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Final Design and Construction of the ERIS Calibration Unit

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ABSTRACT

The Calibration Unit (CU) is a subsystem of the Enhanced Resolution Imager and Spectrograph (ERIS), the new-generation instrument for the Cassegrain focus of the ESO UT4/VLT, aimed at performing AO-assisted imaging and medium resolution spectroscopy in the 1-5 micron wavelength range. The ERIS-CU is aimed to providing both focal plane artificial sources and uniform illumination over the 0.4 - 2.4 micron wavelengh range, for purposes of calibration and technical check of the SPIFFIER spectrograph, the NIX camera and the AO Module. Some challenging aspects emerged during the detailed design phase, mainly related to the need to cover such a broad wavelength range while ensuring adequate photon rates, excellent image quality and high Strehl, properly sized and shaped calibration sources. The technical solutions adopted to achieve the final design goals are presented and their implementation during the construction phase are shown and discussed.

Keywords: VIS/NIR instruments, VLT, Adaptive Optics, Calibration

1. INTRODUCTION

ERIS (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). The ERIS concept maximizes the re-use of existing sub-systems and components[1]. In particular, the AO correction is provided by the AOF Deformable Secondary Mirror (DSM), the artificial Laser Guide Star (LGS) is generated by the 4 Laser Guide Star Facility (4LGSF) at UT4, the wavefront sensor camera detectors are identical to those used for GALACSI and GRAAL (the two GLAO systems of the AOF) and the Real-Time Computer (RTC) is a modified version of SPARTA. In addition, one of the scientific instruments (SPIFFIER) is modified version of SPIFFI, the 1 – 2.5 μm integral field unit used on-board SINFONI.

ERIS consists of the following modules (Figure 1, *left*):

- the **Calibration Unit** which provides facilities to calibrate the scientific instruments and perform troubleshooting and periodic maintenance tests of the AO modules (e.g. calibrate Non-Common Path (NCP) aberrations and flexure pointing models) [2] ;
- the **AO module**, which will use the AOF DSM and one AOF laser, providing NGS and LGS visible wavefront sensing with real-time computing capabilities. It is composed in turn by the following subassemblies:
  - a Natural Guide Star (NGS) Wavefront Sensor (WFS) that provides high-order AO correction or is used as low-order sensor for the LGS mode
  - a LGS WFS providing high-order AO correction

  The AO module will allow for single-conjugate adaptive optics (SCAO) operations[3].
- two **science instruments**:
  - **NIX (Near Infrared Camera System)** which provides high-contrast, diffraction-limited imaging[4], sparse-aperture masking (SAM) and pupil plane coronagraphy[5] capabilities in the 1 – 5 μm (J to M') bands, either in "standard" observing mode or with "pupil tracking" and "cube" readout mode. NIX is a cryogenic

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instrument[6] and is equipped with a 2048 × 2048 detector cooled at 40K by means of a Closed Cycle Cooler (CCC). The camera optics is able to provide a Field-of-View (FoV) of 27” × 27” in the J to Ks bands or 55” × 55” in the J to M’ bands.

- **SPIFFIER**, which is a refurbished version of SPIFFI, modified in order to be integrated into ERIS. Its observing modes are identical to those of SINFONI.

Both NIX and SPIFFIER are fed by a dichroic beamsplitter which reflects the visible light to the AO module.

2. CALIBRATION UNIT OVERVIEW

The Calibration Unit (CU) is a subsystem of ERIS aimed to provide calibration capabilities for the ERIS instruments (NIX, SPIFFIER and AO WFS). In particular, the ERIS-CU has to provide:

- photometric flat fields for NIX, in broad- (J, H, K) and narrow-bands;
- spectroscopic flat fields for SPIFFIER over its full wavelength range (1 – 2.5 μm);
- wavelength calibration for SPIFFIER, in the same range as above;
- point-like (DL) and extended (0.5”, 1.0” and 1.5”) sources over the whole 0.4 – 2.4 μm wavelength range. These sources are used for AO LGS and NGS WFS calibrations and technical checks (e.g. Non-Common Path Aberrations, Differential Flexures between science instruments and AO systems), at optical wavelengths (R-band), and by NIX and SPIFFIER calibrations and technical checks at infrared wavelengths (J, H and K bands);
- two sets of illuminated slits (3 slits per set) for SPIFFIER IFS internal alignment check (North-South test) at its two largest plate scales, in J, H and K band.

