very best photometric precision is required (i.e.  $< 2\%$  variation in flux), for example. The time taken to observe these standards should be included in Phase 1, along with a justification of why they are required to achieve the science objectives. Finding a suitable photometric standard star is not required at Phase 1. Instead, it can be assumed that each observation of a photometric standard will take fifteen minutes: ten minutes for the telescope preset and AO acquisition, and five minutes for integration and associated overheads. This estimate should be appropriately increased if the standard has to be observed with multiple instrument configurations. At Phase 2 the photometric standard(s) should be identified and included in a concatenation with the science target using the `ERIS_nixIMG_cal_StandardStar` template.

Photometric standards will not be observed in narrow-band filters as a part of the calibration plan. If these are required, they must be requested by the user as a part of their proposal and placed in a concatenation with the science target. Photometric standards will also not be observed in any of the APP, FPC, LSS, or SAM modes, regardless of the requested transparency. Users are strongly encouraged not to request PHO conditions for these modes as this significantly reduces the probability that their observations will be taken.

Additional details regarding the selection of suitable photometric standards can be found in Section 7.7.2.

## 7 Observing with ERIS – Phase 2: Observation Preparation

As with all other ESO instruments, users prepare their observations with the p2 web interface. Acquisitions, observations and calibrations are coded via templates and two or more templates make up an Observing Block (OB) (see Section 7.8.2). OBs contain all the information necessary for the execution of an observing sequence.

The web-based p2 tool is used to prepare ERIS observations for both service and visitor mode. The generic guidelines for Phase 2 and the p2 tool can be found at the following links:

- <http://www.eso.org/sci/observing/phase2/SMGuidelines.html>
- <http://www.eso.org/sci/observing/phase2/p2intro.html>

ERIS-specific information can be found at the following page:

- <https://www.eso.org/sci/observing/phase2/SMGuidelines/SMRules.ERIS.html#InsSpec>

The generic and ERIS-specific guidelines must be followed when preparing your observation in the p2 tool.

### 7.1 General guidelines on observing with ERIS

#### 7.1.1 Observation limitation in AO mode

There are practical limitations on observing with AO based on the location of the target in the sky, its magnitude, and the off-axis distance of the AO reference star. The main conditions to be considered in selecting the conditions of the AO observations are reported here.

1. The NGS mode reference star (NGS) must have a Gaia RP magnitude between 1 and 11.
2. The LGS mode reference star (TT star) must have a Gaia RP magnitude between 7 and 17.
3. The NGS or TT star must have Gaia BP magnitude brighter than 19.
4. Maximum off-axis distance from reference star. The reference star must remain within 60 arcseconds, in any direction, of the telescope pointing for all dither positions (excluding sky offsets, which are executed in open-loop). It is recommended for NGS observations to keep the reference star within 30 arcseconds.

#### 7.1.2 NIX Observations

Some important considerations specific to NIX observations:

- The NIX detector has a lot of bad pixels, especially on the left side. The user should consider carefully how to minimize the impact of these on their observations. This can be done, for example, by rotating the instrument or defining a dither pattern so that the highest priority science targets are not placed in that region of the detector. A representative bad pixel map can be found on the ERIS website<sup>9</sup> to help prepare observations with dither patterns.
- When planning to use ADI for the high contrast modes, ensure that the expected field rotation is sufficient to enable good separation of the speckles and science target during post-processing. LST constraints should be used for service mode observations to ensure sufficient field rotation is achieved.
- For APP observing, it is recommended to use an observing strategy with small random jitters plus nodding. The former serves purpose to clean up systematics (such as bad pixels) with efficient closed loop dithers and the latter to estimate the sky background at regular intervals (depending on the weather conditions, typically  $\sim 3, 10$  minutes respectively in L and K bands). It is important to leave enough distance in between nodding positions so that alternating APP PSFs do not overlap (see Figure 26). Nodding between the acquisition position (800, 1550) and (1550, 1550), a  $9.75''$  offset in  $X$ , will avoid the large clusters of bad pixels.

It is possible to specify an arbitrary instrument rotation angle for observations taken in field-tracking mode (e.g., see Figure 29). For APP, FPC, and SAM observations the instrument rotator cannot be changed. North will be at a position angle of  $90 - \text{PUP\_OFF} + \text{PARANG}$  degrees, where:

<sup>9</sup><https://www.eso.org/sci/facilities/paranal/instruments/eris/inst.html>

- PUP\_OFF = 36 degrees for all APP observations,
- PUP\_OFF = 135 degrees for all FPC observations,
- PUP\_OFF = 136 degrees for all SAM observations.

For APP observations it may be desirable to position a faint companion at a given position angle relative to the dark hole. An LST constraint can be used to ensure service mode observations are only scheduled with a specific range of parallactic angles.

### 7.1.3 SPIFFIER Observations

Some important considerations specific to SPIFFIER observations:

- Acquisition is done first with the AO system. This ensures that with good coordinates, the pointing of SPIFFIER is well aligned on the science target. This enables one to do the SPIFFIER acquisition directly with the field of view needed for the science observations, thus avoiding the overhead associated with having to use the largest SPIFFIER field of view for initial acquisition and interactive centering.
- The ERIS\_ifs\_cal\_PSF template must be used if calibration observations of a PSF star are required. This star can either be the AO guide star or a different star of suitable brightness.
- Choice of plate scale should be done carefully: are the observations driven by the available field of view, by signal-to-noise per pixel, or by achieving the highest possible spatial resolution?

