MAORY/MORFEO@ELT: Calibration Unit overview

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ABSTRACT

The Calibration Unit (CU) of MORFEO, the Multiconjugate adaptive Optics Relay For ELT Observations (formerly known as MAORY), is a complex optomechanical subsystem to project on the telescope NGS and LGS focal planes a large number of light sources at different wavelengths. These sources are needed to run calibration, verification and test procedures on MORFEO at the Extremely Large Telescope (ELT). This subsystem will play a critical role not only during operations, but also during the Assembly, Integration and Verification (AIV) phase in Italy, when it will be used in the Test Unit (TU) configuration, including a Deformable Mirror (DM), and in Chile. We present a general overview of the CU preliminary design, focusing on the reasons that led to the current optomechanical configuration and providing a more detailed description of the calibration sources, the light transmission chain and the electronics.

Keywords: Adaptive Optics, Instrument Calibration, Optical Fibers, Visible and Infrared Instrumentation, ELT

1. INTRODUCTION

MORFEO[1] (Multi-conjugate adaptive Optics Relay For ELT Observations) is a post-focal adaptive optics module, designed to enable MICADO[2] to perform high-angular resolution observations in the near infrared, providing real-time MCAO corrections to the atmospheric wavefront distortions over a FoV of about 1 arcmin.

The CU is a complex optomechanical subsystem required to project artificial sources (both diffraction limited and extended) at visible and infrared wavelengths on the ELT focal planes. The sources will enable MORFEO to run templates needed for wavefront sensors, Non-Common-Path Aberrations (NCPAs) and tomographic reconstructor calibrations. Moreover, once at the ELT, the CU will allow to drastically reduce the amount of required night-time for daily and periodic functional health-checks, calibrations and maintenance operations. Finally, the CU (in Test Unit configuration) will be used to perform MORFEO verification and test procedures during the Assembly Integration and Verification phase (AIV) in the Integration Hall in Bologna (Italy).

MORFEO is going to close its Phase B (Preliminary Design) and start the Final Design. First-light is expected in 2028.

2. DESIGN REQUIREMENTS

The CU is asked to provide a set of suitable calibration light sources, different in amount, distribution, size and wavelength. The sources can be grouped in the following three typologies, according to their wavelengths and the corresponding fed camera (i.e. a MORFEO WFS or the MICADO imager):

- Extended LGS sources (589 nm) feeding the LGS WFS;
- Seeing-limited NGS-REF sources (R-band) feeding the REF WFSs technical field;
- Diffraction-limited (H-band) feeding the LO WFSs technical field (NGS-LO sources) and the MICADO field (NGS-MIC sources);

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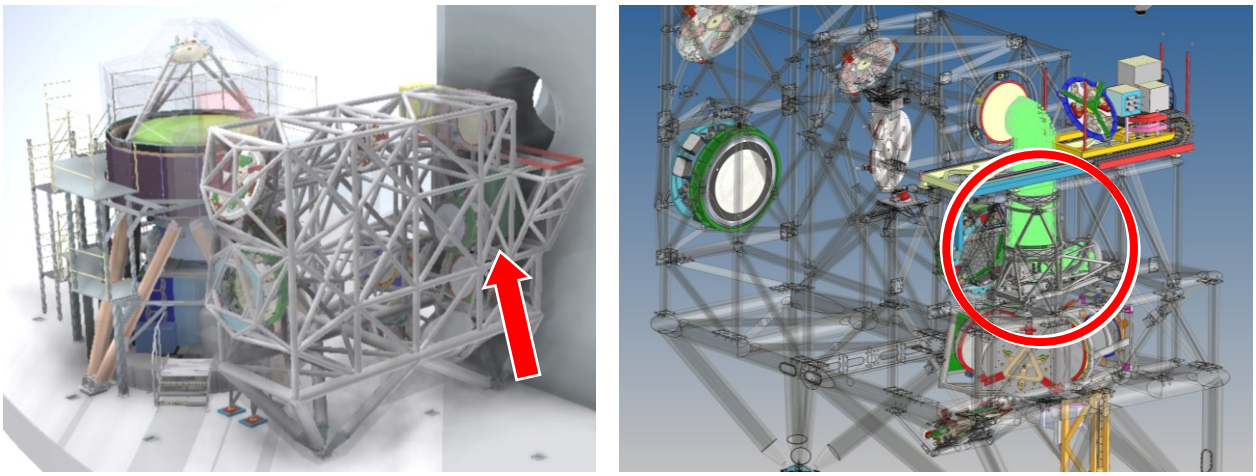


Figure 1. Left: the MORFEO Main Structure (MS) is shown on the Nasmyth platform close to the ELT Post Focal Station. The red arrow shows the position of the CU (not visible here) inside the MS. On the left side of the MS, it can be seen the MICADO tower that hosts the MORFEO NGS WFS module. Right: the red circle indicates the position of the CU on the MORFEO MS (rear view). The green beam shows the optical path from the source masks to the TFP.