Calibration capabilities for NIX higher wavelengths (L, M’ bands) are not foreseen for the CU. At these wavelengths, calibrations shall be made using on-sky sources.

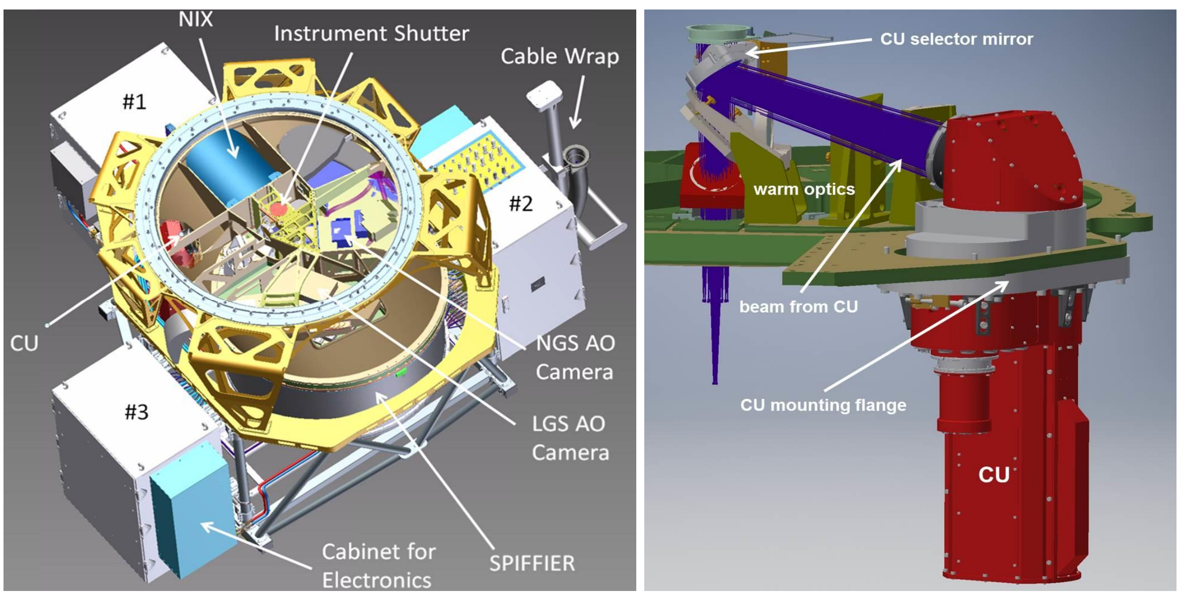

Figure 1. Left: Overall ERIS layout. Right: Calibration Unit main bench (CUMB) and Selector Mirror (CUSM) mounting.

The ERIS-CU is globally composed by three separate units (Figure 1, *right*). The first and second unit, called **Calibration Unit Main Bench (CUMB)** and **Calibration Unit Selector Mirror (CUSM)** respectively, are optically and mechanically interfaced with the ERIS optical plate and the optics therein (AO optics, warm-optics); the third unit, called **Calibration Unit Fiber Switchyard (CUFS)**, is hosted inside one of the ERIS cabinets and interfaced with the CUMB only. It is therefore not directly interfaced with the ERIS instruments and the telescope.

2.1 CU Main Bench

The CUMB is mounted across the ERIS optical plate with the main axis parallel to the telescope axis and the entrance beam tilted by 103° with respect to it (13° to the ERIS optical plate). The main components and devices inside the CUMB are shown in Figure 2.