## 7.2 Target and Guide Star Coordinates

Having precise target and guide star coordinates can greatly improve the efficiency of the acquisition procedure, and are essential for IFS observations given the small field of view.

- The target coordinates and proper motions can be provided at any epoch and/or equinox in the p2 tool. These will be propagated to the correct epoch and reference frame at the time of observation by the telescope and instrument software.
- The NGS/TT star coordinates must be provided in the ICRS reference frame (closely aligned with the J2000 equinox) using the middle of the observing period as the epoch (epoch = 1968 + [observing period]/2, e.g. for P111 epoch = 1968 + 111/2 = 2023.5). Using any other equinox or epoch will degrade accuracy of the initial acquisition.

The propagation of the NGS/TT star coordinates is done automatically in the “ObsPrep” tab of the p2 tool when selecting a NGS/TT star. As such, it is **a this tool is used to select the AO guide star** rather than entering the coordinates manually. Precise coordinates for both the NGS/TT star and the target star will enable a rapid acquisition as the offset between the AO stage and two instruments is known precisely.

The telescope guide star must also be specified at Phase 2. It is strongly recommended to use the ObsPrep utility to select a telescope guide star that is compatible with your offset pattern. Telescope guide star coordinates can be entered manually, although this is strongly discouraged. OBs containing acquisition templates that do not specify a telescope guide star will be rejected.

## 7.3 Acquisition Position in Service Mode

For NIX observations the target indicated in the finding chart will always be acquired at following detector pixel coordinates:

- nixIMG:
  - windowF:  $x = 960, y = 1050$  (laser location on NIX detector)
- nixAPP (the coordinate of the central calibration spot):
  - windowF:  $x = 800, y = 1550$

For IFS observations the target indicated in the finding chart will always be acquired at the center of the selected field of view specified in the acquisition template. An offset can be used to re-center the object for the science exposure if the field of view of the first science template is different from the acquisition template (see Section 3.4), if precise centering is required.

You must not request the target to be centered elsewhere in the field of view during acquisition. Instead, use an offset to move the target to the desired position for the first exposure of the science template.

## 7.4 Detector Coordinate and Offset Conventions

### 7.4.1 Coordinates

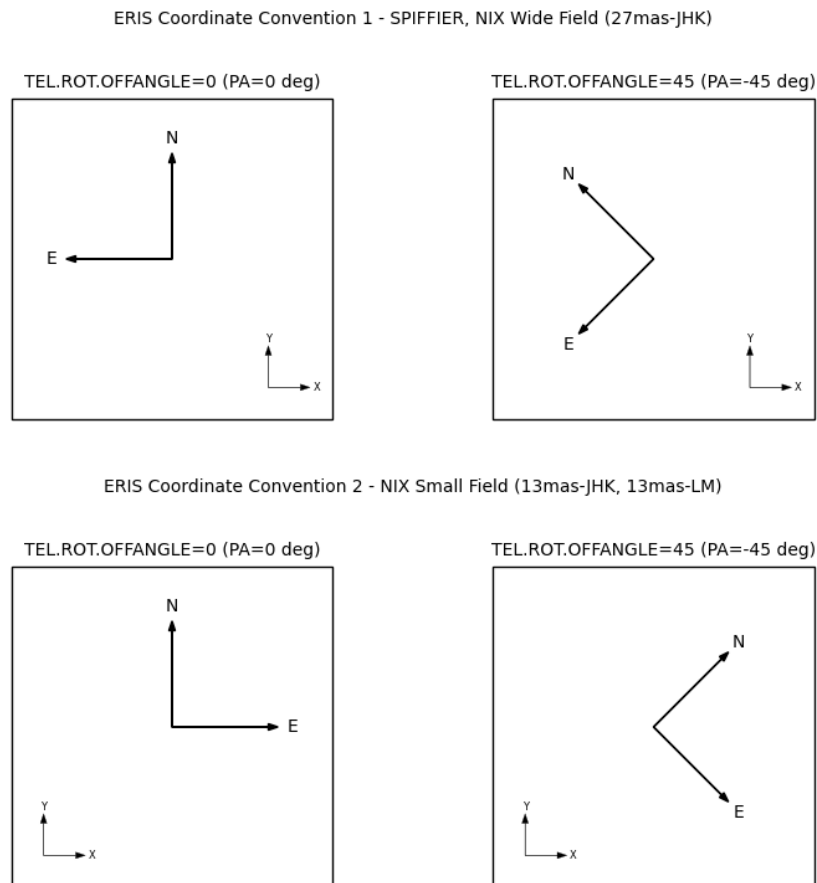


Figure 29: Coordinate system definitions for ERIS.

In Figure 29, we depict the coordinate system definitions for ERIS. There are two configurations depending on the direction of East with respect to the X-axis on the detector when the position angle is zero. The first configuration, when the East points in the opposite direction of the detector X-axis, applies to all SPIFFIER modes and wide field imaging with NIX. The second configuration applies to the all modes of NIX except the wide field imaging configuration.