The main requirements driving the CU design are the following:

- Emulation of 2 LGS asterisms at 45" off-axis, focused at the Laser Focal Planes (LFPs) conjugated at 104 km and 150 km;
- Emulation of (at least) 2 asterisms of 3 NGSs (H-band) in the technical FoV at the Telescope Focal Plane (TFP);
- Emulation of a regular grid of NGS-REF sources across the technical FoV (180" diameter);
- Emulation of an asterism of NGS-REF and LO (coupled sources, with interaxial distance within 0.5 arcsec) distributed in the LOR[3] WFSs technical FoV and on-axis;
- Emulation of a grid of at least 9 NGS-MIC sources in the MICADO FoV (53''x53''), to calibrate NCPA between MICADO focal plane and NGS WFS, diffraction limited in H-band.
- Provision of both technical field sources (NGS-REF, NGS-LO) and science sources (NGS-MIC) at the same time;
- Intermediary pupil (for all sources): shift: <1%; blur <1%; distortion <1% (% of pupil diameter):
- Focal plane f-number and curvature according to conjugation altitudes (NGS tolerance: F-number ± 1%, curvature ± 70 mm);
- Common accessible pupil for all the beams, with a diameter around 100 mm to both preserve the pupil blur quality and to implement a suitable DM needed for operation in Test Unit (TU) configuration.
- High constraints on mass (max 350kg) volumes and opto-mechanical interfaces with the MORFEO Main Structure[4] (MS), see Figure 1.

3. ARCHITECTURE

The CU subsystem is divided in two main components: the CU Main Bench (CUMB) and the CU Electronics cabinet (CUE). The CUMB is positioned into the MORFEO MS just below the TFP. It is the most complex part of the unit. Its mechanical structure holds together the numerous components of the optical system, needed to inject the beacons coming from the LGS and NGS masks into the MORFEO post-focal optics. After passing through the optical relay, the beams are injected into the MORFEO path through the CU Folding Mirror (CUFM), moved by the Calibration Units Selector (CUS), and focused on the corresponding focal planes, according to their conjugation altitude (see Figure 2).

The CUE is located below the Nasmyth platform, together with most of the cabinets required by the other MORFEO subsystems. It hosts the control electronics, the physical light sources and the opto-mechanical modules (Light Source Units – LSU) that feed the optical fibers connected to the CUMB.

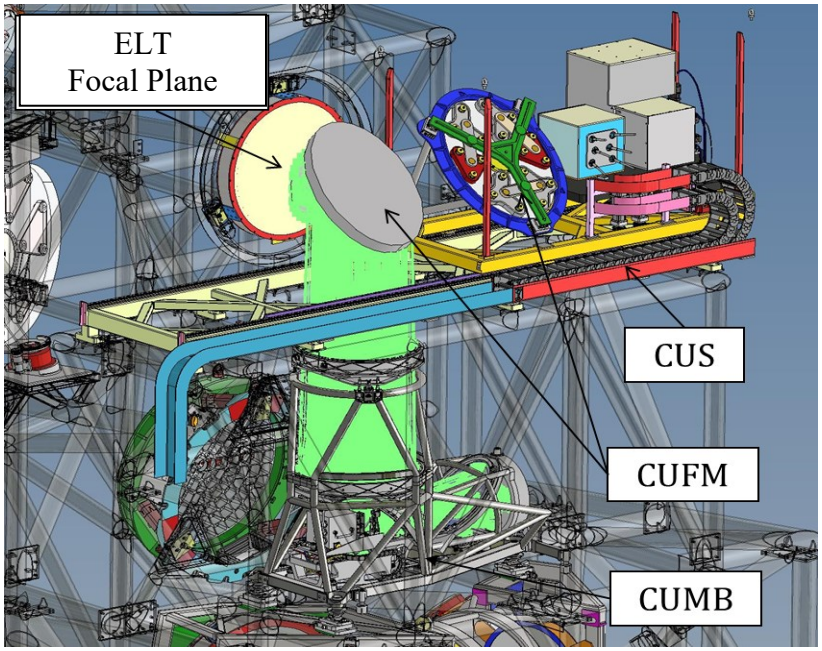


Figure 2. The CU Main Bench (CUMB) inside the MORFEO Main Structure.

