NIX, the Imager for ERIS: the AO Instrument for the VLT

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ABSTRACT

ERIS will be the next-generation AO facility on the VLT, combining the heritage of NACO imaging, with the spectroscopic capabilities of an upgraded SINFONI. Here we report on the all-new NIX imager that will deliver diffraction-limited imaging from the J to M band. The instrument will be equipped with both Apodizing Phase Plates and Sparse Aperture Masks to provide high-angular resolution imagery, especially suited for exoplanet imaging and characterization. This paper provides detail on the instrument's design and how it is suited to address a broad range of science cases, from detailed studies of the galactic centre at the highest resolutions, to studying detailed resolved stellar populations.

Keywords: ERIS, NIX, VLT, Imager, Adaptive Optics, Sparse Aperture Mask, Apodized Phase Plate, Focal Plane Coronagraphy, Slit Mask Spectroscopy

1. INTRODUCTION

The Enhanced Resolution Imager and Spectrograph (ERIS) instrument for the VLT will provide diffraction limited imaging and spectral observations of individual targets, utilizing a new Adaptive Optics (AO) module. The instrument will be mounted on UT-4 at the VLT in Paranal, Chile, in early 2020. ERIS will replace the near- and mid- infrared imaging and spectrographic capabilities currently provided by NACO[1,2] and SINFONI[3]. These two instruments are now working beyond their design lifetimes and the arrival of ERIS will ensure that the VLT remains at the forefront of AO imaging and spectroscopy into the next decade.

The imaging instrument on ERIS is called NIX and is the focus of this paper. NIX will share many properties with NACO, allowing a continuation of the excellent science NACO has delivered. The design of NIX is complemented by the upgrade of the SINFONI spectrograph from SPIFFI to SPIFFIER[4]. Both NIX and SPIFFIER will be fed by a new common AO module[5] that uses visible wavefront sensors and the deformable secondary mirror of UT-4, which forms part of the Adaptive Optics Facility (AOF). Observations will be possible with natural guide stars and/or a single laser guide star. Both NIX and SPIFFIER will be supported by a dedicated calibration unit[6] mounted within the ERIS instrument.

NIX will offer a suite of cutting-edge imaging techniques, described in Section 3, for J – M bands over two plate scales.

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The NIX cryostat vessel houses a Teledyne HAWAII-2RG™ 5 µm cutoff detector, which is cooled to 40 K using a closed cycle cooler. It is controlled using the latest Beckhoff PLC hardware and will have a dedicated software pipeline.

The ERIS project is being led by the Max Planck Institute for Extraterrestrial Physics (MPE) in Garching, Munich, under an agreement with the European Southern Observatory (ESO). The NIX sub-system is being designed, assembled and tested at the UK Astronomy Technology Centre (UKATC), with two of its cryogenic sub-assemblies being delivered by the Institute for Astronomy at ETH Zürich.

NIX has recently passed its Preliminary Design Review at ESO and is progressing to its Final Design Review. While the design is relatively mature it should be noted that some of the details presented below could change prior to first light.

2. NIX SCIENTIFIC OBJECTIVES

ERIS is a highly versatile instrument, offering a range of observing modes that will provide both diffraction-limited imaging and spectrographic capabilities at the VLT. As such it will be a competitive instrument in a diverse range of astronomical disciplines, while also complementing numerous existing ESO facilities. Clearly there will be great complementarity between NIX and SPIFFIER and numerous science cases will utilize both aspects of the instrument, but the following section highlights three areas where NIX would be expected to make significant contributions.

2.1 Detection and characterization of exoplanets

Longer wavelength observations are known to considerably enhance the study of exoplanets. In the L- and M- band the relative intensity of the host star compared to the planet is often considerably reduced, making direct imaging of the planets correspondingly more achievable. While this has provided an excellent method of simply detecting exoplanets, it also offers the possibility to better characterize the atmospheres of gas giant exoplanets by complementing their SEDs with 3-5 micron data[7]. In this respect NIX will build on the tremendous success of shorter wavelength instruments such as SPHERE[8] and GPI[9]. Recent studies have shown that the addition of the L- and M- bands might be critical for understanding the cloud properties in the exoplanet atmospheres[10].