The convention on the rotation is the same. When the user requests `TEL.ROT.OFFANGLE` of 45 degrees via acquisition templates, the instrument will be configured at a position angle of  $-45$  degrees on-sky using the standard definition. *Note the minus sign.*

### 7.4.2 Offsets

In all observing templates of ERIS, the unit of offsets are standardized to arcseconds. The reference system can either be in SKY (RA, DEC) or in DETECTOR ( $x, y$ ) coordinates. **Both SKY and DETECTOR offsets move the telescope (i.e. the source moves in the opposite direction).** For example, a DETECTOR offset of  $(+1, +1)$  moves the object  $-1''$  in  $x$  and  $-1''$  in  $y$  on the detector. Similarly, a  $(+1, +1)$  SKY offset moves the

object  $-1''$  East and  $-1''$  North. Keep in mind that the orientation of the sky coordinate system for NIX depends on which camera is being used (see Section 7.4).

The offsets in the templates are always defined as *relative* offsets. For example, a series of offsets  $(0, -10, 0, 10)$  brings the object back to the origin. The offset given in an observing templates may end at any arbitrary position (ending on a SKY position, for example); the telescope will always return to the origin at the end of a template regardless of the stated offset pattern, returning the object back to the acquisition position. Subsequent templates will start with the object in the acquisition position, regardless of any offset pattern in previous templates.

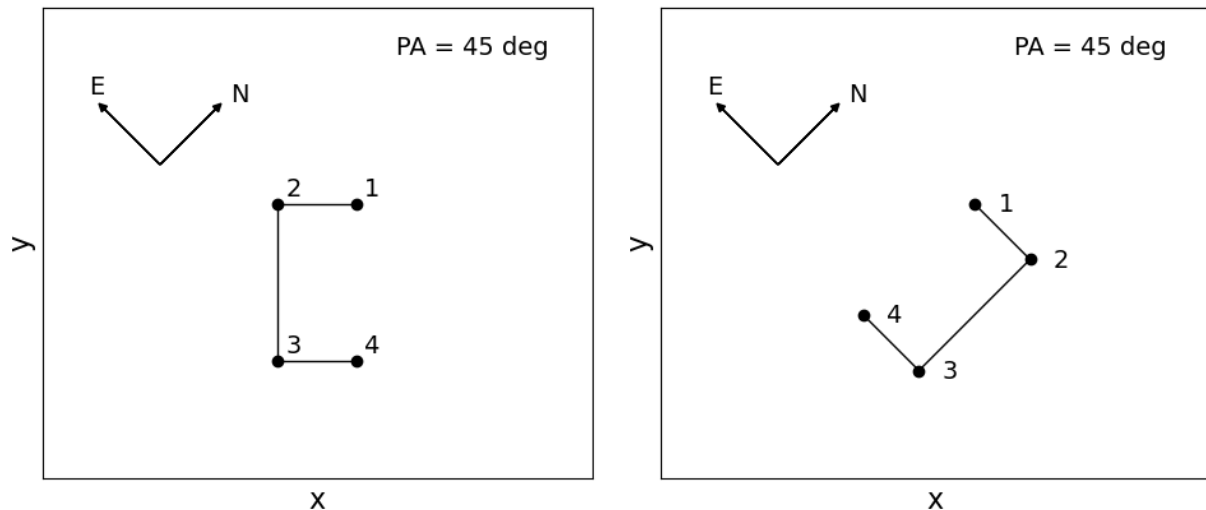


Figure 30: An illustration of the offset sequence for a point source with the on-sky position angle of 45 deg taken with the `ERIS_ifs_obs_GenericOffset` template. Left side: Offset coordinate type `DETECTOR`; Right side: Offset coordinate type `SKY`. This figure is meant to illustrate where on the detector the image of a point source is showing up, if the telescope is doing the following offset sequence:  $(0, +1, 0, -1)$  in  $x$  or RA and  $(0, 0, +2, 0)$  in  $y$  or DEC. The numbers illustrate the order of the offsets.

## 7.5 Blind Offsets

ERIS acquisition templates do not offer explicit blind offset capabilities. In NGS and LGS modes, the exact coordinates of the science target and AO guide star are provided in the OB (see Section 7.2). The ERIS acquisition procedure executes the AO guide star acquisition prior to the science target acquisition. This procedure will place the science target close to the center of the IFS or NIX field of view. Therefore the science target pointing is relative to the AO guide star and no blind offset capability is necessary.

Blind offsets can still be performed using the initial offset within a `GenericOffset` template. In NGS and LGS modes, the coordinates of the AO guide star (or another reference star) can be given as the target. The acquisition is then done on that star, and a blind offset can be implicitly included in the first offset within the science template.

This procedure is recommended for observations of faint targets with noAO and seeing enhancer as these modes do not require the acquisition of an AO guide star. A nearby brighter star should be used to perform the acquisition, followed by a blind offset as the first offset within the science template.

## 7.6 Finding Charts

Finding charts can be generated automatically with `p2`. If finder charts are uploaded to complement those generated by `p2fc` for more complicated acquisitions they absolutely must contain:

- The requested instrument field of view (and, for IFS, the requested field of view in the acquisition template)
- A scale bar and a compass
- A marker indicating the location of the science target

OBs that contain finder charts not meeting these basic requirements are liable not to be observed and will be flagged for revision by the user via USD.