3.1 CU light path

The optical fiber coming from the CUE, when connected to the CUMB, allow the light to reach the Fiber Splitting Unit (FSU) and the LGS Mask (LGSM) respectively (see Figure 3 and Figure 4). In the FSU a set of fiber splitters provide the final number of NGS fibers (plus some ready-to-use spares) to the NGS Mask (NGSM).
As previously described, the CU provides four types of calibration sources. The REF sources (Figure 3) are obtained by means of two Quartz-Tungsten Halogen (QTH) lamps hosted in the REF-LSU, each feeding a 400µm core multimode (MM) fiber from the cabinet to the CUMB. The flux of each channel can be adjusted by moving a Neutral Density Filter (NDF) to select the required magnitude on the mask. Inside the CUMB, the FSU hosts ten 1x8 MM fiber splitters, used to provide up to 64 REF sources of the same flux (including spare fiber terminations). Two terminations (coming from the first level of the splitters cascade) are used to feedback the light to the cabinet, where two flux sensors are used to check the lamps operation and the fiber integrity. A MM fiber between the cabinet and the CUMB (not shown in Figure 3) is used as a spare connection to ensure a fast recovery of the operations in case of break of one of the 4 lines (2 from the lamps and 2 back to the flux sensors).
The LO and MIC sources are produced by three super-luminescent diodes (SLED) hosted in the LO Light Source Unit (LO-LSU) by means of three single mode (SM) fibers connecting the CUE to the CUMB. Here, in the FSU, each line is split in 16 terminations to provide two set of LO sources (including spares): 32 fiber connectors with LO (H-band diffraction limited) and REF (600nm-100nm seeing limited) cores coupled within the same ferrule and 16 terminations for the MICADO field sources (H-band diffraction limited). The sensing of the LO flux is done within the SLED that includes a photodiode to control the source power during operations. A further SM fiber between the cabinet and the CUMB (not shown in Figure 3) is used as a spare connection for fast recovery if a line breaks.

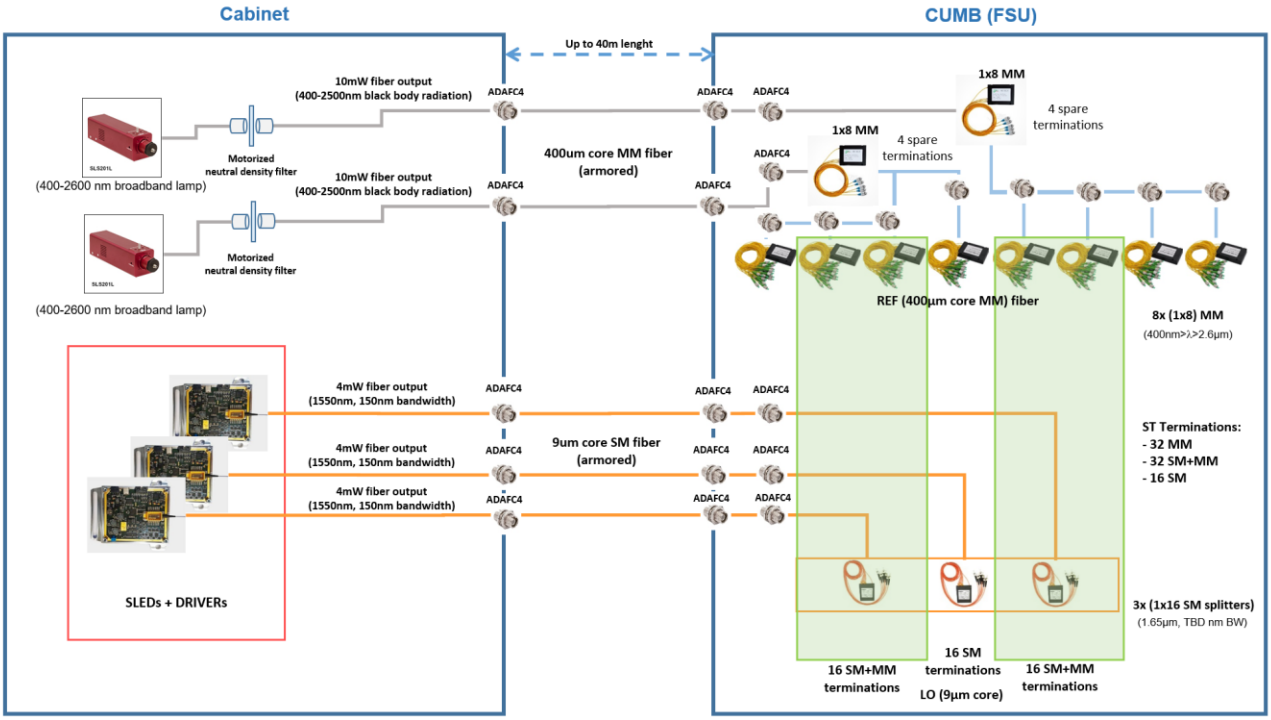


Figure 3. Scheme of the fiber connections between the cabinet and the CU Main Bench for the NGS mask. Several SM and MM fiber splitters in the CUMB FSU allow to multiply the number of terminations used to properly feed REF and LO sources in the NGS mask.