To fully utilize these longer wavelengths and to take full advantage of the diffraction limited PSFs delivered by the AO system, NIX will be equipped with the latest high-contrast imaging techniques: i.e. various coronagraphic options and Sparse Aperture Masking (SAM). Combined with templates for appropriate angular differential imaging techniques, these observing modes will make NIX one of the most important exoplanet instruments in the next decade.

2.2 The galactic centre

The high spatial resolution of NIX allows extremely small spatial scales to be probed around the supermassive black hole at the centre of our galaxy (50 mas resolution is equivalent to 0.002 pc at the galactic centre). Numerous discoveries have been made through astrometric imaging of the galactic centre, including the differing spatial distributions of late types stars, early stars, and Wolf-Rayet stars, as well as the various 3D orbital structures they trace[11]. Frequent and regular monitoring of the orbits of the stars closest to Sgr A* at unprecedented precision for more than two decades has provided exquisite constraints on both the mass of and distance to the supermassive black hole.

The relatively recent discovery of a gas cloud falling towards Sgr A*, and the tracking of its subsequent tidal disruption have led to enormous excitement and numerous theories about what it is and where it has come from. This has not been detected at shorter wavelengths, but is visible in the L-band, allowing strong constraints on the dust temperature[12]. This clearly highlights the need for continued L-band imaging at the VLT, as NIX will have a good chance of observing future unexpected and serendipitous events like this that will reveal a great deal about the evolution of galaxy nuclei and accretion processes onto black holes.

2.3 Resolved Stellar populations

The technique of resolved stellar populations is one for which the high performance adaptive optics of ERIS is ideally suited: AO vastly improves sensitivity for stellar point sources, especially in crowded fields where spatial resolution is the limiting factor. Imaging over the reasonably large field offered by NIX will allow the construction of deep and accurate color magnitude diagrams that will provide a census of the stellar population in different environments. Such observations would allow NIX to address questions relating to difference in star formation histories between globular clusters and local dwarf galaxies, thus acting as a probe on the early universe ('local cosmology') and to understand the formation and evolution of the Galactic spheroid.

3. NIX INSTRUMENT OVERVIEW

3.1 System performance

The primary function of the NIX instrument is to provide imaging capability at wavelengths of 1.1 to 5.1um (J, H, K, L and M bands) over a 24 x 24 and a 53 x 53 arcsec field of view. The top level performance requirements are detailed in Table 1. Note that the Focal Plane Coronagraphy and the Long Slit Spectroscopy are not yet fully confirmed modes and are being investigated to determine the performance that can be expected for the instrument.

Table 1. NIX top-level performance requirements

Property	**Requirement**
Wavelength range	J- to M- band
Image quality	>68% Strehl in K-band, on-axis, visible NGS AO sensing at M_R=8 >54% Strehl in K-band, on-axis, Na LGS + visible on axis TT ref-star at M_R=12
Fields of View	24 x 24 arcsec and 53 x 53 arcsec
Pixel scales	13 mas/pixel and 27 mas/pixel
Modes (*Provisional)	Imaging, Apodized Phase Plate coronagraphy, Sparse Aperture Masking, Long Slit Spectroscopy*, Focal Plane coronagraphy*

3.2 Operating modes

The instrument also contains a variety of aperture masks, filters and pupil masks, which can be combined to offer a wide variety of different operating modes. These modes have been carefully chosen based on their ability to deliver on the ERIS scientific objectives described above. A full list of the operating modes and their associated optical elements is given in Table 2.

Table 2. NIX observing modes

Mode	**FoV** (arcsec)	**Resolution** (mas/pix)	**Filter options**
'Short' imaging	24 x 24	13	J, H, Ks, IB 2.42, IB 2.48, [Fe-II], HS 1-0S(1), H2 cont, Br-g
	53 x 53	27	J, H, Ks, IB 2.42, IB 2.48, [Fe-II], HS 1-0S(1), H2 cont, Br-g
'Long' imaging	24 x 24	13	Short L', L', M', Br-a cont, Br-a
Apodized Phase Plate	24 x 24	13	Short L', L', M'
Sparse Aperture Mask	24 x 24	13	SAM_J, SAM_H, SAM_K
	24 x 24	13	SAM_L
Long Slit Spectroscopy	12 x 86 mas	13	Approximately L band
Focal Plane Coronagraphy	24 x 24	13	Short L', L', M'

3.3 System architecture

NIX is split up into eight sub-systems as shown in Figure 1. The figure shows the interfaces and data flows between the NIX sub-systems and also between NIX and the rest of ERIS and the telescope. The UKATC has overall responsibility for NIX but the Aperture Wheel and Pupil & Filter Wheel are sub-contracted to ETH Zürich and the NIX IR Detector Assembly is sub-contracted to the ESO Detector Group.

