# MORFEO at ELT: the adaptive optics module for ELT


Paolo Ciliegi[a], Guido Agapito[a], Matteo Aliverti[a], Francesca Annibali[a], Carmelo Arcidiacono[a], Nicolò Azzaroli[a], Andrea Balestra[a], Ivano Baronchelli[a], Alessandro Ballone[a], Andrea Baruffolo[a], Federico Battaini[a], Simone Benedetti[a], Maria Bergomi[a], Andrea Bianco[a], Marco Bonaglia[a], Runa Briguglio[a], Lorenzo Busoni[a], Michele Cantiello[a], Giulio Capasso[a], Giulia Carlà[a], Elena Carolo[a], Enrico Cascone[a], Gaël Chauvin[c], Manal Chebbo[c], Simonetta Chinellato[a], Vincenzo Cianniello[a], Mirko Colapietro[a], Jean-Jacques Correia[c], Giuseppe Cosentino[f], Elia Costa[a], Domenico D'Auria[a], Vincenzo De Caprio[a], Nicholas Devaney[b], Ivan Di Antonio[a], Amico Di Cianno[a], Andrea Di Dato[a], Simone Di Filippo[a], Benedetta Di Francesco[a], Ugo Di Giammatteo[a], Chiara Di Prospero[a], Gianluca Di Rico[a], Andrea Di Rocco[a], Daphne Diretto[a], Mauro Dolci[a], Christian Eredia[a], Simone Esposito[a], Daniela Fantinel[a], Jacopo Farinato[a], Philippe Feautrier[c], Italo Foppiani[a], Matteo Genoni[a], Enrico Giro[a], Laurence Gluck[c], Alexander Goncharov[b], Paolo Grani[a], Davide Greggio[a], Sylvain Guieu[c], Marco Gullieuszik[a], Zoltan Hubert[c], Laurent Jocou[c], Salvatore Lampitelli[a], Tommaso Lapucci[a], Fulvio Laudisio[a], Vincent Leal[c], Yves Magnard[c], Demetrio Magrin[a], Deborah Malone[b], Luca Marafatto[a], Christophe Michel[d], David Mouillet[c], Thibaut Moulin[c], Matteo Munari[a], Sylvain Oberti[e], Fabrice Pancher[c], Giorgio Pariani[a], Amedeo Petrella[a], Laurent Pinnard[d], Cedric Plantet[a], Elisa Portaluri[a], Alfio Puglisi[a], Patrick Rabou[c], Kalyan Radhakrishnan[a], Roberto Ragazzoni[a], Edoardo Maria Alberto Redaelli[a], Marco Riva[a], Sylvain Rochat[c], Gabriele Rodeghiero[a], Luca Rosignoli[a], Bernardo Salasnich[a], Salvatore Savarese[a], Marcello Scalera[a], Pietro Schipani[a], Danilo Selvestrel[a], Benoit Sassolas[d], Rosanna Sordo[a], Ludovico Teodori[a], Gabriele Umbriaco[f], Angelo Valentini[a], Marco Xompero[a]

[a] Istituto Nazionale di Astrofisica, Italy; [b] University of Galway, Ireland;
[c] Université Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France;
[d] Institut de Physique des 2 Infinis de Lyon, France
[e] ESO Garching, Germany; [f] DIFA Bologna University, Bologna, Italy



## ABSTRACT

MORFEO is a post-focal adaptive optics module that forms part of the first light instrument suite for the Extreme Large Telescope (ELT). The project is now in the Final Design Phase. In this paper, we report the status of the project.



**Keywords:** Adaptive Optics, Astronomical Instruments


## 1. INTRODUCTION

MORFEO is the Multi-Conjugate Adaptive Optics Relay for the Extremely Large Telescope (ELT) that will provide multi-conjugate correction of the incoming wavefront by means of three deformable mirrors: one on the telescope and two in the instrument optical train. The wavefront sensing is based on six laser guide stars projected on a constellation of 45 arcseconds and three natural guide stars selected into the 2,7 arcminutes corrected FOV. The two post-focal DMs are the core of the instrument and work together with the telescope's adaptive and tip-tilp mirrors, M4 and M5, respectively. MORFEO will provide diffraction-limited focal planes to the near infrared camera and spectrograph MICADO and to a second instrument not yet defined. In this paper we report an overview of the project, while several papers give a detailed description of all sub-systems in this conference.