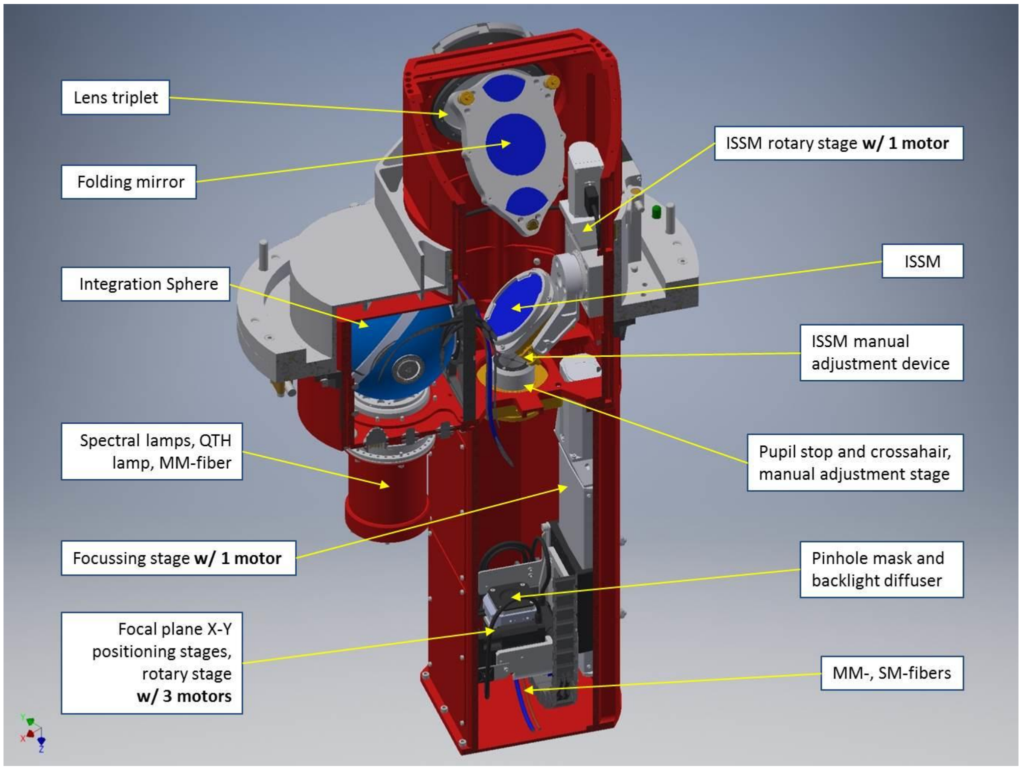

Figure 2. CU Main Bench (CUMB) components

Sources are placed onto a pinhole mask (PHM) and at the entrance hole of a integrating sphere (IS, spectral calibration lamps). The beam from the PHM crosses a fixed pupil stop and is reflected by a folding plane mirror towards the exit triplet lens, which focusses the sources onto the telescope focal plane. The PHM can be moved in X and Y positions across the plane perpendicular to the optical axis, through the action of two motorized linear stages, and can be rotated trhough the action of a motorized stage. A fourth movement along the Z-axis, performed through a devoted motorized linear stage, allows to place the PHM at different positions, in order to simulate point sources used for AO calibration purposes at infinite distance (NGS) or at finite distance (LGS at 80 km).

A second plane mirror, called Integration Sphere Selector Mirror (ISSM), can be placed across the above mentioned path, via a rotating motorized stage, in such a way to feed the folding mirror and the exit triplet with light coming from the output hole of a IS, in such a way to uniformly illuminate the telescope focal plane for flat field purposes.

An independent feedback to check for the correct illumination of both the PHM and the IS is given by a photodiode-based flux sensor, mounted onto a output hole of the Integrating Sphere.

The CUMB is also provided with internal temperature sensors, aimed at monitoring the temperature of heating devices (lamps) or sensitive components. In particular, two temperature sensors are foreseen to be installed at the top and the bottom of the CUMB, in order to monitor thermal deformations of the overall mechanical structure.

A series of manual adjustment mechanisms have been included in the design, for internal alignment purposes. Tip/tilt adjustment is foreseen for the folding mirror, the pupil stop and the ISSM (whose manual mechanism is mounted onto the rotary stage). The triplet lens position can be eventually moved along the optical axis and the position of the integration sphere can be regulated, too.
The height of the CU is less 86.4 cm. The overall envelope, not including the mechanical interface structure, is within 865 mm (height, perpendicularly to the ERIS optical plate) x 570 mm (width) x 505 mm (depth). When the mechanical interface structure (ring and flange) is considered, the section parallel to the ERIS optical plate is included within a 530 mm x 515 mm rectangle.

2.2 CU Fiber Switchyard

The CUFS hosts the LDLS devoted to feed the PHM and the IS through optical fibers connecting it directly to the CUMB. The CUFS mechanical design has evolved to a final version where the components and devices are located inside a standard 19 inch rack (Figure 3). The light source hosted inside the CUFS is a white-light, wide spectrum Laser Driven Light Source (LDLS). It is provided with a output optical fiber, whose other end is used to illuminate alternatively up to five different optical fibers:

1) a multi-mode (MM) fiber feeding the IS;
2) two multi-mode (MM) fibers feeding the PHM (pinholes and slits);
3) two single-mode (SM) fibers feeding the PHM (DL source at VIS and NIR wavelengths).