Light enters NIX via the NIX selector mirror. This selector mirror is part of the ERIS system and, when deployed, directs the light from UT4 into the NIX imager instead of the SPIFFIER spectrograph. Inside NIX the light passes through the Aperture Wheel, Camera Wheel, Pupil & Filter Wheels and the Imager Selection Unit, which are configured according to the selected observing mode (Table 2). The light is then detected by a Teledyne HAWAII-2RG™ 5 µm cutoff detector which is read out using the standard ESO NGC controller. The resulting image frames are passed onto the ERIS operating system for subsequent storage and data reduction. A detector focus stage is included primarily for use during Assembly, Integration and Verification (AIV) but can also be used to correct for any focus adjustments needed to accommodate the various observing modes. The Image Selector Unit has a position which allows the NIX pupil to be imaged on the detector. This is primarily for use during AIV but may also be useful for alignment purposes in the Focal Plane Coronagraphy mode.

The NIX Instrument Control System provides the electronics and software for mechanism and cryo-vacuum control and monitoring. It also includes a Data Reduction Library for use with the NIX data. The NIX Infrastructure provides the necessary mechanical, cryogenic and vacuum support for the other NIX sub-systems.

NIX can be removed from the ERIS system using a dedicated handling frame. This frame will be compatible with the NIX alignment telescope and independent alignment source, thereby allowing potential future instrument modifications and alignment procedures to be performed in any location with suitable cryostat support facilities.