MORFEO is being designed and built by a consortium of partners in Italy (INAF is the lead Institute), France and Ireland, together with ESO. New partners from Canada and Japan are about to join the Consortium.


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## 2. STATUS OF THE PROJECT

The Preliminary Design Review (PDR) of the MORFEO Project was formally closed in February 2023, while in October 2023, the Final Design Review of the Optical Design was completed. This was a very important step for MORFEO, which will allow the early procurement of its first optical components. As a result, in the autumn of 2023, we started the procurement activities, which led to the signature of the contract for the final design and construction of the two deformable mirrors of MORFEO, the most expensive subsystem of the whole project. Similar procurements (Final Design plus Manufacturing) are expected by the end of 2024 for all the other major subsystems (Optomechanical components of the Main Path Optics and Laser Guide Stars Objective, Calibration Unit and Mechanical Main Structure). The Final Design Review of the whole system is foreseen by the end of 2025, while the Preliminary Acceptance in Europe (PAE) is expected by 2030.

## 3. GENERAL ARCHITECTURE

A general overview of the MORFEO global architecture and a functional overview are illustrated in Figures 1 and 2, respectively. The main hardware subsystems indicated in the figures are complemented by the electronics[1] at system and sub-systems level, instrument control software[2] and real-time computer[3,4].

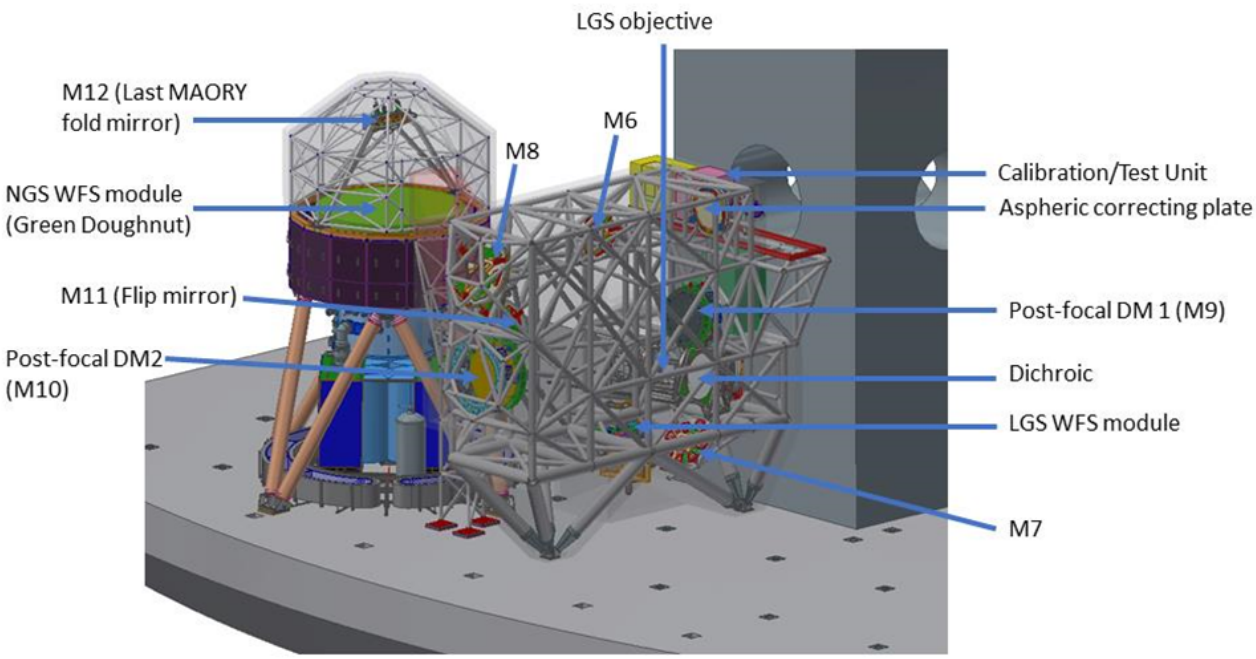


Figure 1. General overview of the MORFEO instrument (thermal cover in transparency) installed on the Nasmyth platform with MICADO.