The five fibers are alternatively selected by moving them across the output beam with a motorized linear stage. In order to adjust the photon flux to be sent to the sources, a Neutral-Density Filter (NDF) is placed between the output fiber and the input fibers. Its position, in turn, can be adjusted by moving it onto a second motorized linear stage.
The optical coupling of the fibers is performed by using fiber collimators. Since the light passing through the system covers a wide wavelength range (400 – 2450 nm), photonic crystal fibers having low attenuation at infrared wavelengths have been selected. Moreover, for the same reason, reflective collimators, based on off-axis parabolic mirrors, have been selected.

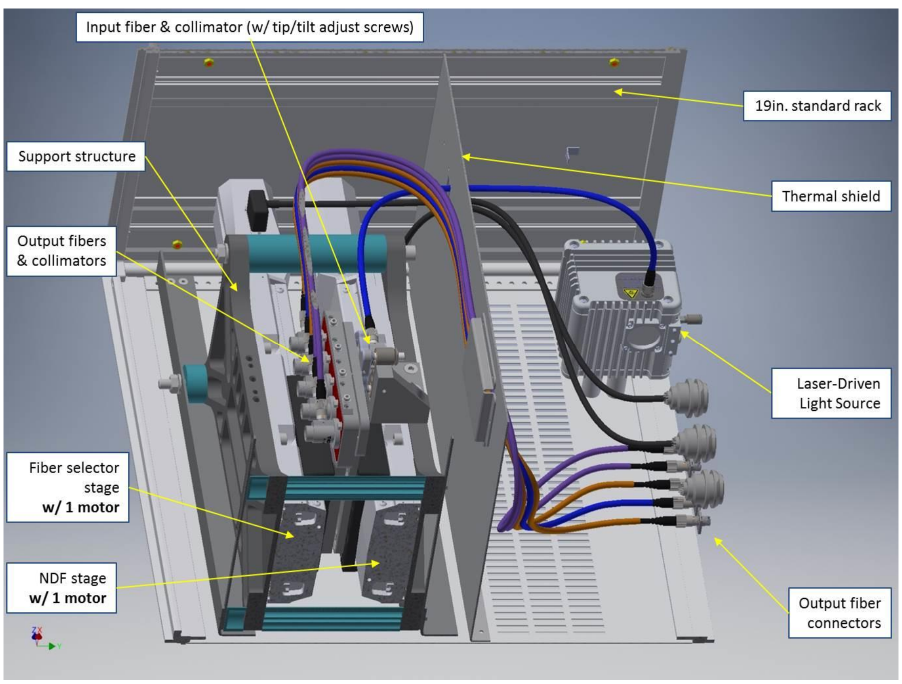

Figure 3. CU Fiber Switchyard (CUFS) components

Both the fixed fiber and the movable fibers are provided with manual adjustment mechanisms for initial alignment purposes. In particular, the vertical position of the movable fibers and tip/tilt of the fixed one can be adjusted.
In order to fully comply with maintenance operations, the connections between CUFS and CUMB (power and signal cable, plus optical fibers) are segmented by means of intermediate connectors. To minimize light losses at every connection, the number of segments for the optical fibers shall be reduced as much as possible.
As for the CUMB, the CUFS is provided with internal temperature sensors, aimed at monitoring the temperature of heating devices (lamps) or sensitive components.

2.3 CU Selector Mirror

The CU Selector Mirror (CUSM) is aimed at redirecting the light beam coming from the CU toward the telescope focal plane (in such a way to be used by both the scientific instruments and the AO module). A manual adjustment device has been designed for the procedures of optical alignment between the CU and the other ERIS subsystems during the integration phase. The device allows for tip/tilt adjustments by using high-accuracy COTS screws.

2.4 Operating Modes

Three operating modes are available:

A) PPL (Pupil Plane). In this configuration the telescope pupil is simulated (through the exit hole of a Integrating Sphere) and used to illuminate the exit pupil into the scientific instruments (for special calibration purposes) or the focal plane (mainly for flat field purposes);

B) FPN (Focal Plane, NGS). In this configuration a set of artificial sources, positioned at the telescope Cassegrain focal plane (i.e. at infinite distance), are used (for special calibrations of SPIFFIER plus the calibration of the NGS WFS);

C) FPL (Focal Plane, LGS). In this configuration the same set of artificial sources is used, but positioned at the telescope focal plane corresponding to a finite distance (85 km). This configuration is used for the calibration of the LGS WFS.