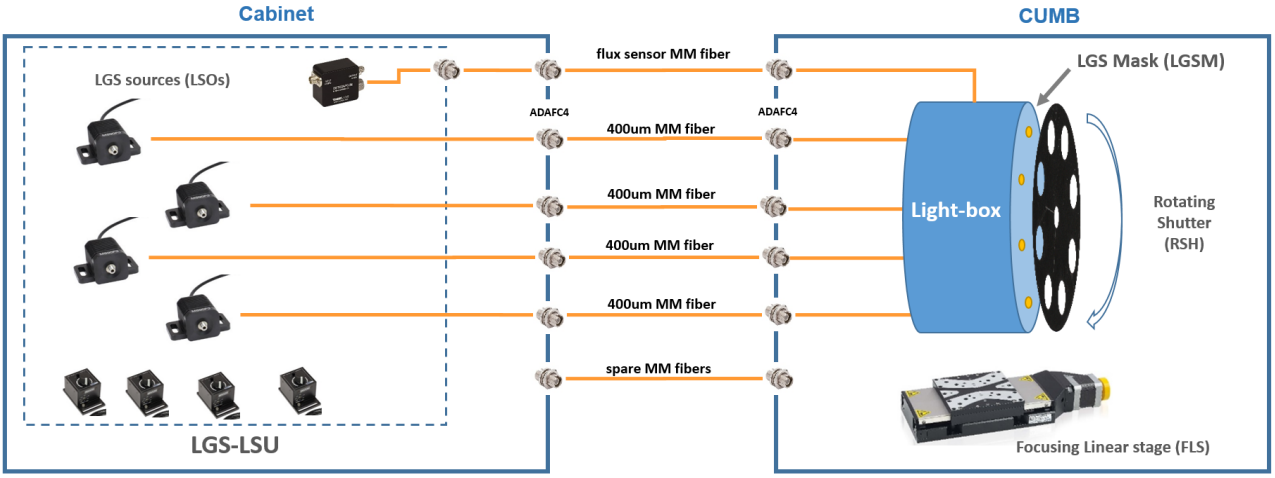


Figure 4 – Fiber connections between the cabinet and the CU Main Bench for the LGS sources.

FC/PC Connectors with 2.0 mm Narrow Keys will be used for all CU fibers (both SM and MM) while ST connectors will be used only at the NGS mask, in order to allow a special tool to easily dismount the fibers when they are all

connected, so preventing accessibility problems to the connectors grid. Anyway, since all fibers connected to the NGS mask are fixed, we do not foresee any ordinary maintenance operation for this component.
All CU fibers from the CUE to the CUMB are armored (stainless steel) and black coated. The black coating prevents reflections (in particular within the MAORY enclosure), while the all-metal jacket prevents possible damages.
The LGS sources are obtained by means of pinholes on a mask in front of a LightBox acting as an integrating sphere (Figure 4). It is fed by four MM fibers, each connected to a narrowband laser diode inside the LGS-LSU in the cabinet. A further MM fiber is used to feedback the light to a sensor inside the cabinet, while a spare MM fiber ensures a fast recovery if a line breaks.



Figure 5. CAD model of the CUE. It hosts the CU control electronics, the optomechanical modules for the fiber and filters selection, visible and infrared light sources and redundant power supplies in a liquid-cooled environment. The interface panel for the connections (cable & fibers) with the CUMB is on the top side. The front side (left) allows the inspection of visual indicator lights and fast maintenance operations. Internal connector interfaces and power switches are placed on the rear side (right).

3.2 Control Electronics

The CUE, positioned far away (up to 40 m) from the CUMB, consists of a standard cabinet from Schroff (model Varistar LXH3 10130-193) which contains seven 19-inch sub-racks (see Figure 5), needed to operate and control the electronic devices of the CU. Among them, three electro-opto-mechanical modules the REF-LSU, the LO-LSU and the LGS-LSU, host the physical light sources feeding the NGS and LGS channels. The strategy to place these devices inside the CUE is due to the limited volume and mass budget available on the MORFEO MS, and to the need to avoid the presence of thermal sources close to the CU optical relay.
The CU control electronics is designed according to the MORFEO Instrument Control Hardware specifications[5] according to a modular approach. About 30U are used by the seven sub-rack units, leaving 8U for auxiliary service and cables routing. The Instrument Control Electronics (ICE) is housed in a Heitec Heipack Vario 3684195 sub-rack. It hosts the current ESO standard Beckhoff CX2030 PLC, the EtherCAT terminals used for motion control and several analog and digital I/O.
Although the modular architecture adds some complexity to the design (more internal interfaces) it allows to better accommodate the electronic components within the available cabinet volume and group them together according to the function they will provide. Moreover, this enables to simplify AIV, troubleshooting and maintenance operations that can be made on separated sub-racks (dismounted and brought on a lab bench), without affecting the availability of the other CU functionalities.

The control software for the acquisition of the natural and laser reference stars during daily periodic health checks and calibrations of MORFEO will be based on the new Instrument Control Framework (IFW), which is currently under development by ESO for the ELT[6].