## 7.7 Standard Stars

### 7.7.1 IFS Telluric Standards

There are two classes of stars that are typically used as telluric standards in the near-infrared. Either single hot stars (spectral type <A0, <B4 preferred) that are relatively featureless in the near-IR, or single solar analogues (G0–G4) for which the solar spectrum can be used to remove stellar absorption lines. Binary stars are avoided; resolved systems complicate the extraction of the spectrum, while unresolved companions may contribute significant flux at longer wavelengths.

A curated list of potential telluric standards, as well as a utility to select a suitable one given the target coordinates and observation duration, is available on the ERIS website <sup>10</sup>.

### 7.7.2 NIX Imaging Photometric Standards

Photometric standard stars will be selected from a variety of sources, e.g. van der Bliik (1996, A&AS, 119, 547), Persson et al. (1998, AJ, 116, 2475), Leggett et al. (2003, MNRAS, 345, 144), Leggett et al. (2006, MNRAS, 373, 781). A curated list of photometric standard stars which can be used to measure zero points in each of the five standard broadband filters will be prepared for the calibration plan, rather than requiring a separate list for the short and long-wavelength filters. This will be ready in preparation for the start of operations in early 2023.

## 7.8 ERIS Observing Blocks and Templates

### 7.8.1 Observing Block

Any ERIS science OB should contain one acquisition template, followed by a small number – often just one – of science and optionally night-time calibration templates. The available templates are listed in the following subsections, and possible night-time calibrations are listed in Section 7.9. Note that it is not possible to mix NIX and SPIFFIER templates in a single OB.

### 7.8.2 Templates

A full list and description of the templates, including their input parameters, is given in the ERIS Template Manual<sup>11</sup> (RD2). To prepare your observations, you will need to look in this manual for a description of the template keywords.

All acquisition, observing, and calibration templates for NIX and SPIFFIER will be visible to users of p2 when configuring OBs. These can easily be separated by the naming convention (which always includes either ‘ifs’ for SPIFFIER or ‘nix’ for NIX). Mixing of inappropriate combinations (e.g. noAO acquisition with the smallest plate scale in SPIFFIER) are not permitted, and will generate an error in p2.

**7.8.2.1 SPIFFIER Science Templates** The summary of SPIFFIER acquisition and observing templates is given in Table 19, and a few additional details are provided here. The common parameters for all templates are: `DET.DIT` (detector integration time in seconds), `INS.SPXW.NAME` (pixel scale either 25mas, 100mas or 250mas), `INS.BAND.NAME` (instrument band configuration, refer to Table 9). The templates will set both filter and grating wheel to appropriate positions for a given configuration.

SPIFFIER acquisition templates:

- The NGS acquisition template is `ERIS_ifs_acq_NGS`. It requires information on the NGS star, target, and the telescope guide star. The instrument mode for interactive centering needs to be specified. The position angle on-sky can be set (keyword `TEL.ROT.OFFANGLE`).
- The `ERIS_ifs_acq_LGS` template is for acquisition in LSG mode. Configuration is similar to NGS mode.
- The template `ERIS_ifs_acq_noAO` is for acquiring the target without the use of the AO system, i.e. seeing limited observations.

<sup>10</sup><https://www.eso.org/sci/facilities/paranal/instruments/eris/tools.html>

<sup>11</sup><https://www.eso.org/sci/facilities/paranal/instruments/eris/doc.html>



*SPIFFIER Acquisition Templates*

ERIS_ifs_acq_NGS	Acquisition using NGS-AO
ERIS_ifs_acq_LGS	Acquisition using LGS-AO and seeing enhancer modes.
ERIS_ifs_acq_noAO	Applicable to seeing limited observations.

*SPIFFIER Observing Templates*

ERIS_ifs_obs_AutoJitter	Automatically generates a pseudo-random sequence of (object only) dither positions within a defined range.
ERIS_ifs_obs_FixedSkyOffset	Similar to the above template, but with an equal number of matching sky positions at a single relative offset.
ERIS_ifs_obs_GenericOffset	Freely definable sequence of object and sky positions.

Table 19: Summary of acquisition and observing templates for SPIFFIER

SPIFFIER observing templates:

- The `ERIS_ifs_obs_AutoJitter` template provides `SEQ.NOFF` number of random offsets inside a square box of size `SEQ.JITTER.WIDTH` arcseconds. `DET.NDIT` and `SEQ.NEXPO` can be used to specify number of DITs and exposures per offset position. Random dithers are useful to average out the effects of the flat fielding. Note that this template does not provide dedicated sky exposures because it is expected that the sky background can be derived from the object exposures. In the following example, SPIFFIER is configured in `K_low` and in `100mas`. The telescope will perform five dithers within a `4x4` arcsecond box. In each offset, the detector will be integrated 3 times for 20 seconds.

