ERIS: preliminary design phase overview

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ABSTRACT

The Enhanced Resolution Imager and Spectrograph (ERIS) is the next-generation adaptive optics near-IR imager and spectrograph for the Cassegrain focus of the Very Large Telescope (VLT) Unit Telescope 4, which will soon make full use of the Adaptive Optics Facility (AOF). It is a high-Strehl AO-assisted instrument that will use the Deformable Secondary Mirror (DSM) and the new Laser Guide Star Facility (4LGSF). The project has been approved for construction and has entered its preliminary design phase. ERIS will be constructed in a collaboration including the Max-Planck Institut für Extraterrestrische Physik, the Eidgenössische Technische Hochschule Zürich and the Osservatorio Astrofisico di Arcetri and will offer 1 – 5 µm imaging and 1 – 2.5 µm integral field spectroscopic capabilities with a high Strehl performance. Wavefront sensing can be carried out with an optical high-order NGS Pyramid wavefront sensor, or with a single laser in either an optical low-order NGS mode, or with a near-IR low-order mode sensor. Due to its highly sensitive visible wavefront sensor, and separate near-IR low-order mode, ERIS provides a large sky coverage with its 1' patrol field radius that can even include AO stars embedded in dust-enshrouded environments. As such it will replace, with a much improved single conjugated AO correction, the most scientifically important imaging modes offered by NACO (diffraction limited imaging in the J to M bands, Sparse Aperture Masking and Apodizing Phase Plate (APP) coronagraphy) and the integral field spectroscopy modes of SINFONI, whose instrumental module, SPIFFI, will be upgraded and re-used in ERIS. As part of the SPIFFI upgrade a new higher resolution grating and a science detector replacement are envisaged, as well as PLC driven motors. To accommodate ERIS at the Cassegrain focus, an extension of the telescope back focal length is required, with modifications of the guider arm assembly. In this paper we report on the status of the baseline design. We will also report on the main science goals of the instrument, ranging from exoplanet detection and characterization to high redshift galaxy observations. We will also briefly describe the SINFONI-SPIFFI upgrade strategy, which is part of the ERIS development plan and the overall project timeline.

Keywords: ERIS, VLT, AOF, DSM, 4LGSF, instrumentation, adaptive optics
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1. INTRODUCTION

ERIS, the Enhanced Resolution Imager and Spectrograph, is a 1-5 µm instrument for the Cassegrain focus of UT4/VLT, equipped with the Adaptive Optics Facility (AOF[1]). ERIS uses and depends on the AOF infrastructure to perform the AO correction. The ERIS concept maximizes the re-use of existing sub-systems and components. In particular, the AO correction is provided by the AOF Deformable Secondary Mirror (DSM) and the artificial Laser Guide Star (LGS) is generated by the 4 Laser Guide Star Facility (4LGSF) at UT4. Any one of the four lasers can be used. The wavefront sensor camera detector in the visible is very similar to the one used for GALACSI and GRAAL (the two GLAO systems of the AOF to be used with the science instruments MUSE and Hawk-I, respectively) and the Real-Time Computer (RTC) is a modified version of SPARTA which is already used in the AOF project[1].

ERIS consists of the following modules:

- The **Calibration Unit** which provides facilities to calibrate the scientific instruments (remove instrument signature) and perform troubleshooting and periodic maintenance tests of the AO modules (e.g. calibrate Non-Common-Path [NCP] aberrations and flexure pointing models).
- the **AO module**[2] interfaces to the AOF and consists of the following AO subassemblies:
    - the Natural Guide Star (NGS) Pyramid Wave Front Sensor (PWFS) providing high-order AO correction or used as low-order sensor for the LGS mode
    - the IR low-order sensor also serving the LGS mode
    - the LGS wave front sensor providing high-order AO correction.
- two **science instruments**,
    - **NIX (Near Infrared Camera System)** provides diffraction limited imaging, sparse aperture masking (SAM) and pupil plane coronagraphy capabilities from 1-5 µm (i.e. J-M'), either in "standard" observing mode or with "pupil tracking" and "burst" (or "cube") readout mode. NIX is a cryogenic instrument and it is equipped with a 2048 × 2048 detector providing a Field-of-View (FoV) of 27" x 27" (J – Ks bands) or 55 x 55" (J – M' bands).
    - **ERIS-SPIFFI** is a version of SPIFFI, the 1-2.5 µm integral field unit used on-board SINFONI, that will be modified to be integrated into ERIS. Its observing modes are almost identical to those of SINFONI but the exchange of the H+K grating with a higher resolution grating and the offering of a sky-spider mode are envisaged.

ERIS-SPIFFI is on the main telescope optical path, with no intervening optics, while NIX receives light by means of a selector mirror.

2. SCIENTIFIC OBJECTIVES AND DERIVED TOP LEVEL REQUIREMENTS

During the Phase A study the main scientific drivers for the ERIS project were established but also considerations of maintaining and possibly enlarging the AO related capabilities of ESO VLT entered the deliberations (see also Amico et al.[3]). For example, CONICA is an infrared camera and spectrometer that was attached to the adaptive optics system NAOS at Nasmyth B of UT4. The ensemble is called NACO. NACO is currently relocated to another focal station and requires some degree of maintenance to ensure a mid-term future. SINFONI consists of SPIFFI, a near-infrared integral field spectrograph, and an AO module, MACAO, at the Cassegrain focus of UT4. In its current form, SINFONI cannot benefit from the AOF, since the MACAO module and the AOF are not compatible. There are two more non-interferometric VLT instruments outside of the AOF using AO. CRIRES is a high-resolution spectrograph and does not have an imaging mode. The second-generation instrument SPHERE is an imager and low-resolution spectrograph optimized for planet detection. It operates only with an on-axis natural guide star (NGS) with limited sky coverage (bright). ERIS will ensure the availability of *general-purpose* diffraction limited imaging at the VLT with improved AO performance w.r.t. NACO, once NACO is decommissioned.