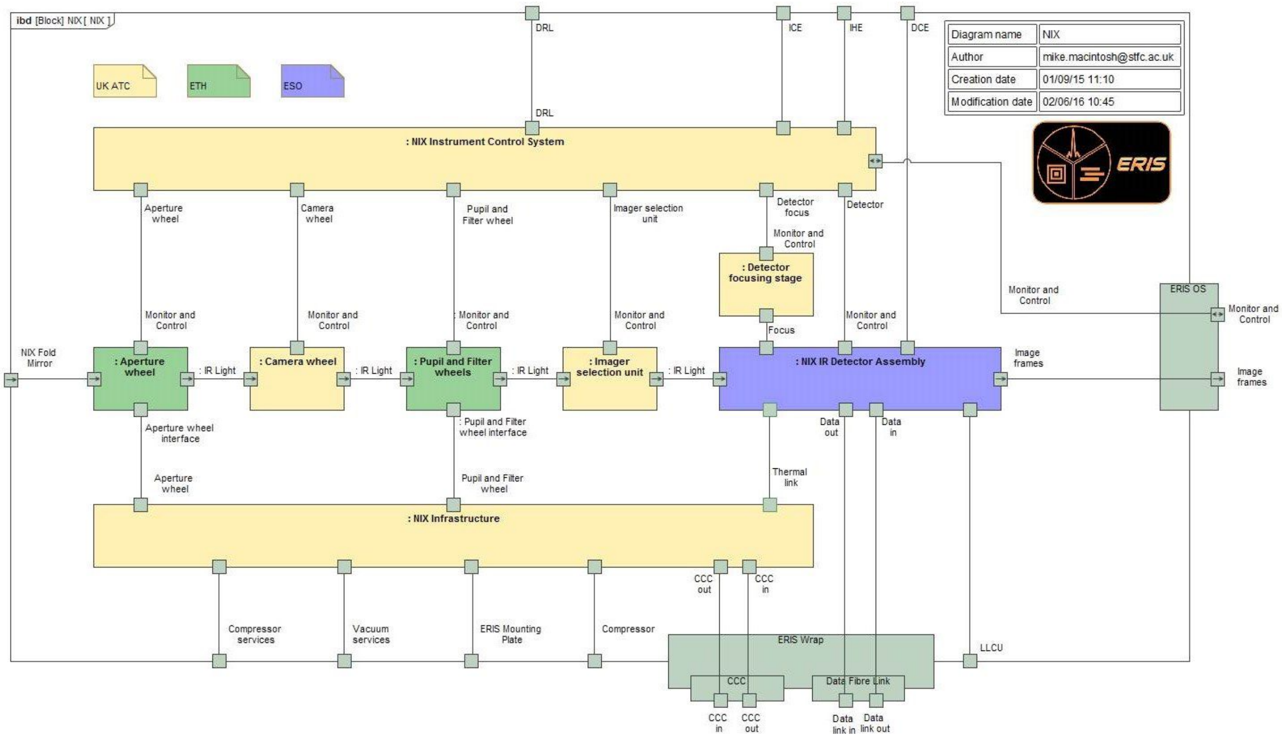

Figure 1: NIX System Architecture

4. OPTICAL DESIGN

The NIX optical system contains three camera assemblies that each form an image on a Teledyne HAWAII-2RG™ 5 µm cutoff detector. The cameras provide imaging of JHK and LM bands at 13 mas/pixel, and JHK bands at 27 mas/pixel. The optical design accommodates a variety of masks and filters to be used at the focal and pupil planes, which allow NIX to provide the large selection of operating modes listed in Table 2.

Figure 2 shows the full optical layout of NIX. Light enters NIX through the cryostat window (Calcium Fluoride). The window is situated a small distance before the telescope focal plane. At this focal plane a field stop (aperture mask) is located. Different field stops are required for the different plate scales; these are interchangeable by means of a deployment mechanism (see Section 5.1).

The light beam then passes through a set of camera lenses. The lenses for the three cameras are mounted in a camera barrel mechanism and are interchangeable. The camera designs are optimized to use the minimum number of elements, thereby maximizing throughput, while being as axially compact as possible. Each camera consists of three lenses. The camera lenses are fabricated from Barium Fluoride, IRG2 and Zinc Selenide. All the lenses have spherical surfaces with the exception of one aspheric (conic) surface in the JHK 27mas camera.

From the camera lens barrel the light beam then passes through a set of filters and pupil masks. Different components are used for different observations and these are exchangeable via a deployment mechanism; the Pupil and Filter Wheel mechanism (PFW). This mechanism contains two wheels in a single housing and each wheel provides 18 slots for optical elements. The 8 mm thick Calcium Fluoride filters are primarily in the first wheel, but can be placed in the second wheel if required. The pupil masks needed for the various operating modes are located in the second wheel. The pupil plane lies at the first surface of the pupil wheel. The filters are required to be tilted by ~2° to reduce ghost imaging, but this does not affect the optical imaging performance.

A set of fold mirrors then bring the beam to a focus on the detector. In the 27 mas/pixel scale a deployable fold mirror folds the beam through 90° directly onto the detector. For the two 13 mas/pixel scales, a series of two fold mirrors are required in order to accommodate the longer back focal length. The detector array has an adjustable focus position.

