Son Of X-Shooter

SOXS

User Manual

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CHANGE RECORD

ISSUE	DATE	SECTION/PARAGRAPH AFFECTED	REASON/INITIATION DOCUMENTS/REMARKS
1.0	30/09/2024	All	First internal issue for PAE
1.1	25-11-2024	All	PAE RIX SOXS-178 PAE RIX SOXS-180 PAE RIX SOXS-226 PAE RIX SOXS-227 PAE RIX SOXS-229 PAE RIX SOXS-234 PAE RIX SOXS-259 PAE RIX SOXS-260 PAE RIX SOXS-261 PAE RIX SOXS-303
2.0	2026-05-21	All	First issue for PAC

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1 Purpose and Scope of the Document

The SOXS User Manual provides extensive information on the technical characteristics of the instrument, its performances, observing and calibration procedures and data reduction.

1.1 SOXS in a nutshell

SOXS is a single target spectrograph for the ESO-NTT (covering in a single exposure the spectral range from the UV to the H band through the splitting into two arms. The spectrograph operates at intermediate resolutions (R>3500, with a 1” slit) and will be mainly aimed at the study of astrophysical transients. The instrument is complemented by an acquisition camera with optical imaging capabilities and a calibration box. A view of the instrument is shown in Figure 1. The main instrument characteristics are summarised in Table 1.
SOXS was built by a Consortium involving institutes from Italy, Israel, the UK, Finland, Chile and with the supporting participation of institutes from Israel and Denmark. The names of the institutes and their respective contributions are given in Table 2.

Figure 1: The SOXS spectrograph installed at the Nasmyth focus of the ESO-NTT.

Table 1: SOXS characteristics and observing capabilities.

Wavelength range	350-2000 nm split in two arms
UV-VIS arm	Range: 350-850 nm in 4 orders Resolution: 5000 (1” slit) Slit width: 0.5”, 1”, 1.5”, 5” Detector: 4k x 2k E2V CCD
NIR arm	Range: 800-2000 nm in 15 orders Resolution: 6000 (1” slit) Slit width: 0.5”, 1”, 1.5”, 5” Detector: 2k x 2k Hawaii 2RG
Slit length	12”
Beam separation	One dichroic
Atmospheric dispersion compensation	In the UV-VIS arm
Acquisition & imaging camera	Field of View: 3.5’ (diameter) Filters: ugVrizY Pixel scale: 0.21”/pixel Detector: 2k x 2k BEX2-DD

Table 2: Collaborating institutes and their contributions.

Collaborating institutes	**Contribution**
INAF (Astronomical Observatories of Brera, Padova, Roma, Napoli, Catania)	Common Path, NIR-arm, cryogenics, integration, management
Israel (Weizmann Institute of Science)	UV-VIS arm optics and mechanics
UK (Queen’s University of Belfast)	UV-VIS CCD, reduction pipeline
Finland (Turku University)	Calibration Unit
Chile (Millennium Institute)	Acquisition & imaging camera
Israel (Tel Aviv University)	Contribution to operations
Denmark (DAWN & Aarhus University)	Contribution to operations

1.2 Abbreviations and Acronyms (add/delete items as appropriate)

AC Acquisition Camera
AD Applicable Document
ADC Atmospheric Dispersion Corrector
AFC Active Flexure Compensation
CU Calibration Unit
ETC Exposure Time Calculator
INS Instrument Software
NISE Near Infrared Slit Exchanger
NTT New Technology Telescope
OB Observing Block
PAC Preliminary Acceptance in Chile
PAE Preliminary Acceptance in Europe
RD Reference Document
SNR Signal to Noise Ratio
SOXS Son Of X-Shooter
TIO Telescope and Instrument Operator

2 List of Applicable and Reference Documents

2.1 Applicable Documents

Ref.	**Document title**	**Document ID**
[AD1]	Memorandum of Understanding No. 11378/LET/CP/AMA *for the SOXS Instrument on the NTT Telescope*	N/A

2.2 Reference Documents

Ref.	**Document title**	**Document ID**
[RD1]	SOXS Calibration Plan	SOXS-PLA-0006
[RD2]	SOXS Pipeline Manual	SOXS-MAN-
[RD3]	SOXS Template Manual	SOXS-MAN-0001

3 Technical description of the instrument

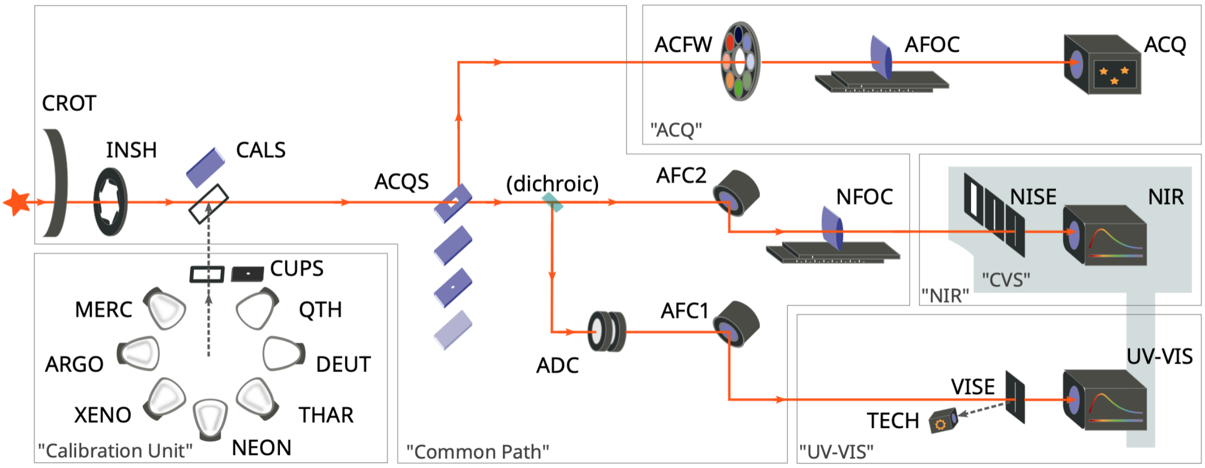

Figure 2: Schematic overview of SOXS. Quoted labels refer to subsystem names. The grey-filled box includes the parts under cryogenics. In this schematic, AFC1 and AFC2 are the tip-tilt mirrors that will be used for active flexure compensation. The NISE and VISE are the NIR and UV-VIS slit exchange linear stages, respectively.

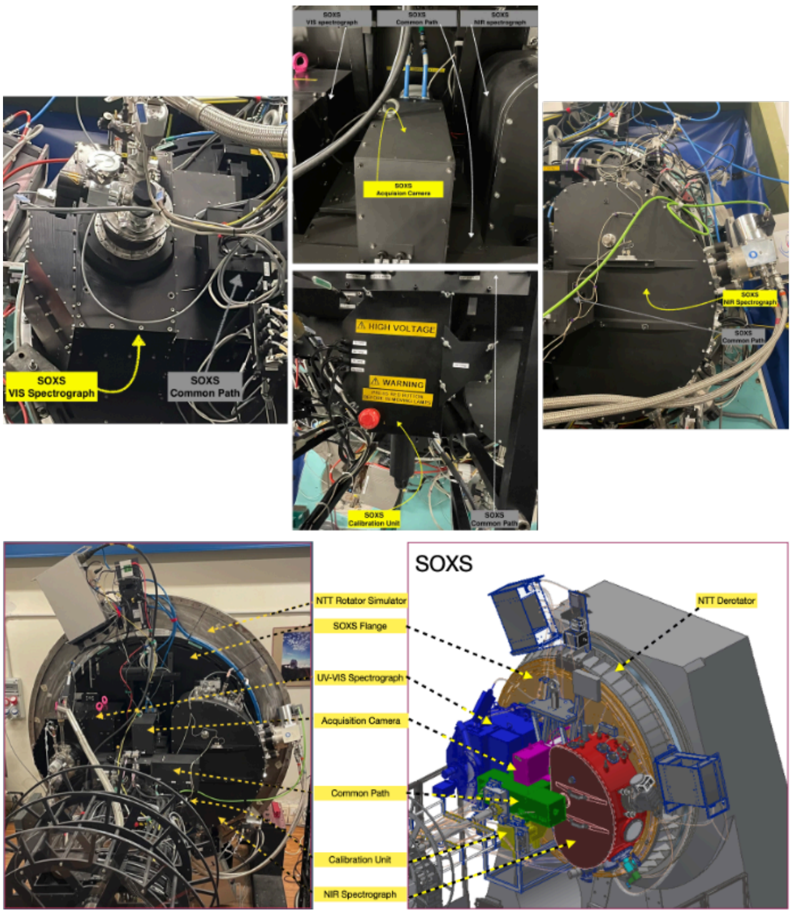

Figure 3: Pictures showing the sub-systems of SOXS.