NACO and SINFONI have both been requested on a constant level close to the VLT average of 150 nights per semester over the last semesters. SINFONI is now requested more often than the classical IR workhorse of the VLT, ISAAC. The number of allocated versus requested nights on both instruments (NACO and SINFONI) is slightly larger than the VLT average demonstrating the large demand in the science community for these instruments.

After a trade-off study made in 2010, it was decided to build a new instrument (ERIS), for the Cassegrain of UT4 since the Nasmyth foci are already occupied by (1) MUSE, a new optical, wide-field integral-field-unit (1' x 1', 4800 – 9300 Å) and (2) by Hawk-I, a wide-field near-IR imager (7.5' x 7.5', J to K-band) which will be used to commission the AOF and then carry out science in ground layer adaptive optics (GLAO) mode. ERIS will comprise a newly designed AO module, a newly designed infrared imager (NIX), and a refurbished integral field unit (SPIFFI).

Key science cases identified a wealth of topics to be covered from the solar system, with asteroids and their multiplicity, satellites, atmospheres and rings of giant planets, to the details of distant galaxies, by resolving their structure and kinematics. Other key areas include stellar disk science, starburst clusters and their initial mass function, nearby galaxy centers and exoplanets. A key goal here is to fully exploit the AO capabilities of the new secondary deformable mirror at UT4, thus reaching, for example, on-axis Strehl ratios in NGS mode of above 68% in Ks-band for m_R=8 of the star. This performance will also be utilized to explore nearby stars for exoplanets adding thereby the L', M' bands to the capabilities of the SPHERE instrument.

At the beginning of Phase B (October 2012), the scope of ERIS was defined by an *initial* set of Top-Level-Requirements (TLRs) which were, over the course of the next months, extensively discussed with the stakeholders and thereby developed into a complete set of TLRs (released September, 2013). One of the significant additions to the ERIS design in Phase B was the IR low-order wavefront sensor in addition to the optical one. The introduction of such a sensor is supported by the science cases, most significantly by the embedded star-formation regions that are otherwise difficult to cover or not observable at all. It is also expected that ongoing and future surveys with e.g. VISTA, ALMA and HERSCHEL will provide ample targets selected in the IR and therefore often in dust obscured regions where an IR wavefront sensor is most powerful or even crucial. While the wide NGS search field of ERIS may often allow one to find a NGS in the optical, the addition of an IR wave-front sensor enables typically to find NGS closer to the target or at brighter relative magnitudes. A possible trade-off between IR on-science-detector sensing or a dedicated IR wavefront sensor was attempted at the time but difficult to achieve with the then available level of information. Overall, the IR wave-front sensor enables the observation of a number of new targets in dust enshrouded environments and, maybe more importantly, it enables the instrument to achieve better and more robust performance (e.g. Strehl ratio) for a number of key targets including the Galactic Center.

For the Galactic Center case, potential visible NGS are rather faint and far away (>15") from the science target. The best visible NGS at the Galactic Centre only yields Strehl ratios in the regime of 47% to 55% for the ERIS baseline design. The relatively bright star at distance r=19" (m_R~14) is routinely used by Keck observatory and also for SINFONI observations. In the infrared, the widely used natural guide star is IRS-7 (m_K~7), which is only 5.5" away from the Galactic Centre. For this science case, an IR wavefront sensor allows the use of a star much closer to the science target (visible 19" versus IR 5.5") thus reducing anisoplanatism effects. Although the near IR star is relatively bright, Strehl ratio estimates remain at about 65%. Given the importance of the science case itself and the time constraints provided by key stars moving around the Galactic Centre (e.g. S2 pericentre passage in April 2018) observations will be pushed to high airmass ranges, which are untypical for AO. Therefore, high stability and robustness of the AO system are requested.

One of the areas ERIS can improve upon existing ESO AO facilities is the sky coverage and wave-font sensor sensitivity. Originating from Phase A, the following TLR is used: "For LGS wavefront sensing the unrestricted search field (including the instrument field centre) for the visible low-order correction NGS shall allow one to find a $m_R \leq 17$ star in at least 30% of the pointings at the Galactic pole." This requirement was translated into a design covering an unrestricted circular area of 2 arcmin diameter for the search field of the two wave-front sensors. An example simulation of the optical low-order wave-front sensing performance supporting the high-order LGS sensing is shown in Figure 1.

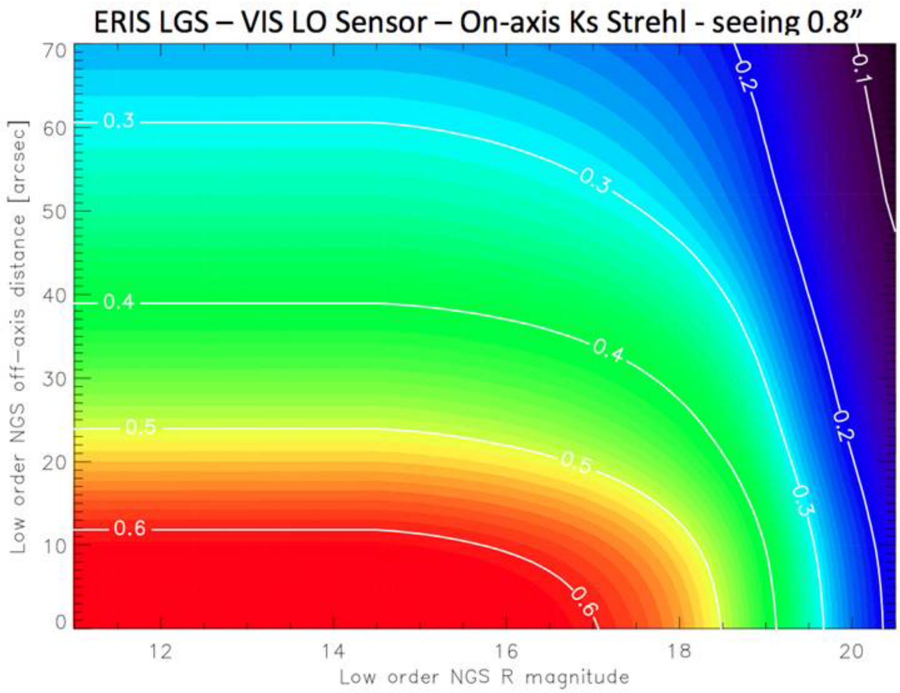

Figure 1. Simulation of on-axis Strehl ratio in Ks band as a function of NGS on-axis distance and R magnitude used for low-order wavefront sensing to support the high-order LGS sensing.