4. OPTICAL DESIGN

The configuration of the MORFEO post focal relay excludes the possibility to place calibration light sources directly at the ELT conjugated focal planes. In principle, this would be feasible for NGS sources, but not for the LGS sources, whose focal planes fall in positions not accessible downstream the TFP. For this reason, to fulfill the requirements, the CU has been designed as an optical relay that projects the calibration light sources at three different focal planes (conjugated to infinity for NGS, and to 104 km and 150 km for LGS) in order to feed MORFEO WFSs for calibrations and periodic system health checks. The main optical features of the CU output focal planes are summarized in Table 1.

Table 1. The main optical features of the CU output focal planes (ELT focal planes).

Name	Conjugation Altitude [km]	F/# [-]	Distance (from TFP) [mm]	RoC [mm]	Plate scale [mm/”]
NGS FP	inf.	17.75	0	-9884	3.316
LGS-150 FP	150	19.34	3398	-9488	3.613
LGS-104 FP	104	20.14	5104	-9302	3.762

The optical design has turned out to be rather challenging, mainly due to the following reasons:

- several wavelengths to be transmitted in the range 580 nm – 1800 nm;
- large FoV, especially for NGSs (160” diameter);
- tight quality requirements (less than 100 nm RMS WFE);
- small and accessible intermediate pupil (common for NGS and LGS paths);
- all calibration source types possibly available at the same time;
- limited available volume and mass budget (max 350 kg).

The CU baseline optical design, shown in Figure 6, consists of three principal parts: an LGS arm that allows to select sources between two conjugation altitudes, an NGS arm and a catadioptric “telescope”.
The two arms consist of two separated optical systems generating NGS sources across the 160’’ technical FoV (R- and H- bands) and 6 LGSs at 45’’ off-axis, respectively. The two optical paths share and illuminate a common pupil, then their beams pass through the third main part of the relay, the catadioptric system that properly focuses the artificial sources to their respective focal planes, according to their conjugation altitudes. The light is folded into the MORFEO post focal relay optics thanks to the CUFM just above the CU (not shown in Figure 6).
The requirement for imaging NGSs (in R- and H-bands) and the interface constraints led to choose this catadioptric design option, in which the NGS light essentially goes through a fully reflective two-mirror system, while the second part for imaging LGSs contains two lenses, since it doesn’t suffer from chromatic aberration due to the monochromatic band of the LGSs. The common third part contains the largest optics in order to provide a common pupil with a diameter of at least 100 mm or larger so that it can be used with the foreseen DM to fully test and verify MORFEO during AIV and Preliminary Acceptance Europe (PAE) in Italy.

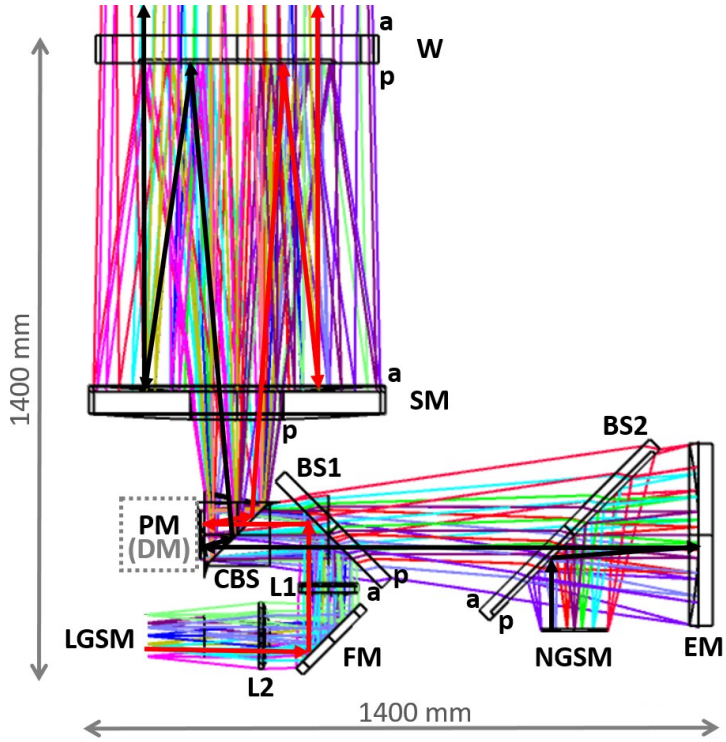


Figure 6. CU optical relay. The colored arrows indicate the two optical paths: LGS path (red, with the mask planes conjugated to 104 km and 150 km) and NGS path (black). The optical surfaces are marked as "a" for anterior and "p" for posterior interface (when going from the ELT focal surface to the NGSs or LGSs sources mask, i.e. the opposite direction of the arrows); the CUFM (not shown) is placed 950 mm above W-a and 250 mm before the TFP (center-to-center distance). Gravity goes from the top to the bottom.