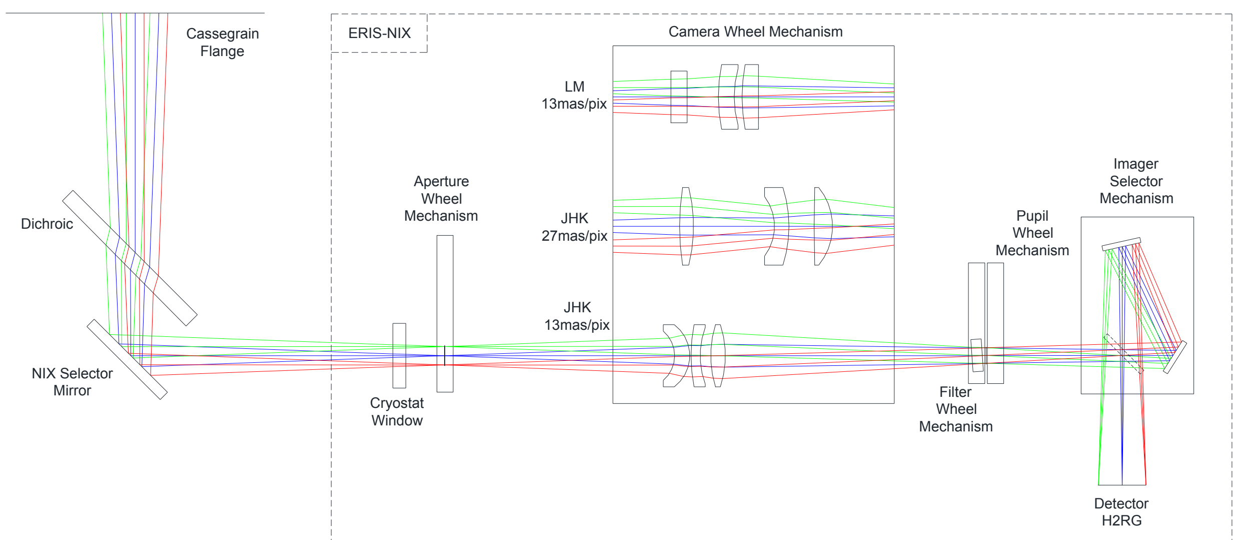

Figure 2: NIX optical layout

5. MECHANICAL DESIGN

The NIX imager is a stand-alone sub-system of the ERIS instrument. It has its own vacuum, cooling and electrical hardware and operates independently of SPIFFIER.

Figure 3 shows the NIX cryostat in its operating configuration. The NIX vacuum vessel is constructed in three parts; it has a central base, a removable lid and a service panel. All of the optical hardware is mounted to the central base, which also forms the interface with ERIS. The instrument can be adjusted in six-degrees of freedom with respect to its ERIS interface to enable precise alignment with the ERIS Calibration Unit[6] and AO sub-system[5]. Access to the NIX optical sub-assemblies is achieved by removing the semi-cylindrical lid, while all the vacuum, cooling and electrical connections are accessed through the lower service panel.

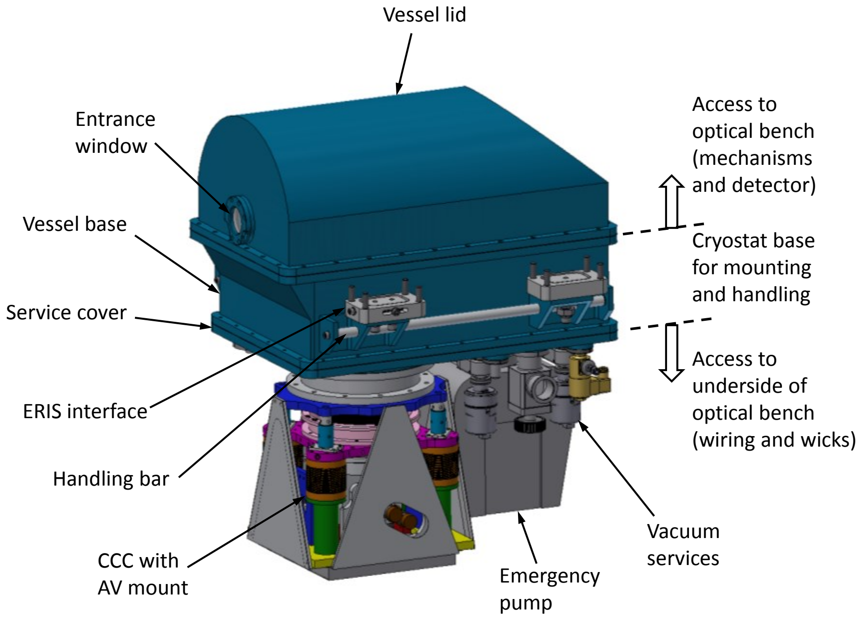

Figure 3. NIX cryostat overview

5.1 Opto-mechanical sub-assemblies

The optical layout of NIX, described above in Section 4, requires five sub-assemblies that operate at a baseline temperature of 80 K. Figure 4 shows all the optical sub-assemblies positioned on the NIX optical bench with the vacuum vessel lid and radiation shield removed. Each of the NIX mechanisms is able to be installed, adjusted or removed without disturbing any of the other mechanisms. This is an important practicality for the alignment process. Furthermore, each mechanism housing will be adjustable in six degrees of freedom to ensure that any unforeseen problems in the final alignment can be accommodated during instrument testing and verification.

Four of the optical sub-assemblies contain rotating-wheel mechanisms that are operated using custom worm gears driven by a stepper motor. The worm gear arrangement was chosen because it is a simple and compact way of producing the required movement resolution at the wheels without the need for more complex gearboxes that likely require lubrication. This is a configuration that has a long heritage of successful cryogenic operation in instrumentation designed at the UKATC. The fifth sub-assembly contains a linear translation mechanism for the detector that allows it to be adjusted in focus. This mechanism is operated using a stepper motor and lead screw arrangement, with a set of four G10 flexures that act as a linear guide.