From the complete set of science cases and general observatory guide lines a new set of 55 Top Level Requirements was established and the most science relevant items are summarized in the following:

ERIS shall consist of an imaging camera, a spectrograph and the AO module as an integrated design. The spectrograph shall re-use and adapt SPIFFI (the existing spectrograph inside the VLT instrument SINFONI) for inclusion into ERIS and the instrument shall be mounted at the Cassegrain focus of UT4. The instrument shall have calibration devices to serve the AO module, the camera and the spectrograph.

The AO module shall feed both the imaging camera and the spectrograph. The AO module shall perform on-axis correction on a natural guide star (NGS) achieving under stable, standard atmospheric conditions [DIMM seeing 0.87 arcsec at 500 nm along the line of sight at 30° off-zenith; airmass = 1.16] an average Strehl ratio in Ks-band over a 15 min duration observation of ≥75% (60%, 35%) in the direction of the NGS (on-axis) for a m_R=8 (13, 15) star. The AO module shall perform on-axis correction on a laser guide star (LGS) and is assisted by visible and near-infrared low-order wavefront correction. For LGS wavefront sensing with on-axis "visible" NGS Strehl ratios in Ks-band: ≥60% (55%, 35%) in the direction of the LGS for a m_R=12 (17, 19) star. For LGS wavefront sensing with near-IR NGS: ≥60% (TBC) in the direction of the LGS for a m_K=10 star. In order to use non-AO suitable weather conditions ERIS shall be able to be operated without the AO module atmospheric correction in place ("seeing limited operation").

The imaging camera shall provide diffraction-limited images across the J, H, Ks, L and M atmospheric windows, in the wavelength range 1.0 µm < λ < 5.4 (TBC) µm. The following observing modes shall be provided: a) Imaging (field and pupil tracking) in J- to L'-band b) Imaging (field and pupil tracking) with chopping in M'-band c) Pupil plane coronagraphy with angular differential imaging (ADI) in L' and M'-band (goal: J to M'-band) d) Sparse aperture masking (SAM) including pupil plane tracking in J to M'-band. The imaging camera shall provide two average pixel scales and minimum effective areas: a) 13 mas/pixel, J to Ks-bands covering >24^2 arcsec^2 and b) 27 mas/pixel, J to M'-bands covering >53^2 arcsec^2. As the imaging camera detector we currently foresee a state-of-the-art Hawaii 2RG device.

The science grade data reduction pipeline for the ERIS spectrograph shall include advanced sky subtraction techniques which enable the use of the sky-spider and also optimal "scaling" of sky exposures obtained from on-off, object-sky, observing sequences. The sky-spider facilitates the simultaneous observation of blank sky in one corner of the field of view, allowing long integrations without nodding the telescope.

The capabilities of the spectrograph are largely determined by the existing SPIFFI module but it will be upgraded to improve the efficiency via e.g. new fore optics and order sorting filters as well as a new science detector. We also envisage replacing the H+K-grating with a new higher spectral resolution (R~8000) one to serve the J, H, and K-bands.

3. INSTRUMENT DESIGN

For details of the ERIS AO system design we refer to the paper by Marchetti et al. in the Adaptive Optics Systems IV conference[3] of this meeting. In the following we briefly describe the current status of the ERIS preliminary design.

3.1 General structure

The optical design has been frozen mid February 2014 so that only minor modifications will be allowed, provided that they will not significantly affect the mechanical design. The design includes the ERIS common optics, NIX, the modifications to SPIFFI, all the AO paths and the calibration unit. The guider arm design has advanced significantly. More work on the pick-off mirror resizing and interface with the adapter/rotator is ongoing, as well as developing a modified maintenance strategy. Figures 2 and 3 provide a CAD design of the instrument and a 2-dimensional schematic overview of the ERIS components and functions.

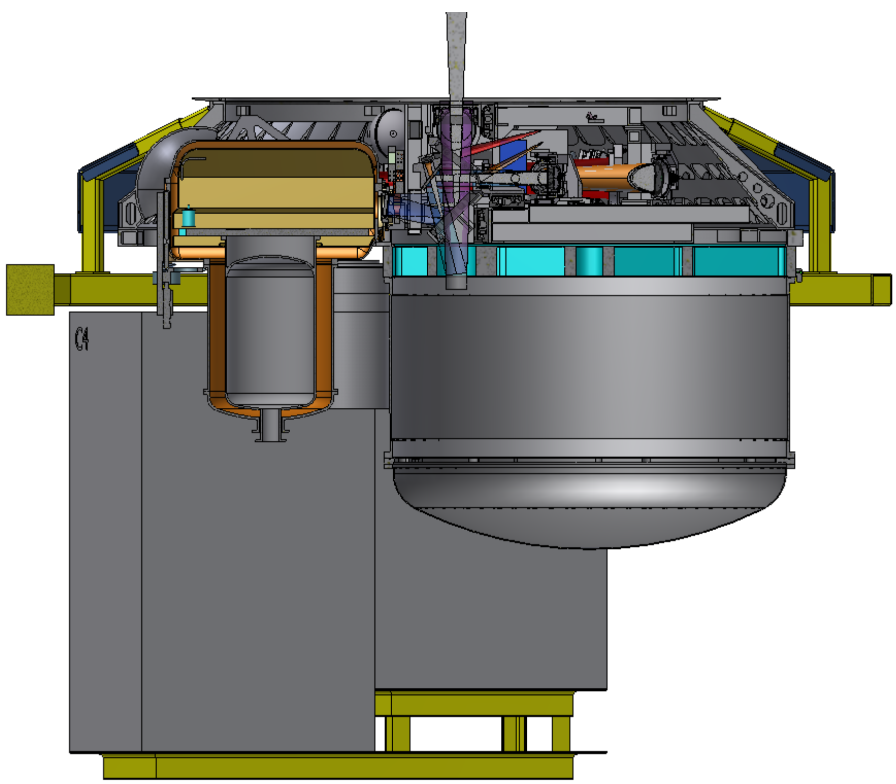

Figure 2. A CAD view of ERIS is shown. The round structure to the right is the SPIFFI spectrograph with cryostat to be reused inside ERIS while the NIX IR camera is shown to the left in orange color.