This optical relay has been designed "in reverse direction", following a standard approach in optical engineering. For this reason, the beams, positioned at the required conjugation altitudes, pass first through the telescope relay and then focus on the CU focal planes (coinciding with the source masks planes), so that the effect of the intrinsic aberrations of the ELT is preserved and can be reproduced by the CU. This also means that the nominal characteristics of the ELT focal planes (f-numbers and curvatures) are automatically reproduced by the CU in nominal design.

The peculiarity of this design is the use of a number of semi-reflective (50% transmission and 50% reflection) optics as the largest optics (W and SM, about 600mm diameter), and the Beam Splitters (BS1 and BS2). The reason for this design choice was to retain the rotational symmetry for all optical elements used for the LGS path, thus avoiding any tilted glass plate beam-splitters that would introduce a large amount of differential astigmatism in the 6 LGS beams. This problem is not critical for NGSs because they have just one conjugation and the beam is kept collimated when passing through the tilted glass plates. The semi-reflective components enable a compact optical design (in particular the W and SM optics), to combine different optical paths (BS1) and to make the pupil accessible (CBS).

In reverse direction, the catadioptric module, containing the flat semi-reflective Window (W) and the Spherical Mirror (SM), forms an image of the telescope pupil on a 104 mm Pupil Mirror (PupMir), replaced by a DM in TU configuration. Following the order identified by the arrows in Figure 6, the light from an array of NGS sources reflects from the semi-reflective surface of the 45 deg inclined BS2 and goes towards the Ellipsoidal Mirror (EM). After reflecting from the EM, the beams are nearly collimated and, as they pass through the tilted parallel plates (BS1 and BS2) and a Cube Beam-Splitter (CBS), are essentially aberration free. The reverse orientation of BS1 and BS2 and their identical thickness ensures that there is no lateral chromatic translation of the central NGS beam. After the CBS, the light reaches

the PupMir, optically conjugated to the telescope pupil. After reflection from the PupMir and the 45 deg semi-reflective inner interface of the CBS, the light enters the catadioptric segment from the back surface of the Spherical Mirror (SM), which has a semi-transparent coating on its front surface (SMa). The central part of the SM acts as an afocal meniscus lens, and after passing through this lens, the light reaches the flat semi-reflective window W. About 50% of this light exits the system, while the other half is reflected back towards the SM, that focuses the NGS sources onto the TFP.
Regarding the LGS path, the beams from the 6 LGS sources pass through the lenses L2 and L1 (which have one aspheric surface each), reflecting on the folding mirror (LGS-FM) placed between them. Then, the beams enter the CBS and the catadioptric module, after reflection by the BS1. The change in axial distance of the LGS mask focal position (between the farther LGS-104km configuration and the closer LGS-150km configuration) is about 126 mm.
Because of the use of several semi-reflective optics, this solution has intrinsic drawbacks (very low throughput, ghost and stray light effects) that have been extensively analyzed to be sure they do not hinder alignment procedures and do not affect the required system performance[7].