3.1 Overview of the opto-mechanical design

Figures 2 and 3 show a schematic view of the layout of the instrument. It consists of five main components:

- the common path (CP) is the subsystem directly mounted on the telescope that relays light from the NTT focal plane to the entrance of the two spectrographs (UV-VIS and NIR). In doing that, the CP selects the wavelength range for the spectrographs (using a dichroic, see Fig. 4) and changes the focal ratio. The CP contains the ADC for the UV-VIS spectrograph and two tip-tilt mirrors to correct for misalignment between the two spectrographs due to flexures;
- the calibration box (CBX);
- the UV-VIS spectrograph, which covers the 350 - 850 nm wavelength range with a resolving power of 4000 (for a 1” slit);
- the NIR spectrograph, which covers the 800 - 2000 nm wavelength range with a resolving power of 6000 (for a 1” slit). This arm is fully cryogenic;
- the acquisition camera (AC).

3.2 Description of the instrument sub-systems

This section describes the different SOXS sub-systems (see Fig. 2).

3.2.1 The common path

The SOXS CP is composed of a T-shaped structure (Fig. 4). The first part of the CP is composed of an instrument shutter (which allows safe daytime use of SOXS for test and calibration without stray-light contamination), the Calibration Box selector, the Acquisition Camera selector, and a dichroic. The light reflected from the dichroic goes to the UV-VIS spectrograph; in the CP, there is a flat mirror, an ADC with 2 counter-rotating prisms and a piezo tip-tilt. The light transmitted by the dichroic will go to the NIR spectrograph; in the CP, there is a flat mirror, a piezo tip-tilt and a refocuser.

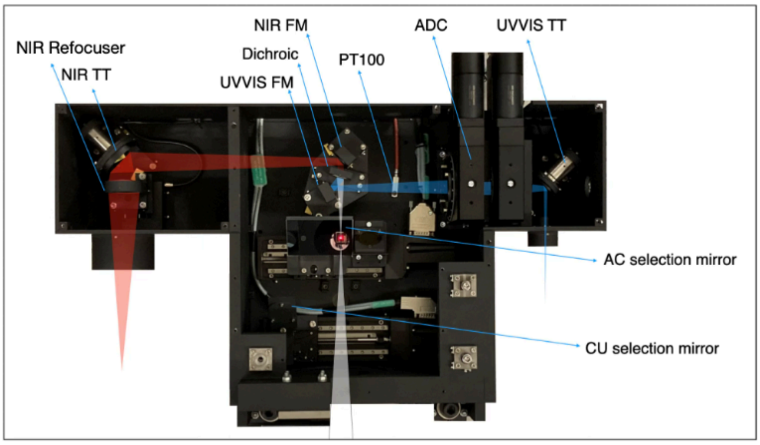

Figure 4: The SOXS Common Path. The light received from the telescope (white beam) is split into UV-VIS (blue beam) and NIR (red beam) wavelengths by the dichroic.

The common path UV-VIS arm

The CP UV-VIS arm hosts an ADC (Atmospheric Dispersion Corrector). The light coming from the Telescope Focal Plane (TFP) is reflected by the CP-Dichroic (CP_DCR) and a flat folding mirror (CP_FM_VIS) into the ADC assembly (CP_LVIS_01 and CP_LVIS_02). The ADC assembly creates a collimated beam for the ADC and transforms the telescope F/11 beam into an F/6.5. After the ADC, the beam is reflected by the tip/tilt mirror (CP_TT_VIS). Finally, a field lens (CP_LVIS_03) matches the exit pupil on the UV-VIS spectrograph pupil. The whole CP UV-VIS Arm layout is presented in Figure 5 (left).

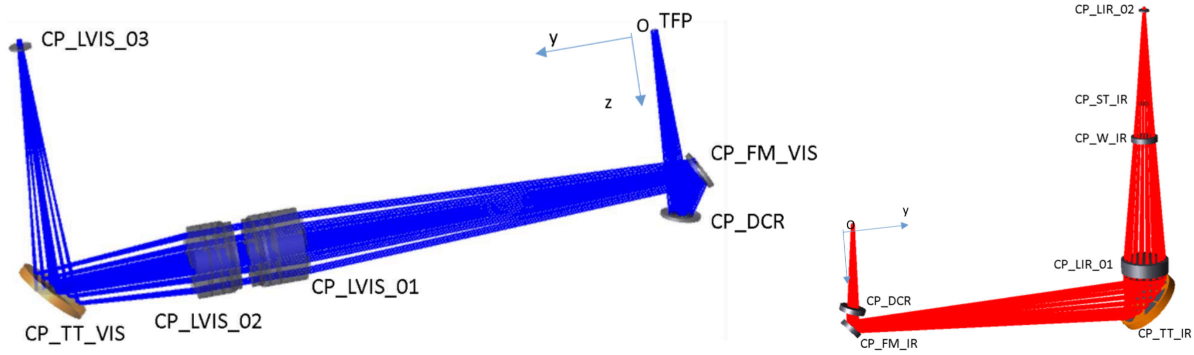

Figure 5: UV-VIS (left) and NIR (right) arm common path layout.

The common path NIR arm

The CP-NIR arm is similar to the UV-VIS arm (same first-order parameters, except the wavelength range). Unlike the UV-VIS, the NIR arm does not include an ADC, since the atmospheric dispersion is less severe than in the UV-VIS range. The CP NIR Arm includes a doublet (CP_LIR_01) in order to reduce the telescope F/11 beam to an F/6.5 beam. Two flat mirrors (CP_FM_IR and CP_TT_IR) relay the light to the slit. In order to allow the entering of light in the NIR spectrograph Dewar, the CP NIR Arm includes a flat window (CP_W_IR), and to reduce noise in the NIR spectrograph, a cold stop was introduced after the window itself (CP_ST_IR). A field lens (CP_LIR_02), placed near the slit, remaps the telescope pupil on the grating of the spectrograph (as in the UV-VIS arm). The whole CP NIR Arm layout is presented in Figure 5 (right).

The flexure compensation tip-tilt mirrors

The light reflected and/or transmitted by the dichroic encounters the AFC1 and AFC2 folding mirrors mounted on a piezo tip-tilt mount. These mirrors are used to fold the beam and correct for CP flexure to keep the relative alignment of the two spectrograph slits at any position of the instrument.

The Atmospheric Dispersion Correctors

The UV-VIS pre-slit arm contains two ADCs. These ADCs consist of two counter-rotating double prisms. The ADCs compensate for atmospheric dispersion in order to minimize slit losses (down to a factor < 10%) and allow orienting the slit to any position angle on the sky. The NIR arm is not equipped with an ADC. If measurement of the absolute flux is an important issue, the slit should be placed at the parallactic angle.

3.2.2 The Calibration Box

The calibration unit (CBX; Fig. 6) is used to provide calibration spectra for the SOXS spectrographs, which are necessary to remove instrument signatures and convert the observed spectrum into one with physical units. Calibration spectra are generated using a synthetic light source, whose light is directed so as to enter and to be dispersed by the spectrographs in the same manner as light from a celestial object would be.

The light source takes form in an integrating sphere, equipped with lamps suitable for wavelength and flux calibrations across the full wavelength range of the instrument (350-2000 nm). The following lamps are used:

- Quartz-tungsten-halogen (QTH) lamp, for flat-field calibration 350-2000 nm.
- Deuterium (D2) lamp, for flat-field calibration 350-500 nm[1].
- NeArHgXe penray lamps bundled together, for IR wavelength calibration. The individual lamps are controlled to operate together as one lamp.
- ThAr hollow cathode lamp, for UVVIS wavelength calibration.

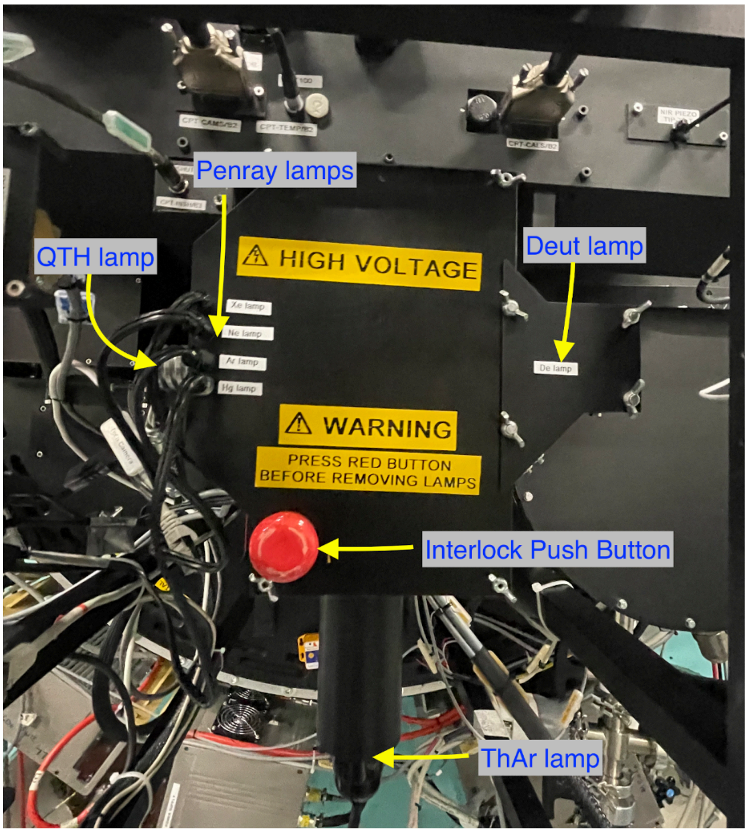

Figure 6: The SOXS Calibration Unit.