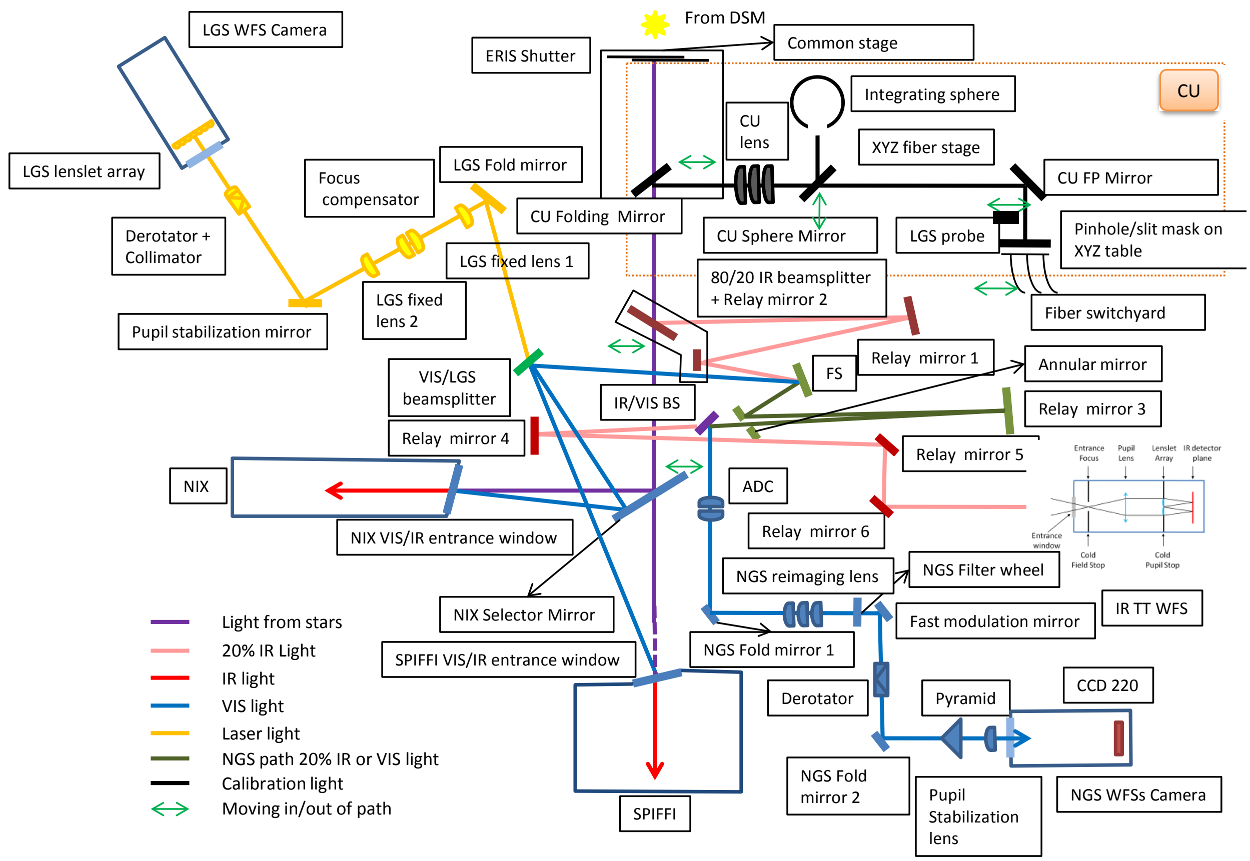

Figure 3. 2-dimensional schematic of the ERIS design.

3.2 IR Camera – NIX

The preliminary optical design of the ERIS Camera (NIX) essentially consists of a CaF_2 dichroic entrance window and three different optical configurations selectable by a camera wheel (CAM1, CAM2, CAM3). The dichroic CaF_2 entrance window has a meniscus shape and its tilt with respect to the optical axis is 7°. The reflected beam goes back via the NIX selector mirror towards the VIS/LGS beamsplitter into the AO system.

CAM1: J, H, K camera for the 27"x27" arcsec^2 FoV providing a 13 mas pixel scale. This is a three lens system with two BaF_2 and one IRG_2 lenses, all of spherical shape.

CAM2: J, H, K camera for the larger 55"x55" arcsec^2 FoV with a respective pixel scale of 27mas. As for CAM1, the specifications are fulfilled with a three lens design with two lenses made of BaF_2 and one out of IRG_2. The convex surfaces of the two BaF_2 lenses are however aspheric with a conical constant of order -1.

CAM3: L, M band camera for 55"x55" arcsec^2 FoV. This camera is also following a Cooke triplet design, where two lenses are made of ZnSe and one of BaF_2. The surfaces of all lenses are spherical.

In order to adapt for the different image scale of CAM1 vs. CAM2 and CAM3 an additional beam selector mechanism is implemented which can move out the default folding mirror to accommodate the larger focal length for CAM1. In this case the beam is routed to the detector via two folding mirrors instead (see Figure 4). This mechanism also holds a two lens configuration for imaging of the pupil, which is required for internal alignment purposes to verify homogeneous pupil illumination at the cold stop.