Three of the rotary mechanisms are contained in the Aperture Wheel and Pupil Filter Wheel sub-assemblies. These two sub-assemblies are designed, manufactured and tested by the Institute of Astronomy at ETH Zürich. They contain all the specialized filters and masks required for the science modes listed in Table 2. Each of the three wheels is independently operated, and each of the optical elements is designed for easy removal and maximum interchangeability. This provides

NIX with a highly configurable and versatile optical system that can be modified to suit new and evolving scientific objectives throughout the operational lifetime of the instrument.

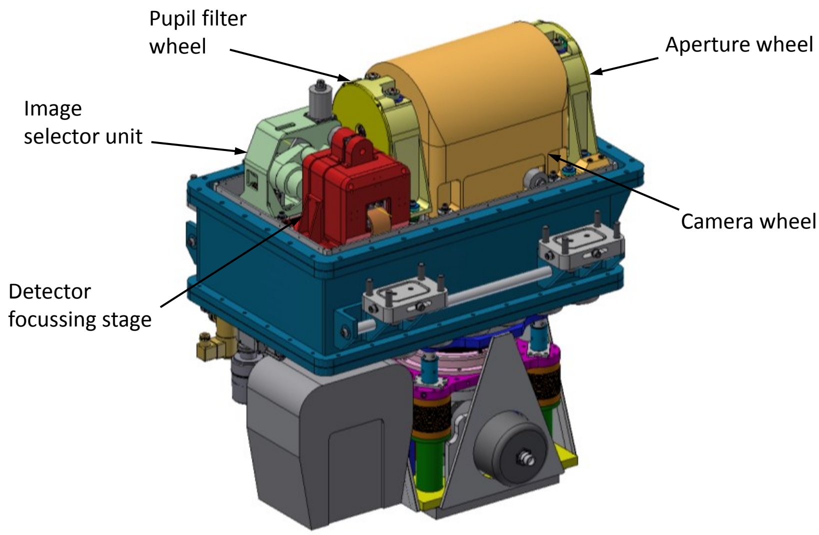

Figure 4. NIX optical sub-assemblies

5.2 Vacuum and cooling systems

The NIX vacuum system is compatible with the facilities at the VLT and is designed to be compliant with ESO best practice. It contains a dedicated emergency pump to prevent damage to the detector in case of an unexpected rise in pressure and it has two wide-range pressure gauges that offer system redundancy. Figure 5 shows a schmatic diagram of the vacuum system layout.

Although NIX does not share cryovacuum components with SPIFFIER, it does share the same supervisory control electronics. The cryo-vacuum supervisory control electronics are designed by MPE using a Siemens S7-1500 PLC.

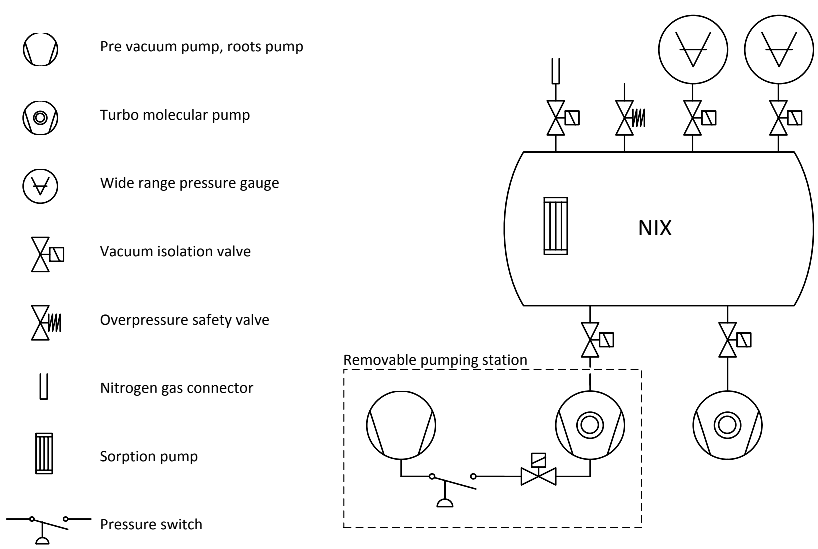

Figure 5. NIX vacuum system layout

The NIX cryostat is cooled using a Leybold 10MD closed cycle cooler (CCC). This cooler was chosen for its high reliablilty, proven performance characteristics and familiarity of operation. It is required to cool the detector assembly to 40 K and all the other optical sub-assemblies to 80 K.