[1] Not currently used.

3.2.3 The UV-VIS spectrograph

The SOXS UV-VIS spectrograph (Fig. 7) is based on a novel concept in which the incoming beam is partitioned into four polychromatic beams (quasi-orders) using dichroic surfaces, each covering a waveband range of ~100-200 nm. Each quasi-order is diffracted by a custom-made ion-etched grating. The four beams enter a three-element catadioptric camera that images them onto a common detector. The resolution is with R=3500-7000 (for 1 arcsec slit).

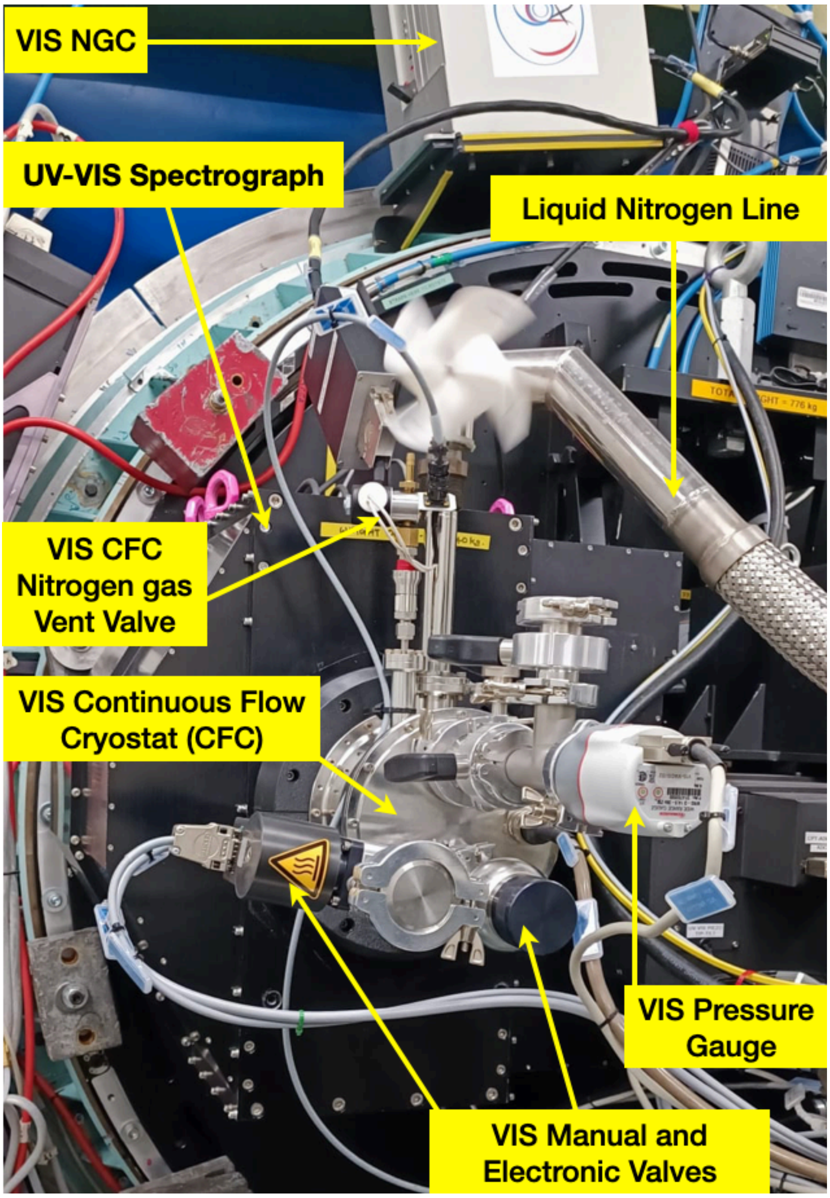

Figure 7: The SOXS UV-VIS spectrograph.

The VIsible Slit Exchanger (VISE)

The VIsible Slit Exchanger (VISE; Fig. 8) allows a precise slit change by linear translation of the slit mask plate. In addition, it allows folding the beam towards the slit-viewing camera. It is mounted on a motorised slide enabling one to select one of the nine positions available. All science observation slits have a height of 12” and different widths of 0.5”, 1”, 1.5”, 5” (the latter for the observation of spectro-photometric standard stars). In addition, a single pinhole for spectral format check and a 9-pinhole mask for wavelength calibration and spatial scale mapping are available. Each pinhole has a 0.5” diameter.

Figure 8: The SOXS VISE unit.

Optical layout

The SOXS UV-VIS spectrograph is divided into two levels, both conceptually and mechanically (Fig. 9). The first level divides the CP beam into four collimated beams, each covering a different wavelength range. The second level includes the dispersers and camera – imaging the spectra of each quasi-order to a common detector.

The beam from SOXS CP is directed into the UV-VIS enclosure and is folded by a flat pickup mirror with a diameter of ϕ=25.4 mm located 70 mm downstream from the CP focus. The beam intercepts a ϕ=62 mm off-axis-parabolic (OAP) mirror at an angle of 30°, creating a collimated beam with a diameter of ϕ=45 mm (The F/# is matched to the CP, i.e. F/6.5). The collimated beam is partitioned into four beams using flat dichroic mirrors at ~45° angle of incidence. The system includes three dichroic surfaces to divide the beam into four quasi-orders. Each quasi-order beam is reflected/transmitted by two dichroic surfaces. The first one is a dichroic mirror tilted at ~45° reflecting u+g and transmitting r+i. The two beams are then further divided by secondary dichroic mirrors, which are tilted at ~45° to ensure proper positioning of the beams on the gratings. The transmitted beams (g + i) are finally reflected towards their gratings by dielectric mirrors at ~ 45°. The mirrors are rotated by a few degrees to feed the gratings at the designed 41° angle of incidence, and the central wavelength ray is parallel to the camera’s optical axis. The dispersed beams are then imaged by the catadioptric camera onto the common detector. The field flattener also serves as a cryostat window and is inserted through a rectangular aperture in the camera’s corrector.

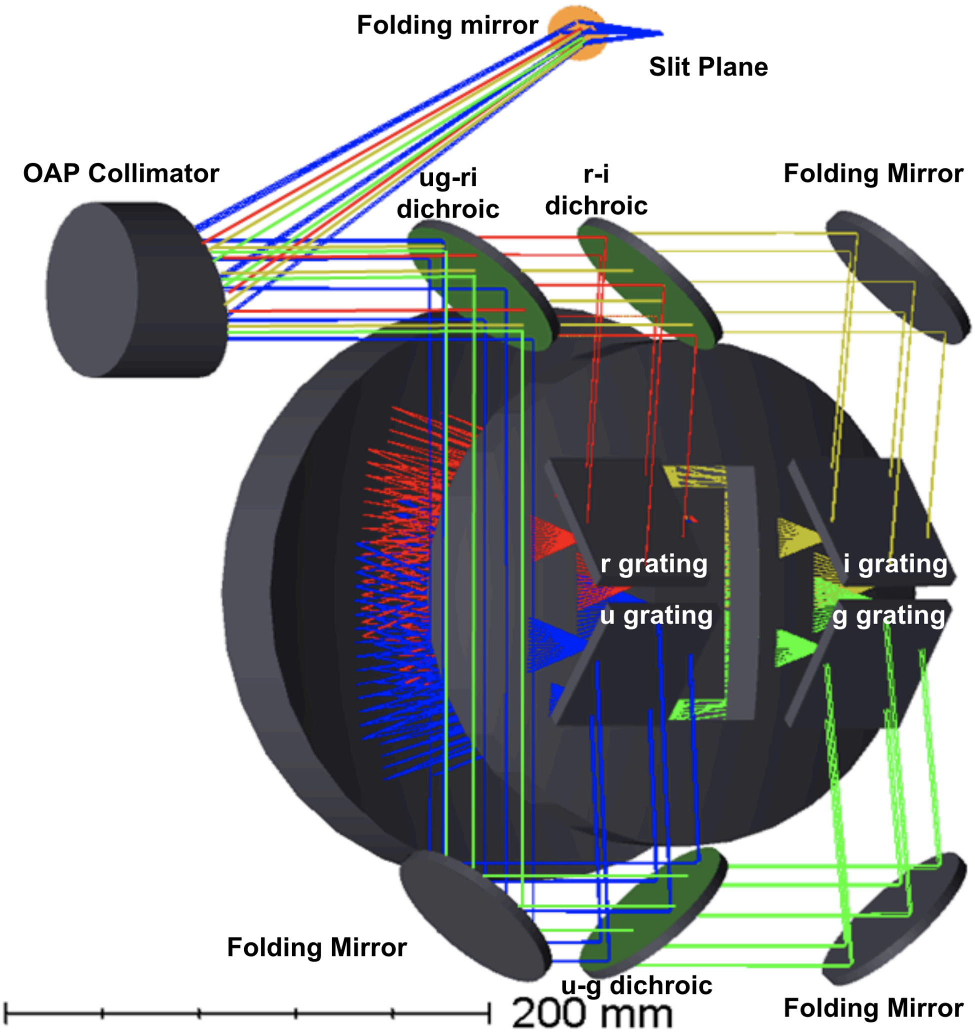

Figure 9: The UV-VIS spectrograph optical layout.