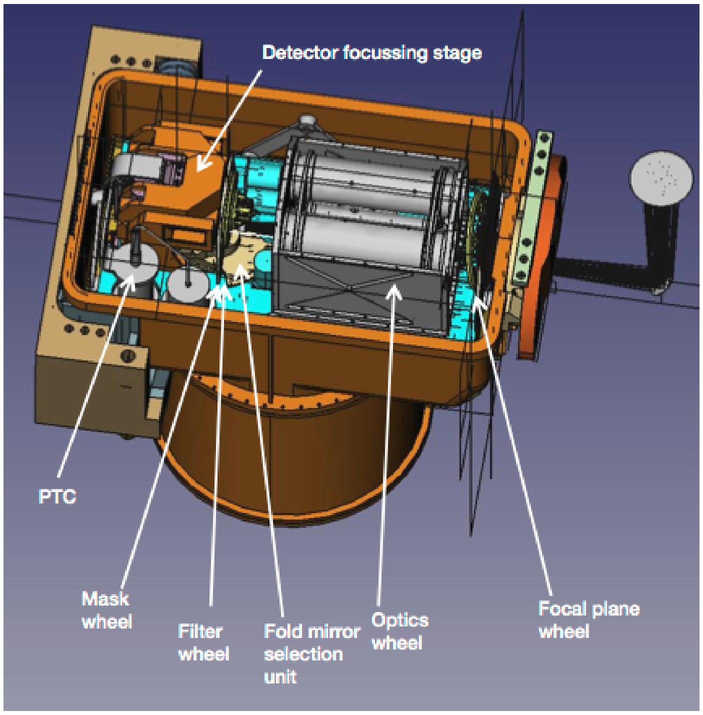

Figure 4. Preliminary 3D-Model of NIX. The vacuum vessel cover and the thermal shield are removed as well as the housing for the three wheels.

The image is recorded on a single 2048x2048 pixel Hawaii 2RG (H2RG) detector array from Teledyne Imaging Sensors (http://www.teledyne-si.com/infrared_sensors/index.html) with a cut-off wavelength at 5.4 µm, facilitating sensitive imaging from J-M bands. At the location of the entrance focal plane of NIX an aperture wheel mechanism is installed which holds field stops to mask the 27"x27" and 55"x55" FoVs. In addition, 4 more free slots can be equipped with masks containing for example hole patterns for test purposes. Between the optics wheel and the exit pupil plane, the design foresees a filter and a mask wheel with 18 slots each. The mask wheel is installed closest to the exit pupil plane where a cold stop will mask out thermal stray light from the telescope support structure.

Sensitive imaging at near-infrared wavelengths requires suppression of thermal self-emission of instrumental components to minimize the level of background radiation. Therefore the entire NIX instrument is integrated in a liquid nitrogen bath cryostat providing optical bench temperatures around 80 K. However at a temperature of 80 K the dark noise of the 5.4 µm cut-off H2RG detector would dominate the sensitivity for narrow band imaging in J-band. In order to lower the dark current, additional detector cooling by a Pulse Tube Cooler (PTC[4, 5]) is implemented in NIX. The cold head of a customized PTC (cooling power ~2 W) is connected to the cooling braid of the H2RG detector assembly. Parasitic thermal loads introduced by the H2RG preamplifier board and its cabling will be routed to the liquid nitrogen heat sink as much as possible. Thermal modeling of the combination of detector setup and PTC in the NIX design predicts that detector temperatures as low as 40 – 41 K can be reached, compatible with the required dark current levels.

Since NIX and the AO system share the dichroic entrance window, the alignment of both systems with respect to each other requires implementing optical adjustment features with several degrees of freedom in the instrument:

- The tilt of the NIX entrance window can be adjusted by about ±10 arcmin in two axes.
- The entire NIX instrument can be tilt around two axes by ±10 arcmin to center the cold stop with respect to the exit pupil image.
- The H2RG detector is mounted on a cryogenic focusing stage with a moving range of about 1.5 mm to allow for residual focal corrections.

3.3 Spectrograph

As soon as the NIX selector mirror (see Figure 3) is moved out, the telescope beam is directly routed into the SPIFFI spectrometer. However for operation in ERIS, a few optical adaptations are required to the instrument compared to SPIFFI inside SINFONI[6]. The entrance window must be replaced by a dichroic CaF_2 meniscus window with a tilt of 7° like for NIX, to direct the reflected beam towards the VIS/LGS beam splitter. The change in focal length between ERIS and SINFONI also requires a change to the collimator optics at the entrance of SPIFFI, and the length of the sky-spider arms must be adapted as well. The remaining optical design inside SPIFFI remains untouched.

The intervention of moving the SPIFFI system from SINFONI to ERIS also opens opportunities to replace or upgrade components. State of the art anti-reflection coatings for lenses show lower reflectivity compared to 15 years ago and new J-band filters with higher in-band transmission are available as well. A replacement of the detector by a new H2RG 2048x2048 device with better quantum efficiency promises another step in improving the sensitivity when migrating SPIFFI from SINFONI into ERIS. Replacing the low resolution (R~1000) H+K grating by a high resolution grating (R~8000) not only leads to more detailed spectra, but even more importantly improves on the suppression of photon noise originating from night sky emission lines. The preliminary grating design operates in diffraction orders 5, 4 and 3 for J, H and K bands respectively. These higher orders require additional order sorting filters, which can be conveniently accommodated in the spare slots on the SPIFFI filter wheel.

ESO standards for electronics applied to VLT instruments have significantly evolved during the past 10 years, as a consequence the old SPIFFI 5-phase stepper motors must be replaced by new PLC (Programmable Logic Controller) driven cryogenic 2-phase stepper motors. The required minor mechanical differences in the mounts for the motors have been designed and implemented. Similarly, improved detector control electronics (New General detector Controller or NGC) are available for operating the latest H2RG detectors. Together with a new detector the electronics will be replaced as well.

The complex alignment strategy of AO + NIX + SPIFFI calls also for adding adjustment features to the SPIFFI design. Like for NIX, the tilt of the entrance window of SPIFFI will be adjustable in two axes by about 10°. However the alignment of the SPIFFI exit pupil with respect to the telescope requires a change of the mounting interface such that two wedged rings can be inserted at the mounting flange. The adjustment is then obtained by counter rotation of the two rings with a granularity given only by the 48 mounting screws.