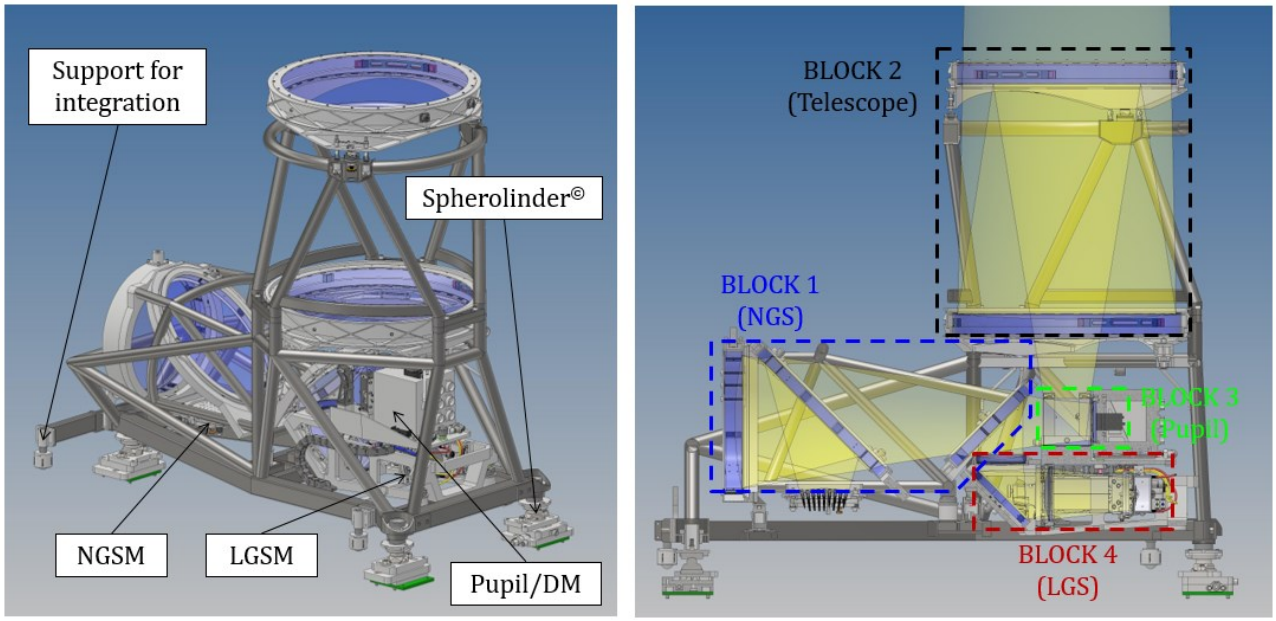


Figure 7. CUMB mechanical design with its blocks (external cover, FSU, fibers and cables are not shown).

5. MECHANICAL DESIGN

The mechanical structure of the CUMB (Figure 7) has recently been completely revised, to be compliant with the alignment needs. It is made of welded tubular profiles (steel) and connected to the MORFEO Main Structure through 3 Spherolinders which ensure the interface repeatability and allow for small displacements capable of compensating thermal effects. The position of the whole CUMB is adjustable in all directions, thanks to push-pull screws positioned just below the Spherolinders.
All the opto-mechanics have been grouped in 4 blocks to ease the alignment process and maintenance operations. They also provide the required DoFs to be aligned each other following a well-defined step-by-step procedure (after their individual internal alignment).

5.1 Sources masks

The NGS mask (Figure 8) is 150 mm in diameter, has a RoC of 363.7 mm and hosts a grid of 7 by 7 REF sources, regularly distributed across the technical FoV (160”), surrounded by 12 more external additional sources, for a total of 61 REF sources. Among them, 24 are coupled with LO sources (by means of two-cores ferrules). A 400µm core multi-mode fiber is used for each REF source and a 9µm core single-mode fiber for each LO source.

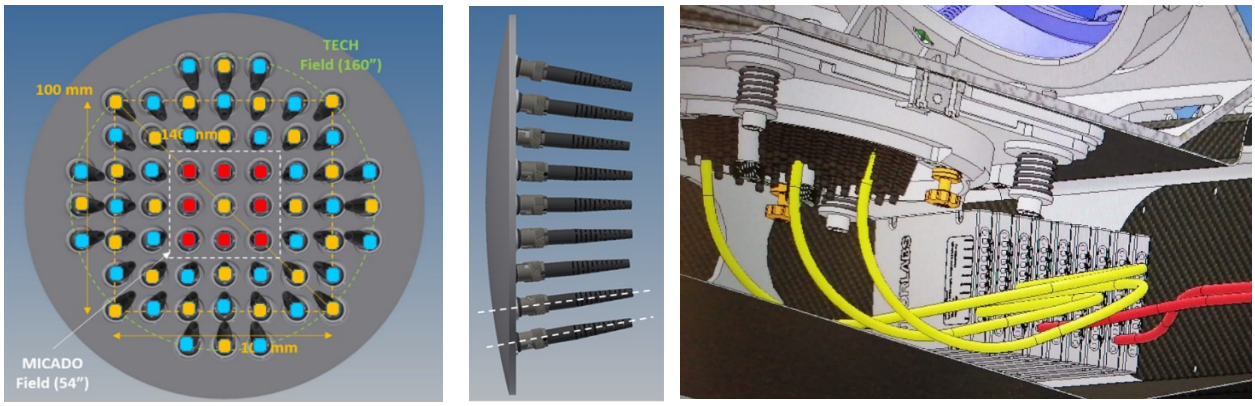


Figure 8. *Left:* Source pattern geometry of the NGS mask: blue circles represent the REF sources (400 mas), red dots the MIC sources (8 mas, DL @ 1650 nm). The LO sources (coupled with the REF ones across the LOR WFSs technical FoV and on-axis) are shown with orange circles. *Right:* The NGS mask assembly mounted on the CUMB (block#1), with some (yellow) fibers attached, coming from the underneath FSU. *Center:* CAD model and geometry of the NGS convex mask, populated with 61 bayonet ST connectors.

The 9 central sources (the MIC sources placed within the MICADO FoV) are single sources, with the exception of the central one on-axis, that is coupled with a REF source.
The large number of connectors on the convex mask has required a careful evaluation of the physical separation among connectors and of the space needed for their mounting and dismounting. Moreover, since the fibers are attached to the mask through connectors, although every connector seat is obtained through a precise machining (so that the chief ray direction can be reproduced with the required accuracy, smaller than 0.1 deg), the coupling of each fiber with its connector and between the connector and the mask could introduce an error in displacement (represented through a cone subtended by a certain angle, estimated in max 0.5 deg). For this reason, a specific sensitivity analysis[7] has been carried out to understand the effect of such uncertainty and allocate a proper WFE budget.