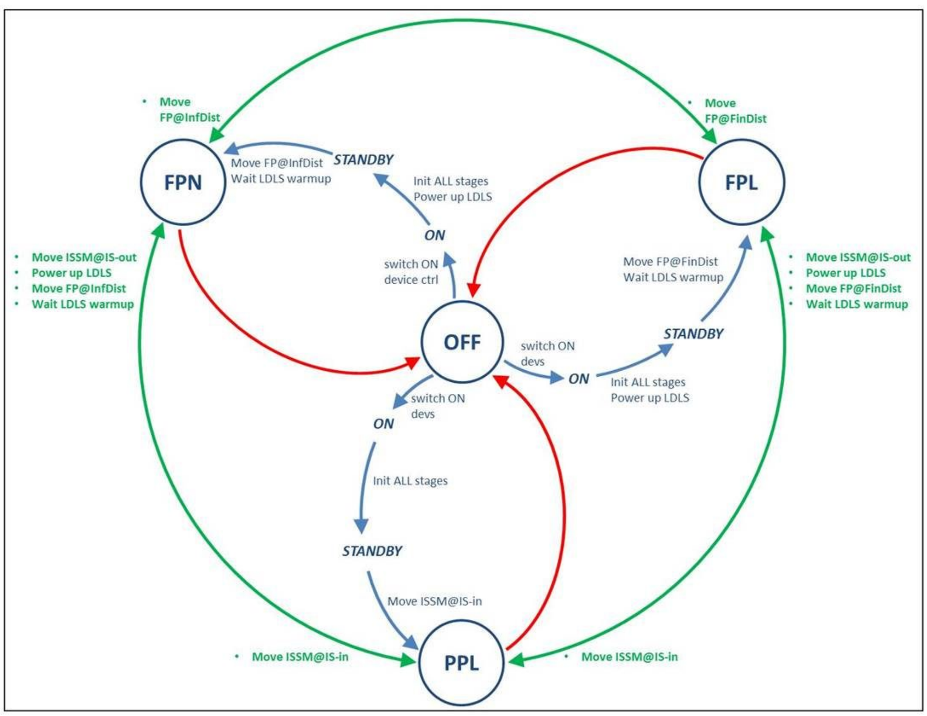

Figure 4. CU Fiber Switchyard (CUFS) components

Setting the CU for each of these three configurations requires a set of steps. A full operational life-cycle for the ERIS CU is based on the following states and state transitions (Figure 4):

1) the system is initially in OFF state;
2) the start-up sequence puts it to the ON state and then in the STANDBY state;
3) additional specific functions (e.g. moving the ISSM; moving the Focus Z stage and waiting for LDLS warm-up) allow it to reach one of the three operating modes;
4) the system can move from each operating mode to each other, or
5) it can move back to OFF state with a shut-down procedure.

2.5 Control system

The CU Instrument Control Electronics (ICE) is based on a Beckhoff CX2030 PLC. Each ICE terminal is connected to the PLC through an EtherCAT bus that is logically identified with three ICE Control Lines. The control system must globally orchestrate 8 motorized stages (linear and rotation), 4 arc lamps, 1 quartz-tungsten-halogen lamp, 1 special source (a Laser-Driven Light Source from Energetiq Inc.) and 3 sensors (temperature and relative humidity probes for the CUMB and a photon flux sensor for the integrating sphere). CU and AO control electronics, as well as control software, are described in more detail by Di Rico and Baruffolo paper in this conference[7][8].

3. FROM DESIGN TO CONSTRUCTION

In spite of having planned all activities and taking for granted any detail during the design phase, problems naturally arise when passing to the construction phase. The reasons for this are complex (generally known by project managers) and have not a technical origin only. Funds availability is often a factor impacting schedules, as well as their contingencies, in such a way that even technical decisions must be taken in order to compensate for those delays.

The ERIS CU does not represent and exception to this rule. Some technical-driven problems, as well as schedule keeping-driven technical decisions, can be reported.

As an example, the lamps holder placed below the Integrating sphere should have been gold-coated according to design: however, gold-coating required rather long waiting times at the companies available for that treatment and the final decision was to replace gold coating with barium sulfate painting – which has nearly the same spectral reflectivity of the Integration Sphere internal walls.