ERIS_ifs_obs_AutoJitter		
Parameter	Value	p2 label
DET.DIT	20	Detector integration time
DET.NDIT.LIST	3	Number of detector integrations
SEQ.JITTER.WIDTH	4	Jitter width
SEQ.NEXPO	1	Number of exposures per offset position
SEQ.NOFF	5	Number of offset positions
INS.BAND.NAME	<code>K_low</code>	SPIFFIER wavelength band name
INS.SPWX.NAME	<code>100mas</code>	SPIFFIER scale size (arcsec)

- The `ERIS_ifs_obs_FixedSkyOffset` template is similar to that above but also provides random dithers for sky exposures centered around a fixed offset from the original pointing of `SEQ.SKY.OFFSETALPHA`, `SEQ.SKY.OFFSETDELTA` (RA,DEC). If `SEQ.ABBA` is T, a (OS)→(SO) pattern will be used, otherwise a (OSO)→(OSO) pattern is adopted. Here, O is for object and S is for sky frames. `SEQ.NABCYCLES` can be used to specify the number of cycles. Note that one full (OS)→(SO) pattern counts as 2 cycles. The number of integrations that are averaged needs to be set individually by `SEQ.NDIT.OBJECT` and `SEQ.NDIT.SKY` respectively for object and sky. `SEQ.NEXPO` defines the number of separate exposures per offset, and it is common to both sky and object offsets. Finally, the AO loop state is tied to `SEQ.OBSTYPE.LIST`, where the AO loops are closed for O exposures and open for S exposures. The example is the same as for `ERIS_ifs_obs_AutoJitter` with the exception of sky frames which are centered 20 arcsec east and 10 arcsec south of the science target. The template will perform (OS)→(SO)→(OS) offsets in this case with `SEQ.NABCYCLES=3`.

ERIS_ifs_obs_FixedSkyOffset		
Parameter	Value	p2 label
DET.DIT	20	Detector integration time
SEQ.ABBA	T	Implement ABBA object/sky sequence
SEQ.JITTER.WIDTH	4	Jitter width
SEQ.NABCYCLES	3	Number of AB/BA cycles or ABA cycles
SEQ.NDIT.OBJECT	3	NDIT for the OBJECT positions
SEQ.NDIT.SKY	3	NDIT for the SKY positions
SEQ.NEXPO	1	Number of exposures per offset position
SEQ.SKY.OFFSETALPHA	20	telescope offset to sky in RA
SEQ.SKY.OFFSETDELTA	-10	telescope offset to sky in Dec
INS.BAND.NAME	<code>K_low</code>	SPIFFIER wavelength band name
INS.SPWX.NAME	<code>100mas</code>	SPIFFIER scale size (arcsec)

- `ERIS_ifs_obs_GenericOffset` is the most advanced template and gives full flexibility to the observers. The observers are expected to provide a list of offsets along two axes with `SEQ.OFFSET1.LIST` and

SEQ.OFFSET2.LIST, while the total number of offsets is defined by SEQ.NOFF. The keyword SEQ.OFFSET.COORDS identifies whether the offset coordinate system is on SKY or on the DETECTOR, see Section 7.4.2 for details. Additionally, the number of DITs (DET.NDIT.LIST) and the observation type (SEQ.OBSTYPE.LIST, either 0 for object or S for sky) needs to be defined for each offset. The example configuration performs a four point dither around the object, following a square box of size 4 arcseconds. Note that the offsets are *relative to the previous position* in all ERIS observing templates.

ERIS_ifs_obs_GenericOffset		
Parameter	Value	p2 label
DET.DIT	20	Detector integration time
DET.NDIT.LIST	3 3 3 3	List of NDITs
SEQ.NEXPO	1	Number of exposures per offset position
SEQ.NOFF	4	Number of offsets
SEQ.OBSTYPE.LIST	0 0 0 0	List of observation types (O or S)
SEQ.OFFSET.COORDS	DETECTOR	Offset coordinate type selection
SEQ.OFFSET1.LIST	-2 4 0 -4	List of telescope offsets in RA or X
SEQ.OFFSET2.LIST	-2 0 4 0	List of telescope offsets in DEC or Y
SEQ.RETURN	F	Return to origin? (T/F)
INS.SPWX.NAME	25mas	SPIFFIER scale size (arcsec)
INS.BAND.NAME	K_low	SPIFFIER wavelength band name

#### NIX Acquisition Templates

ERIS_nixIMG_acq_NGS	Standard acquisition for all closed-loop AO modes using a natural guide star
ERIS_nixIMG_acq_LGS	Standard acquisition for all closed-loop AO modes using a laser guide star or for seeing enhanced observations
ERIS_nixIMG_acq_noAO	Standard acquisition for seeing limited observations.
ERIS_nixAPP_acq_NGS	These templates are similar to nixIMG acquisition templates. Distinct templates are necessary to ensure correct keyword associations. Slight nuances exist if a given mode requires additional steps during acquisition. For example, the target must be along the slit for LSS mode.

#### NIX Observing Templates

ERIS_nixIMG_obs_GenericOffset	Freely definable sequence of pointing positions.
ERIS_nixAPP_obs_GenericOffset	
ERIS_nixIMG_obs_AutoJitter	Automatically generates a pseudo-random sequence of (object only) dither positions within a defined range.

Table 20: Summary of acquisition and observing templates for NIX.