A design consideration in the use of CCCs is that their operation always produces vibration at some level. The Adaptive Optics sub-system of the ERIS instrument is particularly sensitive to vibration and so every effort must be made to isolate the CCC from the NIX vessel (and therefore from the rest of the ERIS sub-systems). A detailed comparison of the vibration levels of five CCCs[13] concluded the Leybold 10 MD was the most suitable cooler for use on VLT instrumentation.

A vibration isolation system for the Leybold 10MD has been developed at the UKATC for use on KMOS[14] and is currently in operation on the VLT. Figure 6 shows the KMOS anti-vibration mount that will also be used on NIX. It uses a balanced-pressure approach in which the vaccum load on the cryocooler is balanced by an equal area of vaccum pressure behind the cooler via four bellows. The equalisation of pressure forces at the cooler flange means that it can be suspended using weak springs and provide vibration isolation in six degrees of freedom.

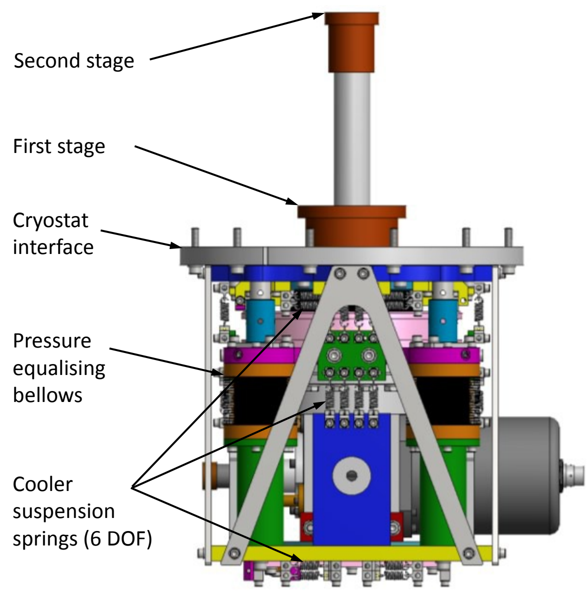

Figure 6. Anti-vibration mount for the 10MD closed cycle cooler

6. ELECTRONIC DESIGN

Internally within NIX, all electrical connections from the optical sub-assemblies will be terminated on the lower radiation shield with a bulkhead connection. This connection ensures the cables are cold-soaked at the radiation shield temperature, and it also provides a useful interface from which the cables can be routed to the vacuum vessel walls. On the outside of the radiation shield it is typical to have long cable lengths to minimize the inter-cable heat conduction losses. These long cable lengths will be wound around the G10 drum before being routed through the cryostat wall using a vacuum compatible connector.

Seven feedthroughs are provided by NIX. Six for the individual NIX optical sub-assemblies and the seventh for cryo-vacuum control functions. NIX uses commercial ultra-high vacuum specified KF flange-mounted 32 pin MIL-C-26482 connectors.

All optical sub-assemblies are designed to use the same commercial parts, such as stepper motors, resolvers and limit / datum switches, to reduce the number of spares required. Phytron 32 mm two-phase stepper motors have been chosen to drive the mechanisms. These motors are specified for operation in ultra-high vacuum and for winding temperatures down to 73 K. The mechanisms will use Marquardt Series 1010 snap action switches for position indexing and a LTN RE-10-1 resolver is mounted on the rear motor shaft to provide additional feedback of the mechanism position. Due to the long heritage at the UKATC of successfully using open loop mechanisms, closed loop is not implemented using the resolver.

The mechanisms are controlled by ESO standard Beckhoff modules using the ES7041-0000 module[15]. The resolver analogue signals are converted to a 24V digital signal by a G-REC incremental interpolator from LTN.

Externally from NIX the electronics are held within cabinets mounted on the structure of ERIS. Providing this local racking reduces cable lengths and prevents extensive alterations to the Cassegrain wrap. The Cassegrain wrap requires only the addition of the CCC helium lines and remote PROFINET data bus for remote monitoring and control of the CCC compressor by the ERIS cryo-vacuum system.