3.4 Calibration unit

The ERIS calibration system not only provides the classical facilities for calibrating the two science instruments, but also allows daytime maintenance, testing and tuning of the four AO systems. It supports:

- Science calibration of NIX and SPIFFI (the usual set of spectral lamps, the flat field lamp is a Laser Driven Light Source) in the range 0.5 – 2.5 µm um using an integrating sphere and a realistic simulation of the telescope pupil, including central obscuration and spiders.
- Projecting a slit on the entrance aperture of SPIFFI to calibrate the spatial arrangement of slitlets on the sky.
- Calibration of differential flexure between science instruments and AO systems to a few milli-arcseconds.
- Calibrating the NGS selection mechanism by offering an array of artificial natural guide stars at precise and stable locations in a 2' diameter NGS focal plane.
- Calibration of on-axis non-common path aberrations by offering diffraction limited point sources in the NGS and LGS focal planes.

The calibration unit is equipped with a diffraction limited objective that is operating at ~1:1 magnification ratio to project point sources of various sizes at the Cassegrain NGS (infinity) and LGS (85 km) focal planes. This mode is used mainly to calibrate the AO and acquisition systems. By inserting a folding mirror, the objective is converted to a classical calibration system for the science instruments. The system then delivers a projected (virtual) position of the pupil that coincides with M2. The stop is placed on the exit port of an integrating sphere and mimics the central occultation and the spiders of the telescope pupil. This is explained in Figure 5.

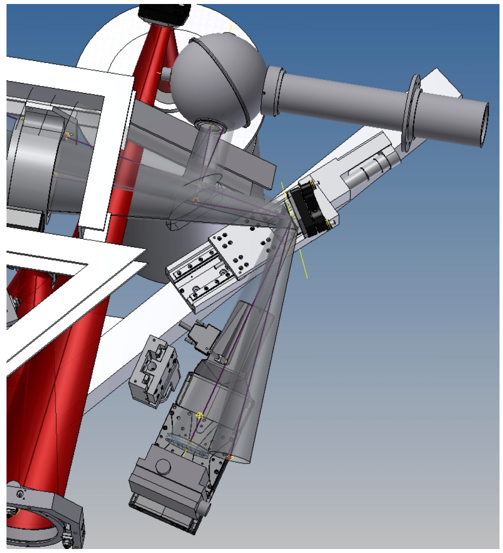

Figure 5. Layout of the ERIS calibration unit. The back-illuminated pinhole mask is mounted on a Z (focus) stage and a compact XY stage. At the left of the slit mask one sees a stage to insert the LGS fibre that will be mounted to the structure. The beam, after hitting a fixed ~45 degree folding mirror, passes a fixed pupil stop (not shown) and enters the projection objective at the left edge of the picture which produces an image of the source in the focal plane of the telescope. The translation stage below the folding mirror mounts a folding mirror for the calibration sphere which is shown here in the IN position.

4. THE ESO DATA FLOW ENVIRONMENT

To support users in the preparation of observations, their execution, archiving and automatic processing of data, instrument health monitoring and in general VLT operations, ESO has developed several tools and a dedicated environment, the so called Data Flow System (DFS). It includes a tool for Phase-2 Observations Proposals Preparation (P2PP), instrument specific Exposure Time Calculators (ETCs), the On-Line Archive System (OLAS), the Data Organizer (DO), the Reduction Block Scheduler (RBS) and a set of instrument specific automatic data reduction pipelines.

The DO uses the information available in the raw data FITS header to automatically classify raw data, to define the location of the local database and the pipeline products filenames, and associates to them the proper pipeline and data reduction recipe. If needed, it also associates reference calibrations and master calibration products, which on Paranal are retrieved from a local calibration database, while for Garching operations are associated the closest in time certified master calibrations. The corresponding information is collected in an ASCII file, the so-called Reduction Block, which is scheduled for reduction from the RBS that has the task to monitor the reduction process. To monitor the data reduction quality and instrument health the pipeline generates the so called Quality Control information that may range between simple quantities that are stored as FITS keywords in the relevant data reduction product to extra products: tables, images or data cubes. This information is monitored and parameter values may be trended by Garching Quality Control operations and made available to Paranal operations and users.

5. THE ERIS DATA REDUCTION PIPELINE

5.1 General concepts

ESO data reduction pipelines are recipes implemented in C and based on the ESO – Common Pipeline Library (CPL). This provides common functionality to input/output and process tables, images, image lists and FITS information. More recently the pipeline developer may also take advantage of the functionality provided by the High level Data Reduction Library (HDRL), a general purpose library collecting common astronomical data reduction algorithms. ESO pipeline recipes can be executed with the ESO-Reduction executor, ESORex, Gasgano, or a Reflex workflow. Gasgano is a GUI providing functionality to browse, organize and classify FITS files and allowing execution of pipeline data reduction recipes. In case of massive, script-based un-supervised and automated data reduction the user may take advantage of the

ESORex tool. To increase efficiency of astronomical data processing the desktop user recommended choice is to run a Reflex workflow under the Kepler engine, usually starting with a non-interactive section, and then, if the workflow allows, with an interactive section to control data reduction parameters, optimize the data reduction quality and display relevant products and information. The Reflex environment provides all actors required to organize, classify, schedule data sets for reduction, and organize data reduction according to the appropriate sequence, leaving the user to concentrate only on the analysis of results and to set proper reduction parameters to optimize the quality of the pipeline products.

The ERIS pipeline will employ all these functionalities. The data reduction will ensure full error and pixel quality determination and propagation along the reduction cascade. The pipeline will use CPL to manipulate images, tables, cubes and FITS header information, and HDRL to share common algorithms, for example, to combine similar images in a master, detect pixel quality, detect cosmic ray hits events, or compute the instrument Strehl.

5.2 Reduction of spectroscopy data

ERIS spectroscopy data will have a very similar layout as SINFONI's ones. The instrument FoV is sliced by the small image slicer in 32 slices that are collimated by the large slicer onto the entrance slit plane of the SPIFFI spectrograph and dispersed on the 2Kx2K pixels detector following a characteristic brick-wall pattern, were each of the 32 slitlets is imaged on a 64x2K pixels long slit spectrum.