A second example, purely technical, concerned the Beckhoff terminals devoted to the management of CU motion stages. Although in the electronics design they were able to drive the stages in any direction, laboratory tests revealed a substantial asymmetry between the two direction of motion. This implied to buy additional terminals, together with corresponding power supplies, and to modify the design in order to allocate the new devices into the devoted racks. The overall effect of this problem has naturally been a longer time and an higher expense of resources (both financial and manpower) than previously expected.

Other situations have implied substantial redesign or prototyping activities. These are described in more detail in Sect. 4

4. CRITICAL ASPECTS OF MANUFACTURING

The manufacture of some items for the ERIS CU has revealed more challenging than expected during the design phase. and alternative or special solutions have had to be adopted. Two example cases are described here.

4.1 Optics

The only optically active element of the CU is the triplet lens. It works in a asymmetric relay system, where the pinhole mask is at a F/10.5 and the reimaged plane is at F/13.6, with a magnification factor of 1.29x. Its focal length is 408 mm, and the corrected field of view in FPN mode is ± 3.5 mm, equivalent to 7x7 arcsec^2 on sky.

This optical component was originally designed as 130-mm clear aperture cemented triplet composed by all spherical surfaces but one aspheric, all obtained by commercial glasses (transmission up to over 2.5 µm), as reported in Table 1.

Surface	Type	Radius of curvature (mm)	Thickness (mm)	Glass
first surface L1	spherical	-268.887	20.00	S-BAL3
second surface L1 first surface L2	spherical	320.773	10.00	S-NBM51
second surface L2 first surface L3	spherical	-159.196	23.00	S-FPL51
second surface L3	aspheric	404.260	4^{th} -8.44e-9 6^{th} 6.278e-14 8^{th} -2.344e-18	

Table 1. Optical manufacturing data for the original cemented triplet

A careful thermal analysis carried when starting the manufacturing phase, however, showed serious risks of damage due to the expected temperature variations during both the storing, transport and operational stages. The important difference in CTEs (9.5, 6.5 and 1.3 ppm per Kelvin for S-BAL3, S-NBM51 and S-FPL51 glass, respectively), together with the non-negligible aperture diameter, did not provide indeed enough guarantees against the risk of loss of adherence or even a complete separation of triplet components. It has been therefore needed to re-design the triplet lens, in such a way to meet all the requirements related to focal planes and pupil planes positions, f-numbers and magnification, Strehl ratio and wavefront error. The solution adopted is composed by spherical surfaces only in an air-spaced assembly. The relative higher ease to manufacture these lenses is overwhelmed by the more demanding mounting and alignment constraints, as well as by the need to perform a complete and careful analysis of the opto-mechanical interfaces and unwanted optical effects, first of all ghosting.

The work has been carried out by Officina Stellare Srl, Italy. Spot diagrams and overall transmission are reported in Figure 4.

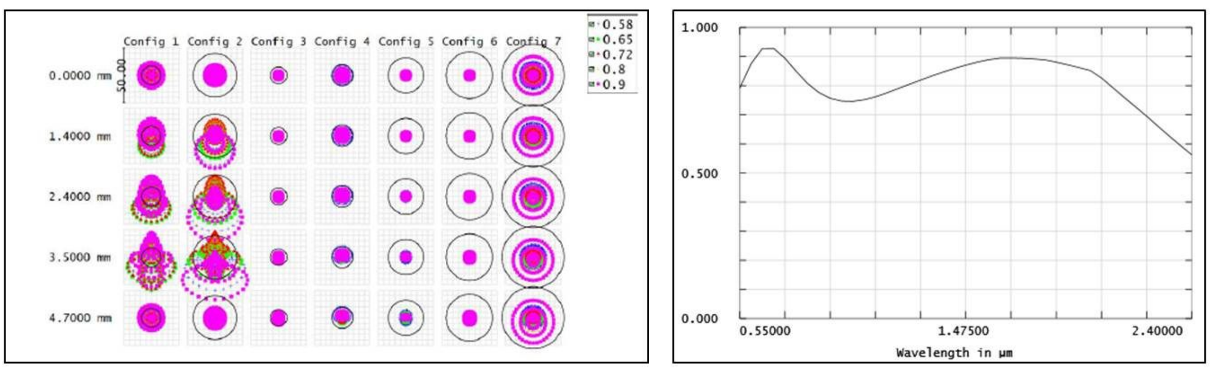

Figure 5. *Left*: new triplet lens spot diagrams. The first two configurations refer to pupil mode. The other five configurations refer to NGS VIS (750 nm), LGS VIS (589 nm), J, H and K, respectively. *Right*: new triplet lens transmissivity over the full 0.4 – 2.4 µm wavelength range.