Detector

The UV-VIS detector is a 2098x4096, 15.0 µm pixel CCD from e2V (type CCD44-82) of which only an 858x4096 pixel box is used. The operating temperature is between 156 K and 160 K. The CCD control system is an ESO NGC (New General detector Controller) controller. The list of readout modes is given in Table 3, while the overall detector properties are summarised in Table 5.

Table 3: List of UV-VIS detector readout modes offered for science observations.

Readout mode number	Readout mode name	Gain [e-/ADU]	Speed [kpix/s]	RON [e-]	Binning (Spatial dir.)	Binning (Dispersion dir)
1	Slow High Gain	1.1	263	3.6	1 2 2	1 1 2
2	Fast Low Gain	2.0	500	5.7	1 2 2	1 1 2
3	Slow Low Gain	2.1	263	4.0	1 2 2	1 1 2
4	Fast High Gain	1.0	500	4.9	1 2 2	1 1 2

During image acquisition, especially for the selected region for the instrument (858 x 4096), it is important to account for the dead times associated with image acquisition and the skipping of non-relevant parts of the image. Table 4 summarizes the readout times for the specific SOXS region in BOX mode.

Table 4: Readout time for the UV-VIS arm for different reading modes and binning combinations.

Readout Time (s)	**Mode**	**BINX**	**BINY**
25	1	1	1
10	1	2	2
19	1	2	1
17	2	1	1
14	2	2	1
25	3	1	1
10	3	2	2
19	3	2	1
17	4	1	1
8	4	2	2
14	4	2	1

3.2.4 The NIR spectrograph

The SOXS NIR spectrograph (Fig. 10) is a near-infrared echelle spectrograph, fully cryogenic, with R=5000 (for 1 arcsec slit), covering a wavelength range from 800 to 2000 nm with 15 orders. The operating temperature is 140 K for the spectrograph bench and 45 K for the detector.

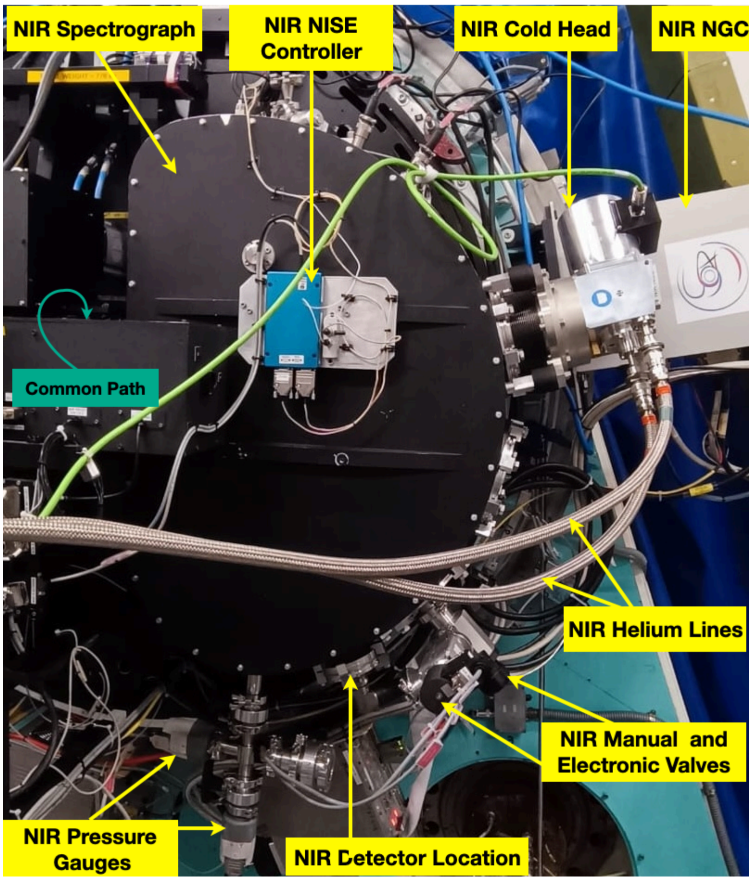

Figure 10: The SOXS UV-VIS spectrograph.

The Near-Infrared Slit Exchanger (NISE)

The Near-Infrared Slit Exchanger (NISE; Fig. 11) allows for a precise slit change by linear translation of the slit mask plate. In addition, it allows folding the beam towards the slit-viewing camera. It is mounted on a motorised slide enabling one to select one of the nine positions available. All science observation slits have a height of 12” and different widths of 0.5”, 1”, 1.5”, 5” (the latter for the observation of spectro-photometric standard stars). In addition, a single pinhole for spectral format check and a 9-pinhole mask for wavelength calibration and spatial scale mapping are available. Each pinhole has a 0.5” diameter.

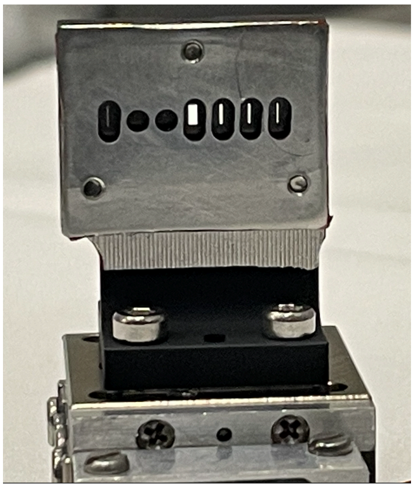

Figure 11: The SOXS NISE unit.

Optical layout

The NIR spectrograph is composed of a double pass collimator and a refractive camera, a disperser (grating) and a cross disperser. The folding mirror is a small mirror placed 60mm after the slit plane, whose aim is to bend the beam by 90°, allowing the accommodation of the spectrograph. The collimator of the system is a Maksutov telescope, used off-axis (and consequently cut). The system has an input f/# of 6.5 (produced by the CP NIR arm) and produces a collimated beam of diameter 50mm. Three Cleartran prisms used in a double pass are the cross-dispersers of the system. The Grating is the main disperser of the system. The Spherical Fold Mirror is a spherical mirror, placed after the second pass through the collimator, whose aim is to fold the beam after the dispersion and before the camera, in order to obtain a more compact design. The mirror, placed approximately in the position of the focus of the collimator, creates a pupil, reducing the necessary diameter of the camera lenses. The design is depicted in Fig. 12.