**7.8.2.2 NIX Science Templates** In general, NIX observing templates follow similar concepts to those for SPIFFIER. There are, however, a different set of parameters specific to NIX. They are described below:

- DET.READOUT is either SLOW\_GR\_UTR or FAST\_UNCORR for the slow and fast modes respectively (see Section 2.4.1).
- INS.NXCW.NAME, INS.NXFW.NAME, and INS.NXPW.NAME are used to set the camera wheel, filter wheel, and pupil wheel positions respectively. Available setups are given in Section 3.5. If there is only single compatible option for a given mode, one or more parameters may be hidden (e.g. INS.NXPW.NAME=APP and hidden in APP templates)
- SEQ.NIX.DET.WINDOWING is used to specify the subarray configuration for the detector readouts from among the pre-defined configurations given in Section 2.4.1.2.
- SEQ.CUBE.ST (T/F) is another keyword specific to NIX, which determines the data format. If set to T, the number NDIT of exposures are taken and tiled along the third axis of the fits cube. The default behavior (F) is to take an average of the individual exposures, then as single mean combined image is saved instead. NDIT limits in cube mode are given 4.2.1.2.

We provide below a set of selected NIX template configurations for completeness and to illustrate relevant detector setups.

- `ERIS_nixIMG_obs_AutoJitter` is similar to `ERIS_ifs_obs_AutoJitter` except for the specific details of the NIX configuration. The following example is representative of a field observations in Lp band. 30 random offsets are requested within a jitter box limited to about half of the FOV. At each dither, an effective exposure of 20 seconds will be taken (`DITxNDIT, 0.2x100`).

ERIS_nixIMG_obs_AutoJitter		
Parameter	Value	p2 label
DET.DIT	0.2	Detector integration time
DET.NDIT	100	Number of detector integrations
DET.READOUT	FAST_UNCORR	Detector readout mode
SEQ.CUBE.ST	F	Store Data Cube? (T/F)
SEQ.JITTER.WIDTH	13	Jitter width
SEQ.NEXPO	1	Number of exposures per offset position
SEQ.NIX.DET.WINDOWING	windowF	NIX Detector windowing
SEQ.NOFF	30	Number of offset positions
INS.NXCW.NAME	13mas-LM	NIX camera wheel
INS.NXFW.NAME	Lp	NIX filter wheel
INS.NXPW.NAME	LM-pupil	NIX pupil wheel

- `ERIS_nixIMG_obs_GenericOffset` is similar to `ERIS_ifs_obs_GenericOffset` except for the specific details of the NIX configuration. In the example, NIX is configured to observe a target with a 5-point dither in Ks band at 13 mas/pix pixel scale. Large offsets may be necessary to avoid the overlap of bad pixels in the final stacked images.

ERIS_nixIMG_obs_GenericOffset		
Parameter	Value	p2 label
DET.DIT	20	Detector integration time
DET.NDIT	1	Number of detector integrations
DET.READOUT	SLOW_GR_UTR	Detector readout mode
SEQ.CUBE.ST	F	Store Data Cube? (T/F)
SEQ.NEXPO	1	Number of exposures per offset position
SEQ.OFFSET.COORDS	SKY	Offset coordinate type selection
SEQ.OFFSET1.LIST	0 -7 14 0 -14	List of offsets coordinates in RA or X
SEQ.OFFSET2.LIST	0 -7 0 14 0	List of offsets coordinates in DEC or Y
SEQ.NIX.DET.WINDOWING	windowF	NIX Detector windowing
SEQ.NOFF	5	Number of offset positions
INS.NXCW.NAME	13mas-JHK	NIX camera wheel
INS.NXFW.NAME	Ks	NIX filter wheel
INS.NXPW.NAME	JHK-pupil	NIX pupil wheel

- `ERIS_nixAPP_obs_GenericOffset` is equivalent to `ERIS_nixIMG_obs_GenericOffset`. The following example is designed to use two alternating positions on the detector and slightly jitter around each one. At each dither, data is recorded continuously for about 2 minutes with `DIT=0.5` in cube mode. Jittering would allow averaging detector effects and alternating nodding positions (with large enough offsets) to monitor skies at each position.

ERIS_nixAPP_obs_GenericOffset		
Parameter	Value	p2 label
DET.READOUT	FAST_UNCORR	Detector readout mode
SEQ.CUBE.ST	T	Store Data Cube? (T/F)
SEQ.NEXPO	1	Number of exposures per offset position
SEQ.NIX.DET.WINDOWING	windowF	NIX Detector windowing
SEQ.NIX.DIT.LIST	0.5	List of detector integration time
SEQ.NIX.NDIT.LIST	240	List of number of detector integrations
SEQ.OBSTYPE.LIST	0 0 0 0 0	List of observation types (O or S)
SEQ.OFFSET.COORDS	DETECTOR	Offset coordinate type selection
SEQ.OFFSET1.LIST	0 0.05 15 -0.1 -15	List of offsets coordinates in RA or X
SEQ.OFFSET2.LIST	0 0.05 0 -0.1 0	List of offsets coordinates in DEC or Y
INS.NXCW.NAME	13mas-LM	NIX camera wheel
INS.NXFW.NAME	Br-a	NIX filter wheel

## 7.9 Required Calibrations

The details of all the calibrations required for ERIS are given in the ERIS Calibration Plan<sup>12</sup> (RD1). Table 21 and 22 summarize the calibration templates respectively for SPIFFIER and NIX.