4.2 Focal plane mask

Focal plane sources are directly obtained as pinholes and slits on a thin metal sheet that can be moved across the focal plane through two linear stages and can be rotated around its center. The rotation is used to place the desired pinhole above an back-illuminating diffuser (only a pinhole needs to be used at a time) or above the single-mode fiber tip (in case a DL source has to be used), as well as to rotate the slits for SPIFFIER tests.

The pinhole mask pattern is shown in the left part of Figure 5. Proper safety spaces are left around each pinhole in order to avoid interference on the light coming from the desired pinhole and the straylight possibly coming from other pinholes. Pinholes and slits are back-illuminated by a diffuser rear-fed by two multi-mode optical fibers. Other two, single-mode optical fibers are directly exposed to simulate DL sources at the various working wavelengths.
A summary of the artificial sources (fiber tips, pinholes and slits) is reported in Table 2.

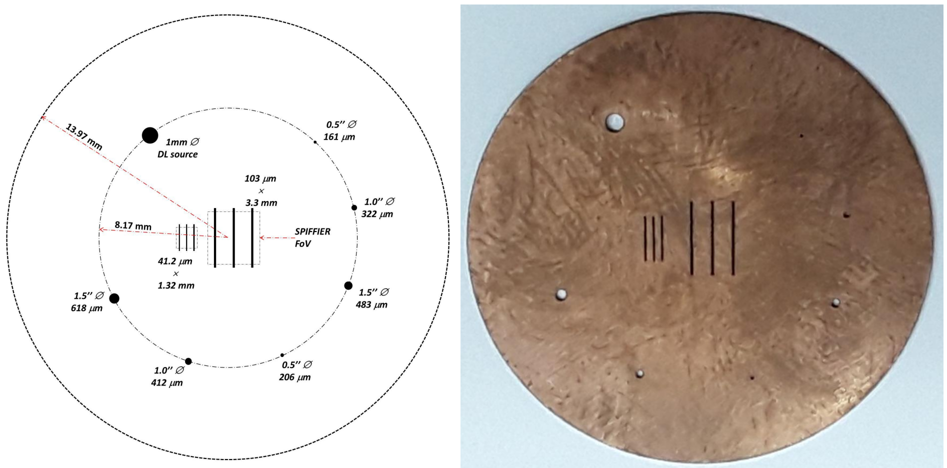

Figure 6. *Left*: designed pattern for the Focal Plane Mask. *Right*: first prototype manufactured by EDM at Scarimec Srl, Italy.

Source ID	**Source type**	**Size on sky**	**Size on PHM**	**Configuration**
DLVIS	9.6-μm SM fiber tip	22.47 mas @ 750 nm	9.77 μm @ 750 nm	FPN
DLNIR	12.5-μm SM fiber tip	37.45 mas @ J 49.43 mas @ H 65.91 mas @ K	16.21 μm @ J 21.59 μm @ H 29.03 μm @ K	FPN
NGS05	Circular pinhole	0.5 arcsec	206 μm	FPN
NGS10	Circular pinhole	1.0 arcsec	412 μm	FPN
NGS15	Circular pinhole	1.5 arcsec	618 μm	FPN
LGS05	Circular pinhole	0.5 arcsec	161 μm	FPL
LGS10	Circular pinhole	1.0 arcsec	323 μm	FPL
LGS15	Circular pinhole	1.5 arcsec	484 μm	FPL
SLIT1	Set of 3 slits	0.25 (w) x 9 (l) $arcsec^2$	103μm x 3.72mm	FPN
SLIT2	Set of 3 slits	0.1 (w) x 4 (l) $arcsec^2$	41μm x 1.65mm	FPN

Table 2. Summary of focal plane sources characteristics. Fiber tips useful diameters (MFD, mode-field diameter) must be smaller than the requested source size. They are imaged through a 1-mm hole properly placed onto each of them.

The mask (right part of Figure 5) is being manufactured by the Italian company Scarimec srl, by using sinking electrostatic discharge machining (EDM) on a 0.2-mm thick copper plate. Microscope inspection and measurement (Figure 6) revealed the first prototypes already very promising, showing almost all the parameters within specifications with the exception of slits parallelism, as reported in Table 3. At the moment this paper is being written, improvements on the prototypes are being attempted by acid corrosion (with NH_4 or $FeCl_3$ based solutions), in order to meet the slit parallelism specification, too.