7. SOFTWARE AND PIPELINE

7.1 Instrument Control System

NIX Instrument Control Software (ICS) will run on the ERIS supplied Instrument Work Station (WS). The NIX ICS will be compatible with the ERIS Instrumentation Software Requirements and Functional Specifications. The design of NIX is based on ESO VLT standard ICS approach. It will control the NIX NGC IR detector and several FieldBus devices connected via PLCs. Figure 7 shows an overview of the NIX ICS architecture, with all the major interfaces and components identified.

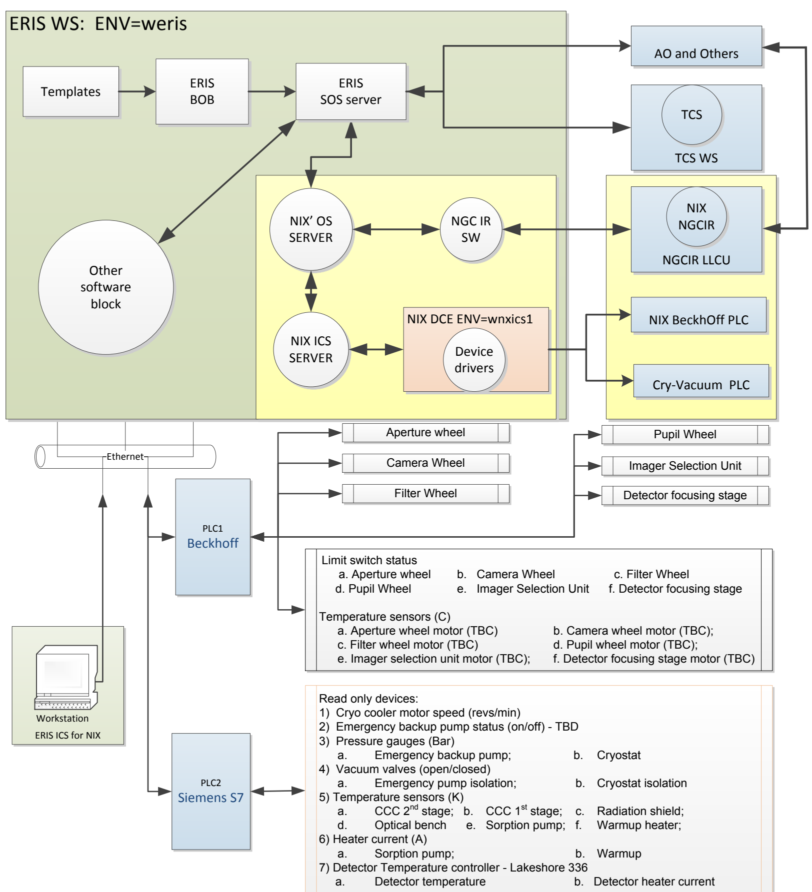

Figure 7. NIX Instrument Control System overview

7.2 Data reduction pipeline

The data reduction pipeline will be used to produce calibration products (e.g. master darks and flats), data quality control metrics for the monitoring of instrument performance (e.g. number of bad pixels, image Strehl ratios), and calibrated science products for the main instrument modes (jitter imaging and grism spectroscopy). Data reduction for the more specialist operating modes, namely the APP (Apodized Phase Plate), SAM (Sparse Aperture Masking) and Focal Plane Coronagraphy, will be limited to the basic steps of dark subtraction and flat-fielding.

Following VLT practice the raw data will be stored as a set of FITS files, each self-described via header keywords. The reduction pipelines will be executed automatically at the telescope, and can be rerun under user control at a later date using, for example, ESO's workflow tool Reflex. Off-line reduction will allow the user to weed out bad data frames and vary pipeline parameters to improve the result.

The pixel data and variance in raw frames are derived from multiple reads of the detector. The variance will be propagated through the reduction process using the ESO HDRL (High Level Data Reduction Library). This library will also provide 'best practice' algorithms for master frame combination of bias/dark/flat data, cosmic ray detection, bad pixel detection and the computation of Strehl ratios.

In an extension to normal ESO practice, it is the intention that the off-line pipeline will be able to reduce and combine data from more than one Observation Block.

8. ROUTE TO COMMISSIONING

The NIX imager design will be finalized in 2017, with the manufacture, assembly and test of the optical sub-assemblies completed by 2018. An extensive alignment and test campaign at UKATC is then scheduled, with delivery of the completed NIX sub-system to MPE for integration into the ERIS instrument at the beginning of 2019. Commissioning of ERIS at the VLT is planned to occur in 2020.

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