To reduce spectroscopy data it is planned to follow the following sequence:

- Run a routine to reduce dark frames and determine the dark current correction and a hot pixel map.
- Run a routine to detect pixels with non-linear response on a sequence of flat fields of increasing intensity.
- Run a routine to measure the detector distortions on a frame obtained by illuminating with a slit all slitlets edges.
- Run a routine to combine a set of images acquired by illuminating the entrance aperture of the instrument with a flat field lamp to determine detector pixel-to-pixel gain variations.
- Run a routine to wavelength calibrate the data by reducing a frame obtained with an arc-lamp exposure.
- Run a routine to determine the instrument response on images obtained by observing a flux standard star.
- Run a routine to reduce science data that means to reconstruct the full spectral and spatial FoV information along a 3D IFU data cube, so that each plane corresponds to an image of the instrument FoV at a given wavelength.

Because the spectroscopy data will be very similar to SINFONI's ones, ESO has agreed with the MPE partner to implement the data reduction as an upgrade of the current SINFONI pipeline[7]. Still we foresee some significant changes. The most relevant ones include the support of the new higher spectral resolution grating and the sky-spider modes, the employment of advanced sky subtraction techniques (e.g. Davies[8], Noll et al.[9]) that allows the maximization of observation time on science objects, the possibility to optionally correct the wavelength calibration solution obtained with arc lamp data using the additional information coming from the position of OH lines, the implementation of a recipe to measure the instrument response and efficiency and to use this information to flux calibrate science products, and the computation and full propagation of errors and bad pixel quality information to the final science products. Additional expected minor changes include a modification of the recipe to measure the spectral format optical distortions, because the corresponding data will be more efficiently acquired with a flat field lamp illuminating a slit instead of a moving fibre as done for SINFONI; some minor changes in the wavelength calibration recipe to take into account different flux levels we will measure as consequence of the detector and instrument pre-optics upgrade and eventually to take advantage of the availability of error and bad pixel information; master dark and flat frames and detector pixel quality will be determined using more accurate and common algorithms from HDRL. A Reflex workflow will assist desktop users in the reduction of ERIS data. We plan to implement interactive workflows to optimize the wavelength calibration, the computation of the instrument response and the reduction of science data.

For the proposed changes we would like to add more details on the planned use of optimal extraction techniques because of its scientific relevance. As described by Davies[8] and Noll et al.[9] it is possible to model the airglow emission lines which dominate the (optical to) near infrared sky radiation, calibrate this on a few sky frames, or even in a defined portion of the detector which is known to be illuminated only by the sky, as may occur in standard nod observing mode and in particular is the case for observations with the sky-spider, and scale this emission to fit the sky emission lines on object observations and subtract the corresponding fitted sky spectrum. This technique almost doubles the time that may be allocated to object observations, as separate sky observations are not required. In the case of observations of extended objects or crowded fields, using the sky-spider mode allows correction of the NIR dominant sky emission while the instrument continuously integrates signal from the science object. As part of the preliminary design work we have evaluated the performance of both the algorithms described by Davies and Noll methods, finding that both provide good results and the second one, which implements a more detailed model, provides slightly better ones (see Figure 6) but it is computationally more expensive. Moreover we could verify on a test-data set obtained with the sky-spider in November 2013 that both methods allow a good sky subtraction. The current plan is to provide the user with both methods.

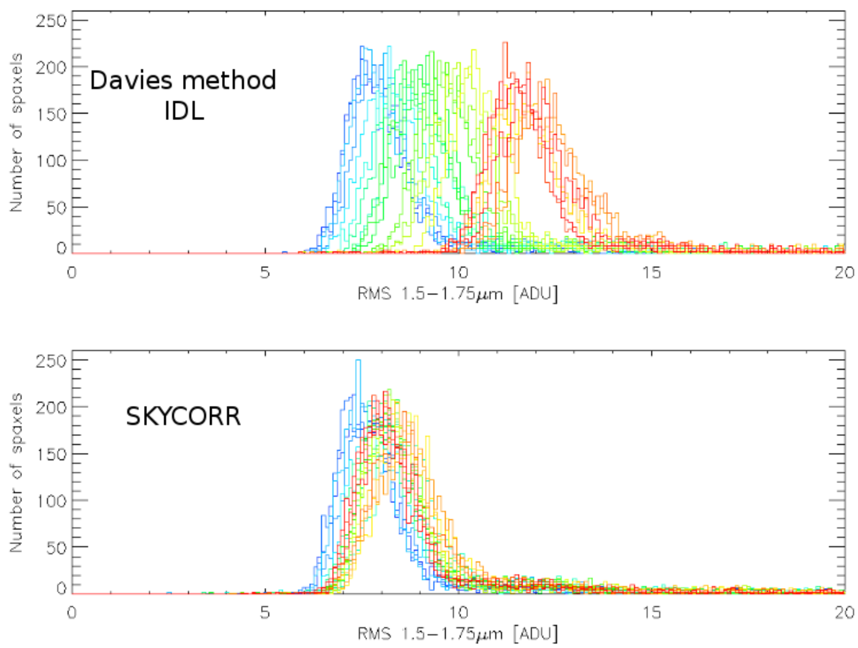

Figure 6. Standard deviation histograms for all SINFONI spaxels (1.5 -1.75 μm) after correcting cubes#1 with cube#n (n=2,3, ... 24). Colour coding from blue to red for cube#2 to cube#24. The first and last observations are separated by 2h 14m.

5.3 Reduction of imaging data

NIX, the imaging arm of the ERIS instrument, will make use of the full image correction supplied by the AOF module. With a NGS, the on-axis Strehl ratio is expected to approach 70% in the Ks-band, and 31% and 88% in the J and M'-bands, respectively. The primary goal of the image reduction software will be to preserve this image quality.

The data reduction cascade (shown in Figure 7) is expected to include the following steps:

- A routine that reduces dark frames in order to remove the zero-level offset from subsequent images, detect hot pixels and compute the detector read-out noise (the latter is intended for instrument quality control (QC) only).
- A recipe to measure the dark current inherent in the detector (QC).
- A recipe to measure the detector gain and linearity from a set of flat frames that span the full exposure time range.
- A recipe to combine a set of lamp flat images into a master lamp flat and to detect weakly-responding pixels (cold pixels). The master flat will be used to correct the pixel-to-pixel gain variations across the detector in subsequent images.