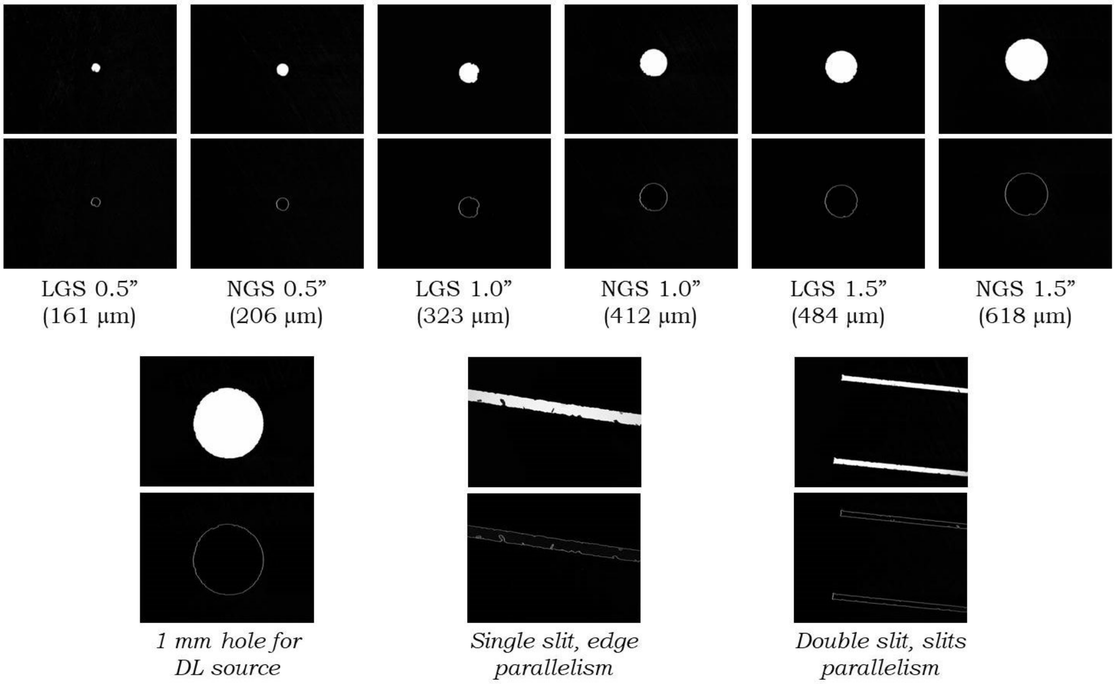

Figure 7. Pinholes and slits at the microscope. Each image is provided with its edge-detected profile, for measurement purposes.

Source ID	Size specification	Measurement
NGS05	206 μm	148.0 μm ± 19.2 μm
NGS10	412 μm	342.2 μm ± 16.4 μm
NGS15	618 μm	554.9 μm ± 4.7 μm
LGS05	161 μm	111.0 μm ± 81.0 μm
LGS10	323 μm	263.6 μm ± 6.7 μm
LGS15	484 μm	427.7 μm ± 8.1 μm
SLIT1	103μm width 1.03 mm separation 2.31 arcmin edge parallelism 2.31 arcmin slits parallelims	66.0 μm ± 2.6 μm 1.070 mm ± 2 μm 1.01 arcmin ± 0.88 arcmin **6.9 arcmin ± 3.4 arcmin**

Table 3. Some measurement results on focal plane sources characteristics for first pinhole mask prototypes. All pinhole diameters are smaller than the requested ones and are therefore suitable for acid corrosion by ammonia or iron chloride. Slits parallelism, written in boldface, appear still out of specification (1/10th of pixel on SPIFFIER for one end to the other end of the slit).

5. CONCLUSIONS

In this paper the final design and manufacturing of the ERIS Calibration Unit have been described. Particular attention has been given to the design details which have requested unplanned reworking or new solutions during the construction phase. Although often driven by the tight schedule, the solutions appeared suitable to compensate for the effects of such unplanned activities on the schedule itself. The ERIS CU is planned to be integrated with the other ERIS subsystems starting from October 2018. The whole instrument installation at VLT and first light is expected in spring 2020.

6. ACKNOWLEDGEMENTS

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