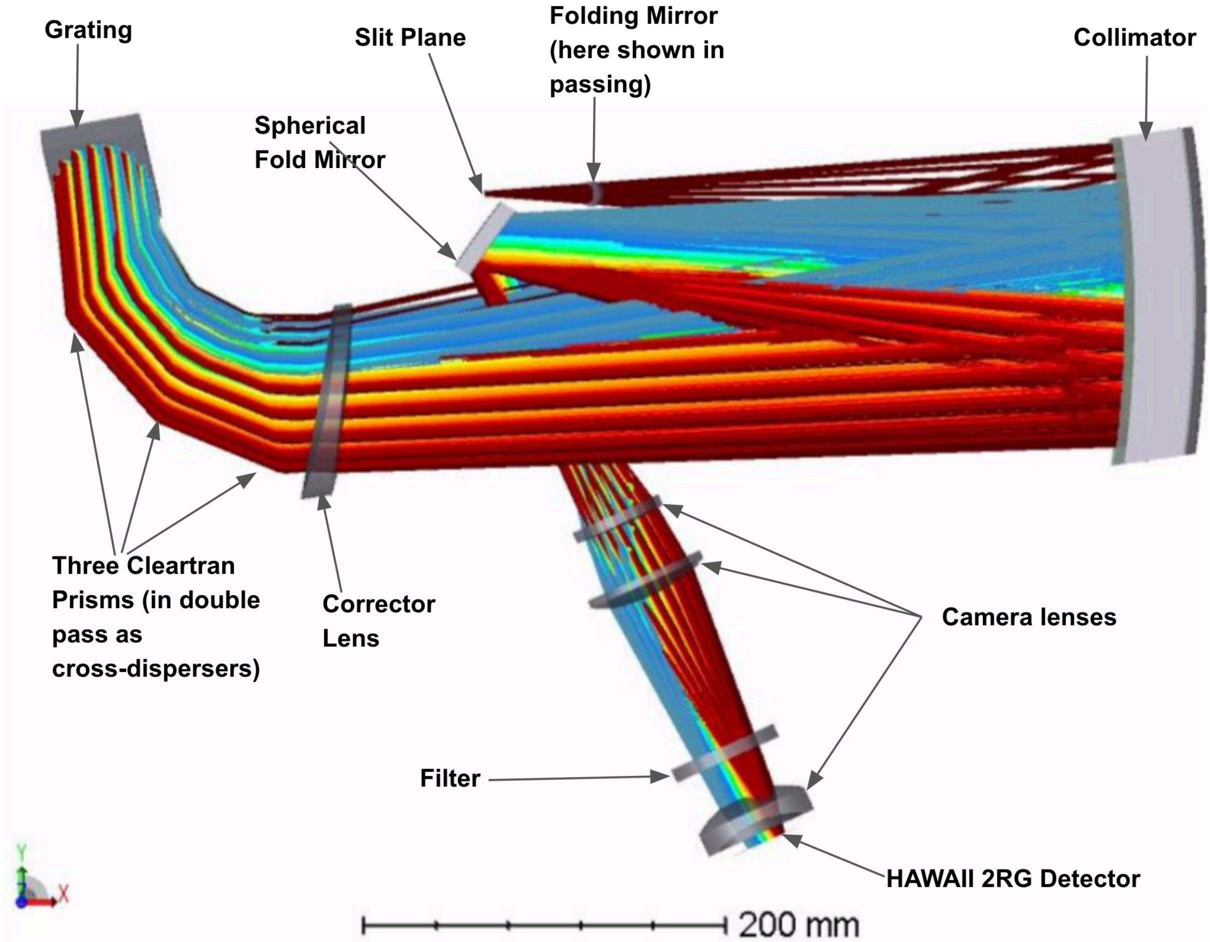

Figure 12: The NIR spectrograph optical layout.

Detector

The detector is a Teledyne substrate-removed HgCdTe 2k x 2k, 18.0 μm pixel HAWAII 2RG detector. The operating temperature is 45 K. The detector control system is an ESO NGC (New General detector Controller) controller. Up-the-ramp readout mode is used. The NIR spectrograph detector properties are summarised in Table 5.

3.2.5 The Acquisition Camera

The SOXS Acquisition Camera (AC; Fig. 13) has the primary function of acquisition of the target for the spectrographs. It can be effectively used as a science multi-filter imager and for technical purposes (e.g. monitoring of spectrographs co-alignment). It consists of a CCD camera, focal reducer optics, filter wheel, folding mirror and a mirror carriage.
At the level of the Nasmyth focal plane, a linear stage carries a single mirror with three positions for different functions and a pellicle beam splitter. The mirror and the pellicle are tilted at 45° and direct light from the sky or from the slits, respectively, to the camera optics. A refocuser linear stage is foreseen at the level of the first collimator lens.

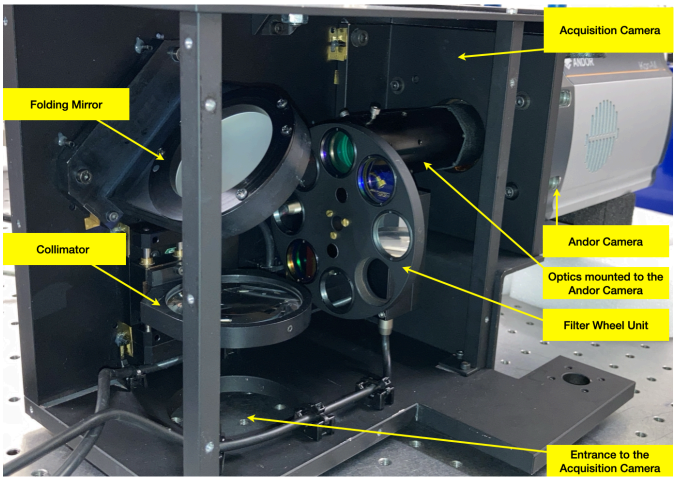

Figure 13: The Acquisition Camera optical layout.

The AC main characteristics are:

- a circular Field of View with a diameter of 3.5’.
- a filter wheel with the u, g, r, i, z, Y (LSST) and V Johnson bands.
- a 1024x1024 pixel detector CCD optimised for NIR QE with a pixel size of 13.0 μm and a pixel scale of 0.21”/pixel.

The properties of the three SOXS detectors are summarised in Table 5.

Table 5: Measured properties of the SOXS detectors.

	UV-VIS	**NIR**	**AC**
Detector type	e2V CCD44-82	H2RG	BEX2-DD: Back Illuminated, Deep Depletion with fringe suppression, extended range dual AR coating
Operating temperature	158 K	45 K	173 K
QE	37.4 % at 350 nm 79.3 % at 400 nm 75.3 % at 500 nm 78.4 % at 650 nm 54.4 % at 900 nm 4.0 % at 1000 nm	70.0 % at 800 nm 82.0 % at 1000 nm 77.0 % at 1200 nm 78.0 % at 1400 nm 78.0 % at 1600 nm 83.0 % at 2000 nm	50.0 % at 350 nm 90.0 % at 450 nm 88.0 % at 550 nm 92.0 % at 650 nm 94.0 % at 750 nm 60.0 % at 950 nm
Number of pixels	2048 x 4096	2048 x 2048	1024 x 1024
Pixel size	15.0 µm	18.0 µm	13.0 µm
Gain (e-/ADU)	Slow High Gain: 1.1 Fast Low Gain: 2.0 Slow Low Gain: 2.1 Fast High Gain: 1.0	2.3	1.0
Readout noise (e- rms)	Slow High Gain: 3.6 Fast Low Gain: 5.7 Slow Low Gain: 4.0 Fast High Gain: 4.9	16.3	3.1
Dark current level	< 2 e-/pix/h	< 30 e-/pix/h	< 7 e-/pix/h
Non-linearity (deviation)	< 1% (mode 1)	< 5% @ ~ 40k counts	< 1%

3.3 Spectral format, resolution and overall performances

3.3.1 Spectral format

The spectral format of SOXS is fixed. The spectral ranges on the detectors and blaze wavelength for each order are given in Tables 6 and 7. The whole spectral range is covered by 4 straight quasi-orders in the UV-VIS and by 15 curved orders in the NIR. In both spectrographs, the spectral lines tilt varies along orders. An example of a halogen (QTH) flat slit frame for each arm is shown in Fig. 14. The dichroic crossover region between UV-VIS and NIR is at 850 nm.

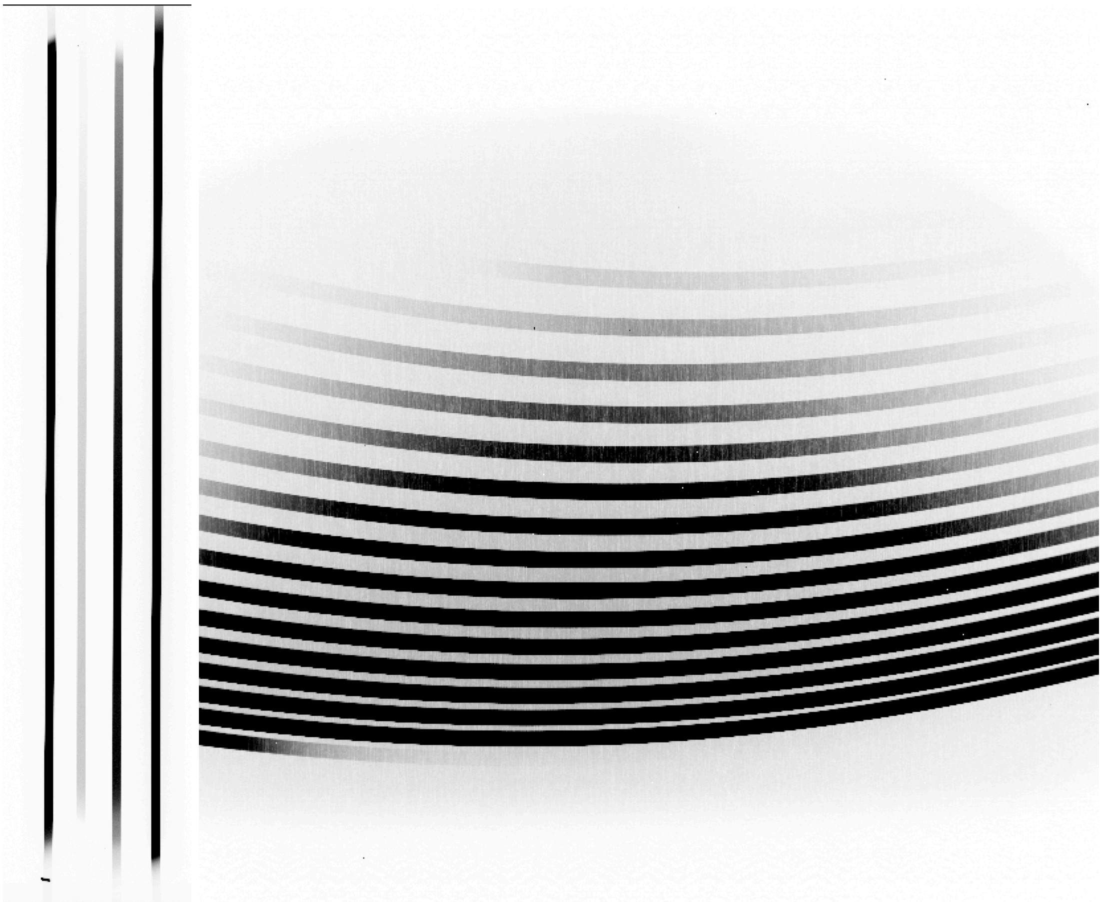

Figure 14: Example of UV-VIS (left) and NIR (right) halogen lamp (QTH) flat calibration frames. In the UV-VIS spectrograph, the orders are (from left to right): r, u, g, i.