<sup>12</sup><https://www.eso.org/sci/facilities/paranal/instruments/eris/doc.html>

When possible, calibrations are done internally to the instrument using the calibration unit during day-time. However, there are a few exceptions to this. For example, the 3-5  $\mu\text{m}$  modes for NIX cannot be calibrated internally. Flat-fielding in L and M bands will have to be performed on the sky during twilight. The day-time and twilight calibrations are provided by default by the observatory, and do not need to be requested by the user. In each of the following two tables, calibrations listed among the upper set are part of the standard calibration plan and do not need to be requested by the user.

In addition to these, there are a number of calibrations that are performed on sky during night-time. *These night-time calibrations are charged to the observing time of the user.* In each of the following two tables, calibrations listed among the lower set must be specifically requested by the user and will be charged to their observing time. Note that not all of these are required for all types of observations. The following sections provide recommendations for what calibrations are generally requested for various observing modes to help you decide which calibrations to request.

### SPIFFIER Calibration Templates

standard calibration plan:	
ERIS_ifs_cal_Arcs	Take internal arc frames during daytime
ERIS_ifs_cal_Darks	Take dark frames during daytime
ERIS_ifs_cal_LampFlats	Take internal flatfield frames during daytime
charged to user:	
ERIS_ifs_cal_StandardStar	Observe a standard star for telluric and flux calibration.
ERIS_ifs_cal_PSF	Take an image of a different star to use as PSF reference

Table 21: Summary of calibration templates for SPIFFIER

### NIX Calibration Templates

standard calibration plan:	
ERIS_nix_cal_Darks	Take dark frames during daytime.
ERIS_nixIMG_cal_LampFlats	Take flatfield frames during daytime using calibration unit.
ERIS_nixIMG_cal_TwFlats	Take flatfield frames during twilight.
ERIS_nixIMG_cal_SkyFlats	Take flatfield frames night time (three sets at varying air-masses)
ERIS_nixIMG_cal_StandardStar	Only if photometric conditions requested for broad-band imaging, otherwise must be requested by the user
charged to user:	
ERIS_nixIMG_cal_StandardStar	Standard star observation in imaging mode.

Table 22: Summary of calibration templates for NIX

#### 7.9.1 Recommended night-time calibrations for SPIFFIER

In general, on-sky calibrations for SPIFFIER observations are limited to spectroscopic standard stars for atmospheric correction ERIS\_ifs\_cal\_StandardStar and PSF standards ERIS\_ifs\_cal\_PSF.

#### 7.9.2 Recommended night-time calibrations for NIX

**7.9.2.1 Imaging** In case accurate photometric calibrations are required, ERIS\_nixIMG\_cal\_StandardStar can be used on a star that is known to be a stable photometric reference (catalogs are provided on ESO webpages). If photometric conditions are requested with the science OB, weather assessment via observations of standard stars, with compatible configurations to the science OB, is provided by the observatory. This doesn't apply to non-standard configurations, e.g. narrow-band imaging, or any APP, FPC, LSS, or SAM observation.

**7.9.2.2 High Contrast Imaging** For observations with the APP, the central PSF provides both an astrometric and photometric reference, and so dedicated photometric calibration exposures are not needed.

### **7.9.3 Recommended night-time calibrations for AO**

The only relevant calibration is to acquire the DSM best flat, which is part of the standard calibration plan and so carried out by observatory staff as part of routine operations. For visitor mode observing, it is recommended to be done at the beginning of each observing run.

## 8 Data Reduction

This section summarises the templates, data, and recipes necessary for the processing of NIX/SPIFFIER observations.

### 8.1 SPIFFIER

#### 8.1.1 Day-time Calibrations

The following items are necessary calibrations for SPIFFIER to generate a reconstructed cube corrected for detector and instrumental signatures.

##### Master Dark

Template: `ERIS_ifs_cal_Darks`

Data: Five dark images (DIT).

Purpose: Generate master dark for a given DIT and locate hot pixels.

##### Master Flat

Template: `ERIS_ifs_cal_LampFlats`

Data: five lamp-on and five lamp-off flat images.

Purpose: Generate master flat for a given band and pre-optics in order to correct the pixel-to-pixel sensitivity of the detector.

##### Wavelength Maps

Template: `ERIS_ifs_cal_Arcs`

Data: Pre-defined number of calibration spectra with combinations of Ne, Ar, Kr and Xe pen ray lamps and additional exposures with all lamps off.

Purpose: Wavelength calibration solution for a given band and pre-optics.

##### Distortion

Template: `ERIS_ifs_tec_NorthSouth`

Data: Pre-defined number of images of the triple slit mask (slits oriented along the detector columns) with back illumination on and off.

Purpose: Measure the relative positions of the slitlets with respect to each other on the detector and determine distortion correction map.

##### Gain and Linearity

Template: `ERIS_ifs_tec_GainLinearity`

Data: A series of flat images with increasing DIT (two of each) followed by a series of darks for the same DITs (two of each).

Purpose: Determine read-out noise, gain, detector linearity, bad pixel map.

#### 8.1.2 On-sky Calibrations

The following items list on-sky calibrations for SPIFFIER to correct for the atmospheric transmission and provide photometric and PSF calibrations.

##### Standard star

Template: `ERIS_ifs_cal_StandardStar`

Data: A set of object and sky exposures of a telluric standard star.