The LGSM assembly (Figure 9) is composed of:

- A backlit flat pinhole mask, 100 mm in diameter, with two regular asterisms of six sources each (3 mm diam.), mutually rotated about 23 deg, to simulate the rotation on sky of the LGS asterisms between 104km and 150km;
- The LightBox, fed with large core MM fibers to provide uniform profile distribution within the extended LGS;
- A motorized linear stage to adjust for focus at the two nominal altitudes;
- An adjustment system, to align the mask to the optical path;
- A motorized shutter, to stop the light coming out from the unused/unselected LGS asterism.

The light coming from stabilized light sources in the CUE, and carried to the CUMB by means of four multi-mode fibers, is injected into the LightBox. Redundancy of the fibers (each one fed by a laser diode) ensures to continue the operations in case of failure of a LED lamp. The LightBox is internally coated with a highly diffuse reflectance material (e.g. Spectralon), so that the output beams have a very uniform intensity profile.

A rotating shutter has been implemented to select only one LGS asterism at a time, preventing the stray light that would come from pinholes of the out-of-focus asterism. The whole assembly is mounted on a linear stage, necessary to move it between the two LGS focal planes.

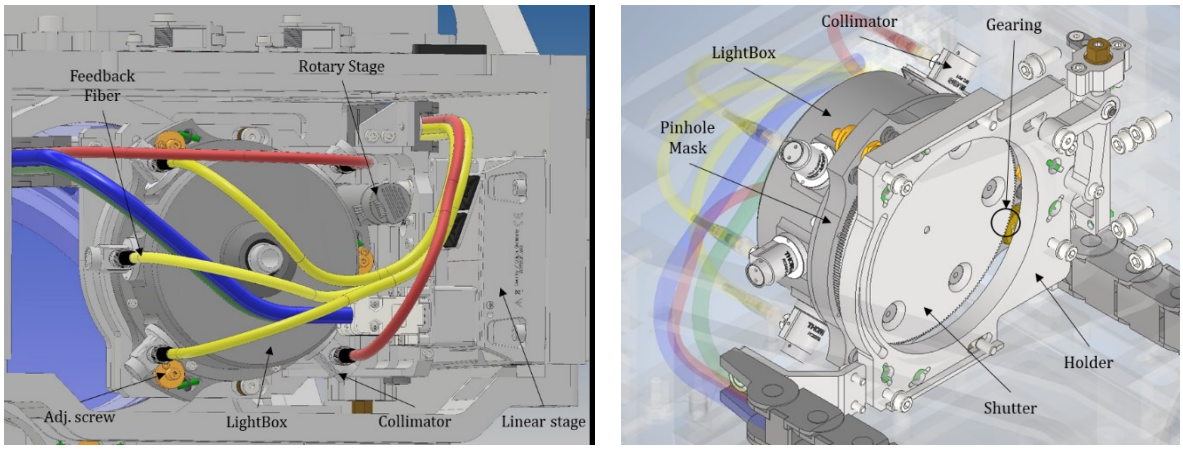


Figure 9. LGSM assembly. *Left*: rear side of the LGSM, showing the fiber connections to the LightBox and the motorized focusing stage. *Right: f*ront side hosting the pinhole mask and the motorized shutter in front of it.

6. CONCLUSIONS

During the last year, the Preliminary Design of the CU has been extensively revised and improved, especially in the mechanical aspects. Further and more detailed analyses on the expected CU performances confirmed the validity of the design in matching the provided requirements, in particular in terms of overall WFE. Despite the intrinsic complexity of this subsystem and some less favourable peculiarities, the extensive analyses carried out on the effects produced by the low throughput and the ghost and stray light, proved that they are not harmful, while the definition of a step-by-step alignment procedure leads us to be confident about the reliability and the robustness of this preliminary design, whose formal closure is expected by early next October.

REFERENCES

[1] Ciliegi, P., et al., “MAORY@ELT: general overview up to the preliminary design and a look towards the final design”, Proc SPIE 12185-40, this conference (2022)
[2] Davies, R., et al, “The MICADO first light imager for the ELT: overview, operation, simulation”, Proc. SPIE, 107021S (2018)
[3] Bonaglia, M., et al., “MORFEO/MAORY Low-Order and Reference WFS module preliminary design”, Paper 12185-175, this Conference (2022)
[4] De Caprio, V. et al., “Mechanical design overview for the Main Structure of MAORY” Paper 12184-106, this Conference (2022)
[5] Cascone, E., et al., “General overview of MORFEO (formerly known as MAORY) Instrument Control Hardware design”, Paper 12184-110, this Conference (2022)
[6] Salasnich, B., et al., “MORFEO (formerly known as MAORY) instrument control software: toward a consolidated design.” Paper 12189-36, this Conference (2022)
[7] Di Antonio, I., et al., “The Calibration and Test Unit of MAORY/MORFEO: analyses and performance evaluation”, Paper 12185-205, this Conference (2022)