Table 6: SOXS UV-VIS Quasi-Orders.

Quasi-order	Wavelength Range (nm)	Blaze wavelength (nm)
u	349.9 - 433.3	391.2
g	433.4 - 533.5	483.0
r	533.6 - 668.5	600.4
i	668.6 - 850.1	758.4

Table 7: SOXS NIR orders.

Order	Wavelength Range (nm)	Blaze wavelength (nm)
24	793.2 - 826.8	809.8
23	826.9 - 863.5	845.0
22	863.6 - 903.6	883.4
21	903.7 - 947.7	925.5
20	947.8 - 996.1	971.7
19	996.3 - 1049.9	1022.9
18	1050.0 - 1109.8	1079.7
17	1110.2 - 1176.8	1143.2
16	1177.3 - 1252.7	1214.6
15	1253.1 - 1338.8	1295.5
14	1339.2 - 1437.8	1388.0
13	1438.3 - 1552.4	1494.8
12	1553.0 - 1686.9	1619.3
11	1687.6 - 1846.8	1766.4
10	1847.7 - 2040.2	1943.0

3.3.2 Spectral resolution and sampling

The user can only affect the spectral resolution through the choice of the slit width (and, to some extent, with the binning in the spectral direction). The resolution and pixel sampling (without binning) as a function of the slit width are given in Tables 8 and 9 for the UV-VIS and NIR spectrographs, respectively.

Table 8: UV-VIS resolution as a function of the slit width.

Slit width (arcsec)	R (lambda/delta_lambda)	Sampling (pix/FWHM)
0.5	9200	1.8
1.0	5500	3.0
1.5	3500	4.8

Table 9: NIR resolution as a function of the slit width.

Slit width (arcsec)	R (lambda/delta_lambda)	Sampling (pix/FWHM)
0.5	12300	1.9
1.0	6800	3.4
1.5	4600	5.0

3.3.3 Overall sensitivity

The total efficiency has been measured on sky using several standard stars observed during commissioning. Based on these values, the expected limiting AB magnitudes at blaze wavelength in 1 hour for a S/N of 10 per spectral bin are given in Figure 15.

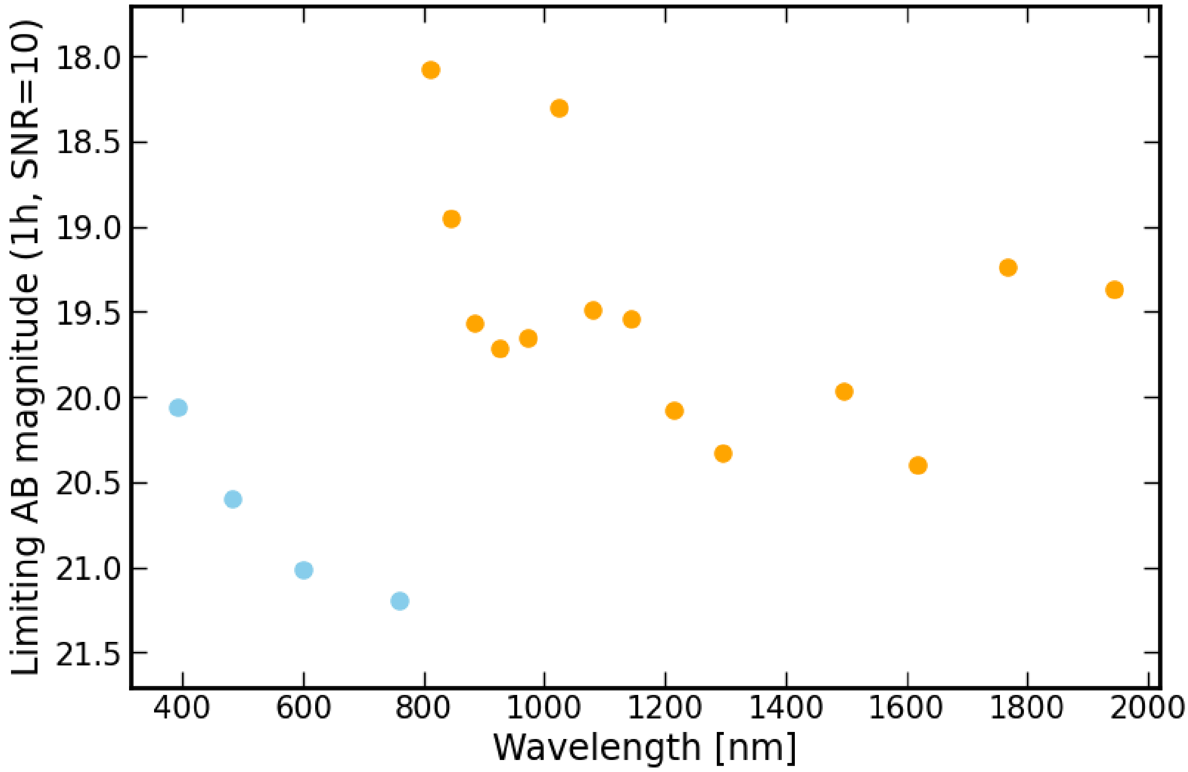

Figure 15: Limiting AB magnitude of SOXS at S/N=10 in a 1-hour exposure. Other parameters: airmass 1.2, 0.8" seeing, 3 days from new moon, 1" slit for both UV-VIS and NIR. The model uses the overall efficiencies measured during commissioning.

3.4 Instrument features and problems to be aware of

3.4.1 Persistence in the NIR

From tests carried out during commissioning, persistence effects are found in the NIR spectrograph. The persistence effect for a source with a brightness of ~ 25000 counts/pixel is reduced by a factor of > 1000 after 120 seconds, becoming negligible after ~300 seconds. Further characterisation of this effect for brighter sources is ongoing.

3.4.2 Spectrograph Flexures

For any rotator angle, the spectral format in both arms stays within ~ 12 and 4 pixels for the UV-VIS and NIR arm, respectively, from the zenith position. Considering the dispersion scales, this equals about 2.5 Angstrom in each arm.

4 Observing with SOXS

For science observations, SOXS can be used in imaging or spectroscopic mode. The spectral format is fixed. The two arms (UV-VIS and NIR) can operate in parallel. The user can select, for each arm independently, a slit width among those listed in Tables 8 and 9.
All SOXS science observing blocks (OB) are composed of an acquisition template followed by one or several science templates selected depending on the observing strategy chosen by the user.

4.1 Observing modes: Imaging

A simple imaging mode with limited functionalities, which uses the AC camera and its set of filters, is offered. Acquisition images can be used to flux calibrate spectra in addition to the usual spectrophotometric observations and to determine the magnitudes of transient objects. A minimal calibration plan is provided (Sect. 5.11), and no pipeline support is currently planned to be provided for the imaging data.
The AC zeropoints were determined during commissioning for each filter under photometric conditions (Table 10).

Table 10: Average photometric zeropoints measured for the AC camera filters during commissioning.

Filter	Mean Zeropoint (AB mag)
u	23.25 +/- 0.09
g	25.70 +/- 0.08
r	25.54 +/- 0.06
i	25.08 +/- 0.06
z	24.83 +/- 0.06

4.2 Observing modes: Spectroscopy

4.3 Target acquisition

The main steps of a typical target acquisition sequence are the following:
1. Preset the telescope to the target coordinates and set the adaptor-rotator to the chosen position angle.
2. The UV-VIS ADCs start tracking to compensate for atmospheric dispersion.
3. Commands are sent to the two tip-tilt mirrors based on the flexures lookup table.
4. The AC slide is set to the acquisition position: the field is now visible in the acquisition camera, and an acquisition image can be acquired.
5. The spectroscopic target is identified (or the reference object in case of blind offset)
and its coordinates on the detector are determined by a centering algorithm.