- A recipe to reduce twilight (sky) flats into a master sky flat that will be used to correct the large-scale variations across the detector.
- A recipe to measure and correct illumination variations across the detector.
- A recipe that converts an observed standard star into physical units, and for QC purposes computes the instrumental efficiency.
- A recipe that combines the results of the reduction cascade to process the science images, thereby removing all unwanted instrumental signatures, and computes an astrometric and photometric solution. The means to combine multiple science images into mosaics and image stacks will also be provided.

Each stage of the ERIS/NIX reduction cascade will be accounted for in an error-propagation map, and the quality information of each pixel will be retained.

A number of ancillary data reduction recipes will be created to help monitor the instrument health and performance. These will include a routine to measure the Strehl ratio for each standard star and science image, in order to measure the performance of the adaptive optics, and to define a PSF for subsequent science image processing. A number of the recipes implemented for ERIS/NIX will make use of the high-level data reduction library (HDRL) being developed at ESO.

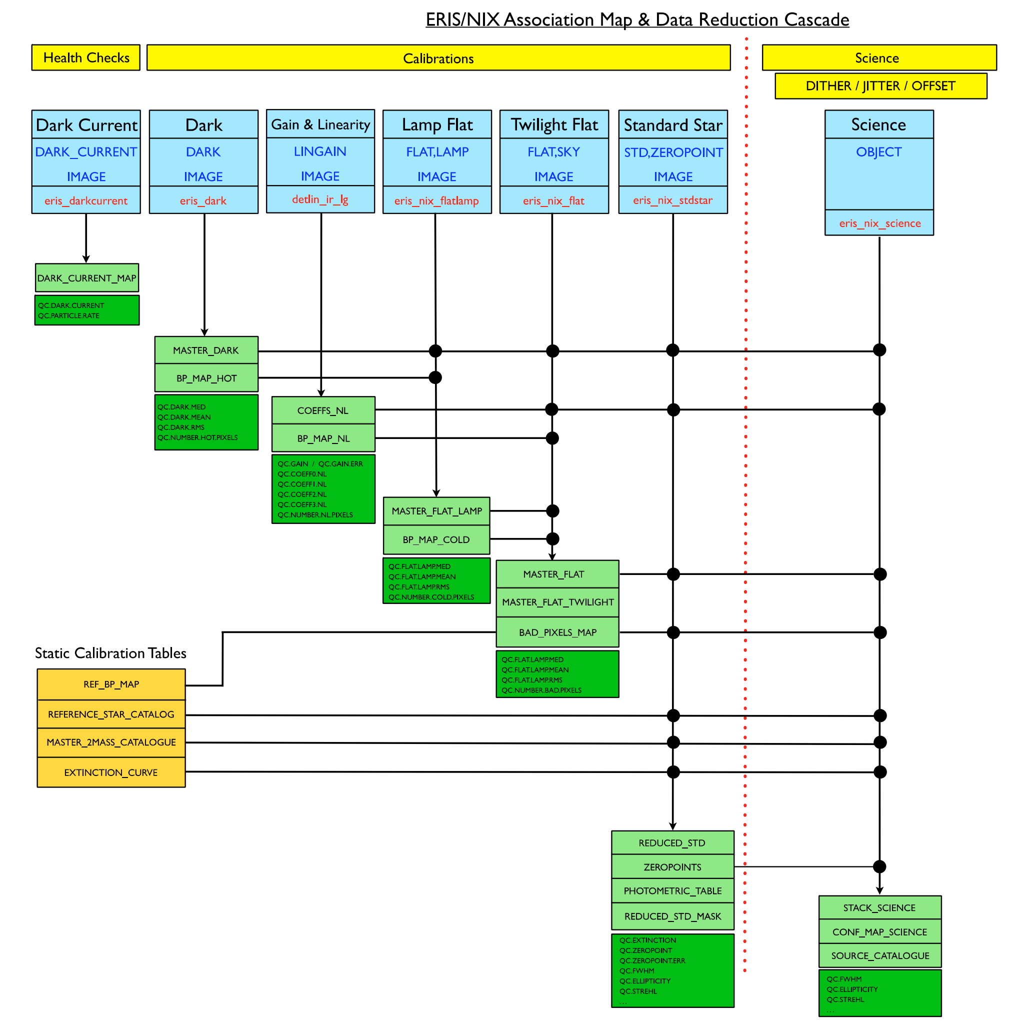

Figure 7. Preliminary data reduction cascade and association map for ERIS NIX

6. CONCLUSIONS

We presented a summary of the current preliminary design phase status of ERIS, the next-generation AO instrument being built for the Cassegrain focus of UT4. It will work together with the Adaptive Optics Facility (AOF) to provide high Strehl images at 1 – 5 μm and 1 – 2.5 μm integral field spectroscopy.

REFERENCES

[1] Arsenault, R. et al., "ESO adaptive optics facility progress and first laboratory test results", SPIE Proc. 9148-1 (2014)

[2] Marchetti, E. et al., "The ERIS adaptive optics system", SPIE Proc. 9148-75 (2014)

[3] Amico, P. et al., "The design of ERIS for the VLT", SPIE Proc. 8446 (2012)

[4] Korf, H.; Ruhlich, I.; Mai, M.; Thummes, G., "Pulse tube cryocooler for IR applications", SPIE Proc. 5783, 164 (2005)

[5] Yang, L. W.; Thummes, G., "Medium-size pulse tube coolers with linear compressor", AIPC 613, 745 (2002)

[6] Eisenhauer et al., "SINFONI - Integral field spectroscopy at 50 milli-arcsecond resolution with the ESO VLT", SPIE Proc. 4841, 1548 (2003)

[7] Modigliani, A. et al., "The SINFONI pipeline", Proceedings ADA IV (2006)

[8] Davies, R.I., "A method to remove residual OH emission from near-infrared spectra", MNRAS, 375, 1099, (2007)

[9] Noll, S. et al., "Skycorr: A general tool for spectroscopic sky subtraction", arXiv 1405, 3679 (2014)