Purpose: Correct for the atmospheric (and instrument) transmission in the observed science data. Photometric calibration is achieved by using telluric standards of known magnitudes.

##### PSF star

Template: `ERIS_ifs_cal_PSF`

Data: A set of object and sky exposures of a PSF standard.

Purpose: Determine instrument/AO point spread function.

### 8.1.3 Recipes

In this subsection, methods used by the pipeline to generate calibration and science products are briefly described.

#### Detector linearity determination

Recipe: `eris_ifu_detlin`

A series of flat images with increasing DIT are used to determine non-linear pixels on the detector.

#### Bad pixel map and master dark determination

Recipe: `eris_ifu_dark`

A set of dark calibration frames is stacked to produce master dark frame. For each pixel, the standard deviation of intensity is computed to detect bad pixels and generate bad pixel map.

#### Master flat determination

Recipe: `eris_ifu_flat`

The lamp-off frames are subtracted from the lamp-on frames. The frames are combined via stacking into a master flat image.

#### Spectral distortion determination

Recipe: `eris_ifs_distortion`

Arc lamp and slit images are used to calculate the distortion of the slitlets on the detector. The information will then be used to map raw data to proper coordinates.

#### Wavelength calibration

Recipe: `eris_ifu_wavecals`

Using reference line tables, various lines are detected on arc lamp images. A polynomial fit on the detected lines allows to generate a wavelength calibration map.

#### Standard star data reduction

Recipe: `eris_ifu_jitter`

A series of object-sky frames of telluric standard are reduced and collapsed into data cubes. Standard star spectrum is optimally extracted from the cube to be used as scientific calibration input.

#### PSF star data reduction

Recipe: `eris_ifu_jitter`

A series of object-sky frames of the PSF reference are reduced and collapsed into data cubes. The PSF file is generated and `strehl` is computed.

#### Science data reduction

Recipe: `eris_ifu_jitter`

A series of object-sky frames of a science target are reduced and collapsed into data cubes. When a normalized telluric spectrum is given as input frame it will be used to correct the telluric features.

## 8.2 NIX

The approach to NIX data reduction is slightly different to SPIFFIER. The first step is to correct each exposure for detector signatures. Dark and gain-linearity are common calibrations for all observing modes,

- **Master Dark**

Template: `ERIS_nix_cal_Darks`

Recipe: `eris_nix_dark`

Data: Five dark exposures with matching (DITxNDIT)

Purpose: Generate a master instrumental dark and detect hot pixels.

- **Gain Linearity**

Template: `ERIS_nix_tec_GainLinearity`

Recipe: `detmon_ir_lg`

Note: This recipe was developed by ESO, for details see <https://www.eso.org/sci/software/pipelines/detmon/detmon-pipe-recipes.html>

Data: Set of dark and illuminated exposures with increasing DIT up to or near full well. Two of each.

Purpose: Estimate the pixel-wise linearity curve, detect non-linear cold pixels.

## 8.2.1 Imaging

**8.2.1.1 Master Flats** There are two options for flats in the imaging mode. Lamp flats at  $<2.5 \mu\text{m}$  will be taken with CU flat lamp. In  $>2.5 \mu\text{m}$ , sky flats will be used for flatfielding purposes. The corresponding recipes provide; low-frequency flatfield (optical flatfield), high-frequency flatfield (pixel-to-pixel sensitivity) and a bad pixel map. Alternatively, twilight flats can be used in conjunction with lamp flats to replace the low frequency flatfield.

### Lamp Flats

Template: `ERIS_nixIMG_cal_LampFlats`

Recipe: `eris_nix_flat_lamp`

Data: Five illuminated and five dark frames at the same configuration of science observations.

### Sky Flats

Template: `ERIS_nixIMG_cal_SkyFlats`

Recipe: `eris_nix_flat_sky`

Data: Seeing limited sky observations with 5 dithers at least two airmasses.

### Twilight Flats

Template: `ERIS_nixIMG_cal_TwilightFlats`

Recipe: `eris_nix_flat_twilight`

Data: Sky exposures while the telescope is at zenith during twilight time as the background decays.

**8.2.1.2 On-sky Calibrators** `ERIS_nixIMG_cal_StandardStar` can be used to observe a standard star at selected configurations. If requested, it is charged to the user. Reduction of this data follows the description in Section 8.2.1.3.

**8.2.1.3 Data Reduction** The workflow for the NIX imaging data reduction is `eris_nix_img_cal_and_stack`. In a nutshell, this involves five steps each associated with their corresponding recipe:

1. `eris_nix_cal_det` – Removes detector signatures from each frame.
2. `eris_nix_img_skysub` – Calculates and removes sky background from each frame.
3. `eris_nix_img_cal_wcs` – Find catalogue sources in each frame to refine WCS coordinates
4. `eris_nix_img_cal_phot` – Calculates photometric zeropoint of each frame.
5. `eris_nix_img_hdr1_stack` – Stacks all processed object frames.

## 8.2.2 High Contrast Modes

In high contrast imaging modes, corresponding dark, gain linearity and flat field calibrations (with nominal imaging pupil and aperture) will be provided. The data can be reduced in the same manner discussed in Section 8.2.1 up to `eris_nix_cal_det` step. NIX pipeline does not provide any post-processing option from here onwards.