6. The telescope is offset to the reference pixel on the detector, corresponding to the position of the image in the AC reference pinhole.
7. When the observer is satisfied with the object centering, an acquisition image is saved, and the AC slide is set to the spectroscopic observation position.
8. In case of a blind offset, the offsets are applied. Another image is saved after the offset.

This acquisition sequence is performed by the acquisition template, *SOXS_slt_acq*.

4.4 Spectroscopic observations

SOXS science templates support different observing strategies: staring (commonly used for UV-VIS observations), nodding along the slit (classical near-IR observations), offsetting to a fixed sky position (for extended objects) or letting the user free to choose any sequence of offsets (e.g. for mapping). Effects of the atmospheric dispersion are automatically corrected in the UV-VIS arm thanks to the two ADCs.

4.4.1 Staring

With the *SOXS_slt_obs_Stare* template, one or more spectra are taken with each arm independently at a fixed position on sky. For each arm, the user chooses the exposure time and the number of exposures. Exposures are completely asynchronous, i.e. in each arm, whenever an exposure is finished, the next one starts immediately, independently of what is happening with the other arms.

4.4.2 Staring synchronised

Whenever exposures in the two arms have to be parallel, the template *SOXS_slt_obs_StareSynchro* should be used. In this case, the number of exposures is fixed to one per arm. Exposure times can still be different in each arm, but the exposures are synchronised to their mid-time. In case the exposure times in both arms are identical, exposures in the two arms will have the same start time within approximately one second. In case of different exposure times, the mid-exposure time of the two will coincide within about one second. Synchronised exposures might represent the preferred choice when observing science targets characterised by variability over time scales comparable with the chosen exposure time.

4.4.3 Nodding along the slit

This corresponds to the standard way of observing in the NIR, primarily aimed at a double pass sky subtraction. The template *SOXS_slt_obs_AutoNodOnSlit* automatically nods the telescope between two positions (A and B) along the slit. The user defines a Nod Throw and optionally a small jitter box (in the slit direction). The Nod Throw is defined as the distance between the two nodding positions, i.e. the centre of the two jitter boxes inside the slit (see Figure 16). One cycle is a pair of AB or BA observations. Cycles are repeated in ABBA sequences. For each arm, the user chooses the number of exposures at each position and the exposure time (both identical for all A and B positions). Exposures are asynchronous.

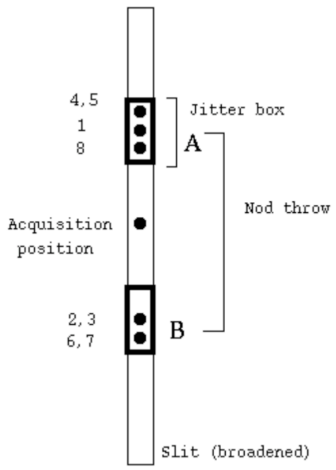

Figure 16: Conventions used for nodding along slit observations. The sequence illustrated here corresponds to 4 cycles (8 exposures, ABBAABBA) with a non-zero jitter box.

4.4.4 Fixed offset to sky

When observing extended objects for which there is no or not enough pure sky in the 12” slit to perform a good sky subtraction, one should use the template *SOXS_slt_obs_FixedSkyOffset*. It allows alternating between an object (O) and sky position (S), with the possibility of adding a small jittering around the object and the sky position. One cycle is a pair of OS or SO observations. Cycles are repeated in OSSO sequences. For each arm, the user chooses the number of exposures taken at each position and the exposure time (both identical for all A and B positions). Exposures are asynchronous.

4.4.5 Generic offset

The *SOXS_slt_obs_GenericOffset* template allows the user to define any pattern by providing a list of (cumulative) telescope offsets. This is particularly useful in case one wants to map on an object with several slit positions. The number of exposures taken at each position and the exposure time (both identical at all positions) have to be defined. Exposures are asynchronous.

4.5 Instrument and telescope overheads

4.5.1 Summary of telescope and instrument overheads

Table 11: SOXS overheads

Acquisition and setup	
Telescope pointing, guide star acquisition, flexure measurement.	210s
AC detector readout	21s
Interactive acquisition loop	120s
Instrument setup at the end of the acquisition	30s
Observations	
UV-VIS detector readout	1x1 slow / fast: 25s / 17s 2x1 slow / fast: 19s / 14s 2x2 slow / fast: 10s / 8s
NIR detector readout	5s
Each telescope offset	15s

4.5.2 Example of execution time computation

Below is a generic example of how total execution time shall be estimated, taking into account the overheads reported in Table 11. For a nod on the slit sequence with:

- 1 acquisition image (exposure time: 1s, readout time: 21s)
- 1 cycle (AB sequence)
- 1 UV-VIS and 2 NIR exposures per position
- integration times 900s in UV-VIS in 1x1 slow, and 450 in NIR

the total execution time splits as follows:

- Pointing / acquisition / SLIT setup: 232s + 120s + 30s = 382s

At each position, the total integration and readout time per arm is:

- UV-VIS: 1x(900+25) = 925s
- NIR: 2x(450+5) = 910s

With the two arms operating in parallel, the total time spent at each position is given by the slowest arm, in this case, the UV-VIS one: 925s. So the total integration and readout time is 2x925s=1850s

Total telescope offsets: 2x15 = 30s

So, the total execution time for this observing block is: 382s + 1850s + 30s = 2262s

5 Calibrating and reducing SOXS data

5.1 SOXS calibration plan

The calibration plan of SOXS is described in detail in document [RD 1]. A summary is given in Table 12 for the spectroscopic calibrations and in Table 13 for the imaging calibrations.

Table 12: SOXS calibration plan summary for spectroscopic observations.

Calibration	UV-VIS frames	NIR frames	Frequency	Purpose
Bias	5/read mode		daily	Master bias and CCD properties
NIR darks		5 per DIT: 2s, 5s, 10s, 15s	daily	Master dark, bad pixels map
Slit flat	20/setting	20/setting	daily	Pixel-to-pixel variations, blaze function correction
Arcs single pinhole	1	1	daily	First guess disp. solution
Flat single pinhole	1	1	daily	Order localization
Arcs multi-pinhole	1	1	daily	Wavelength and spatial scale determination.
Arcs Through slit	1/setting	1/setting	daily	Wavelength shift between multi-pinholes and slits, spectral resolution
Radial velocity standard	1	1	On request	Accurate radial vel. calibration
Telluric standard	2	2	On request	Correct for telluric abs.
Spectrophotometric standard	2	2	daily	Response curve, absolute flux calib.

Table 13: SOXS calibration plan summary for imaging observations.

Calibration	AC frames	Frequency	Purpose
Bias	10	daily	Master bias and check CCD bias properties
Sky flats	3/filter	Monthly (or on request)	Pixel-to-pixel response variation
Photometric standards	2	On request	Absolute flux calibration

5.2 Wavelength and spatial scale calibration

As described in sections 3.3.1, the spectral format of SOXS is relatively complex with curved orders (NIR), variable line tilt (UV-VIS and NIR), dispersion and spatial scale along each order (UV-VIS and NIR). Using just long slit arc spectra is not sufficient because it is essential to also calibrate the change of spatial scale.

Wavelength and spatial scale are well calibrated simultaneously with a dedicated mask of 9 equidistant pinholes present in each slit unit, in combination with the ThAr lamp. Exposure time for each arm is given in Table 14. An example of such frames is given in Figure 17. The templates used for this calibration are *SOXS_slt_cal_VISArcsMultiplePinhole* and *SOXS_slt_cal_NIRArcsMultiplePinhole.*

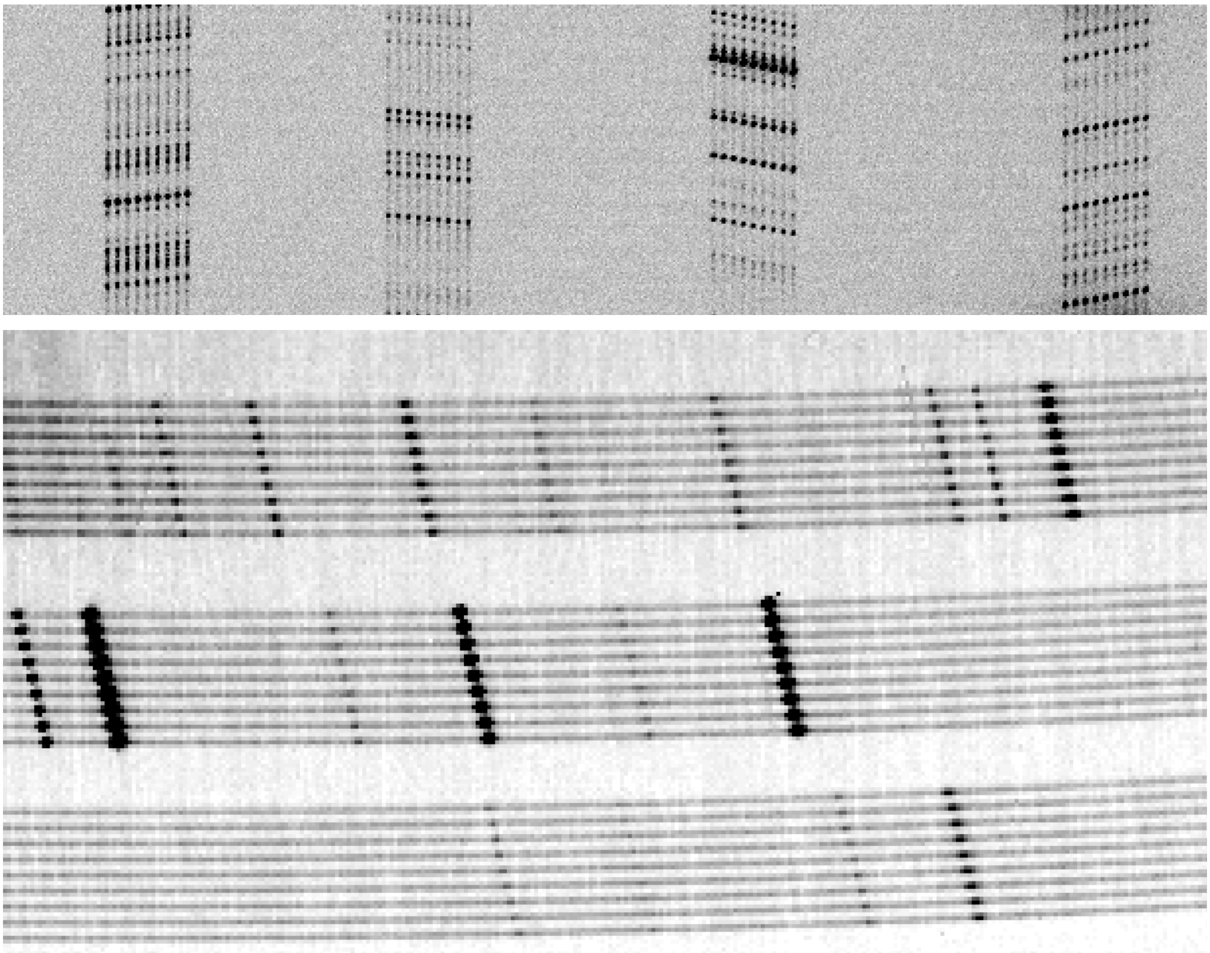

Figure 17: Portion of the 9-pinhole ThAR VIS (top) and NIR (bottom) frame.

Table 14: exposure times for the ThAr (UV-VIS) and ArHgNeXe (NIR) arc frames.

UV-VIS	NIR
Slit 0.5” 20s	Slit 0.5” 5s
Slit 1.0” 15s	Slit 1.0” 4s
Slit 1.5” 10s	Slit 1.5” 3s
Pinhole 30s	Pinhole 15s
9-pinhole 30s	9-pinhole 15s

5.3 Flat-field

Flatfield spectra allow correction for the pixel-to-pixel variations in detector sensitivity as a function of wavelength of the light, and to correct for the structures introduced by imperfections of the slits. They also provide a good correction of the blaze function of the echelle.

For each arm, a dedicated halogen lamp with appropriate balancing filters is available to give well-exposed, flat continuum spectra at all wavelengths within a reasonably short exposure time (see Table 15).

Table 15: exposure times for the halogen flat field frames.

UV-VIS	NIR
Slit 0.5” 20s	Slit 0.5” 7.5s
Slit 1.0” 10s	Slit 1.0” 3.75s
Slit 1.5” 7s	Slit 1.5” 2.5s
Pinhole 10s	Pinhole 10s
9-pinhole 10s	9-pinhole 10s

5.4 Spectrophotometric calibration

5.4.1 Telluric absorption correction

The visible-red and the near-IR part of the spectrum are strongly affected by the absorption lines of the Earth’s atmosphere. Many of these telluric lines do not scale linearly with airmass, so it is necessary to observe a star with a well-known spectrum at the same airmass and with the same instrument setup as that used for the science target. Furthermore, the strength of the telluric lines varies with time, so it is also necessary to observe the telluric standard soon after or soon before the science observation. Two templates are designed for this purpose: *SOXS_slt_cal_TelluricStdNod, SOXS_slt_cal_TelluricStdStare*.

However, after a first period of commissioning and testing, routine telluric correction will be carried out with dedicated software packages (e.g. *MolecFit*[2]).

5.4.2 Absolute flux calibration

Spectrophotometric standard stars can be used to obtain the absolute efficiency of the instrument and derive an absolute flux calibration of the science data. These observations

[2] https://www.eso.org/sci/software/pipelines/skytools/molecfit

are done with the wide 5.0” slit with the dedicated templates *SOXS_slt_cal_SpecphotStdNod, SOXS_slt_cal_SpecphotStdStare*.

The set of spectrophotometric standard stars used for the same purpose with the ESO X-shooter spectrograph[3] is perfectly suitable for SOXS, covering the same spectral range.

5.4.3 The SOXS pipeline

The SOXS data reduction pipeline[4] [RD 2] is being developed and tested. It is expected to be fully ready by the start of operations. It will deliver the following products:

- Sky subtracted, cosmic ray hits cleaned, flux and wavelength calibrated 2D spectra, rectified to a regular grid in wavelength and spatial directions. 1D extracted spectra will be produced whenever a bright enough object is detected.
- Additional products to verify the quality of the results, a set of Quality Control parameters, an instrument health check and trend analysis.

6 Reference material

6.1 Templates reference

In the following sections, all the currently defined SOXS templates are listed with their free and fixed parameters. When using the p2ls[5] tool, the user has to fill only the fields (keywords) shown on a white background in the following tables. Keywords shown on a grey background colour are fixed within the template itself and can only be modified by the astronomer operating the instrument during the night or during daytime calibration activities.

6.1.1 Orientation and conventions

SOXS follows the standard astronomical orientation and offset conventions and definition.
The positive position angle (PA) is defined from North to East. Offsets are always given in arc seconds, but the reference system can be chosen to be the sky (Alpha, Delta) or the SOXS slit coordinate system (X, Y). As can be seen from Fig. 18, an offset of 90 deg - PA must be applied to position the slit along a given position angle. The slit can be aligned along the parallactic angle (calculated at the start of the OB) automatically by specifying a value of 9999 for the Rotator Offset Angle in the acquisition templates.

[3] https://www.eso.org/sci/facilities/paranal/instruments/xshooter/tools/specphot_list.html
[4] https://soxspipe.readthedocs.io/en/main/
[5] https://www.eso.org/p2ls/home

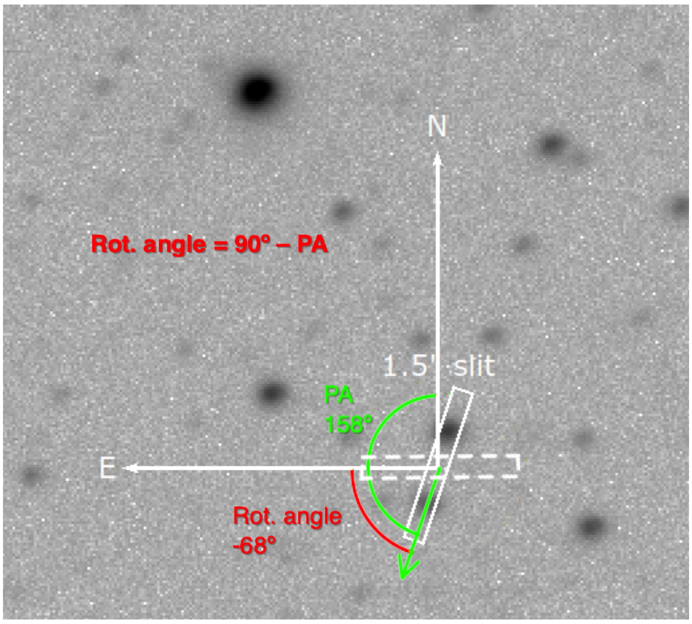

Figure 18: The slit coordinate system. A positive offset in the x or y direction will move the object in the direction of the +x or +y axis.

Templates use cumulative offsets: the position at a given time is derived from the sum of all offsets specified so far in the template. For example, the series of offsets: 0, -10, 0, 10 brings the telescope back to the original position for the last exposure. This example could have been, for instance, the definition of a series in which we define an exposure on an object, followed by two sky exposures at -10" of the original position, before pointing back on the object for the fourth exposure.

NOTE: *from here on, a list with all the templates' descriptions will be provided (**TBD**). These are **already** available in the document SOXS-MAN-0001 [RD 3].*

6.1.2 Acquisition templates

6.1.3 Science templates

6.1.4 Daytime calibration templates

6.1.5 Night-time calibration templates

6.2 Detector QE curves

TBD

6.3 Acquisition Camera filter curves

TBD