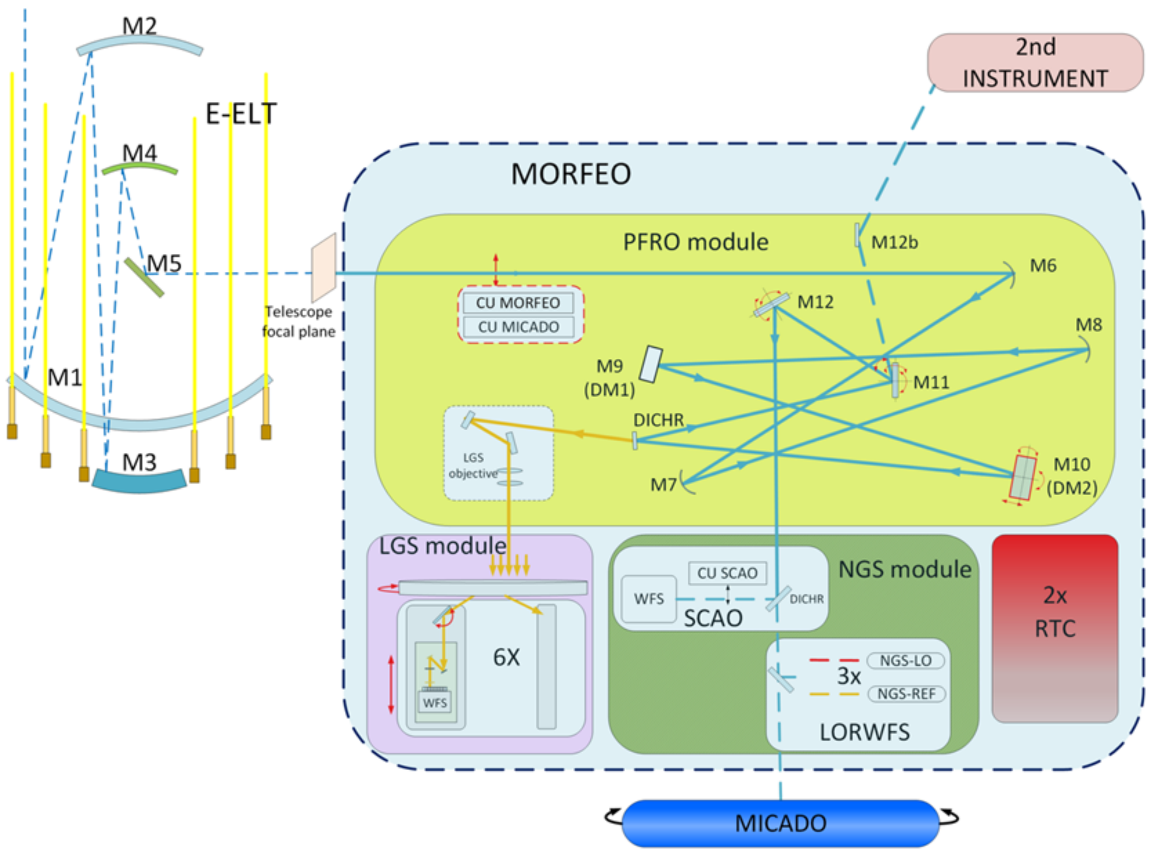


Figure 2. Functional overview of the MORFEO module in the context of the ELT and MICADO client instruments

Both the Low-Order and Reference (LOR) WFS and SCAO modules are hosted in the same structure, the so-called Green Doughnut (GD). The data produced by the cameras of the LGS WFS and of the NGS WFS are collected by the MORFEO Real-Time Computer, which drives the deformable mirrors, i.e. the telescope's M4/M5 adaptive/tip-tilt mirrors and two post-DMs inside MORFEO itself. All the wavefront sensors in MORFEO are placed downstream of the deformable mirrors, ensuring optical feedback.

### 3.1 MAIN STRUCTURE

The MORFEO Main Structure (MSS)[5] includes the following items:

• MORFEO Main Support Structure (MORFEO_MSS) → the mechanical structure that hosts all the Optomechanical elements.

• Thermal Enclosure → the cover structure of the MORFEO MSS.

• MORFEO – MICADO Thermal Duct → the structure between MORFEO and MICADO, which includes the mechanical frame and the Thermal Duct with its proper structure.

• MICADO Thermal Enclosure → the cover structure around M12 installed on the top side of MICADO.

• Calibration Unit Selector for MORFEO Folding Mirror CU and MICADO Calibration Assembly (MCA) → the linear guide carriage that allows the system to switch between the different positions.

A general overview of the MSS is available in Figure 3. while the latest results for the MSS FE analysis are available in [6].

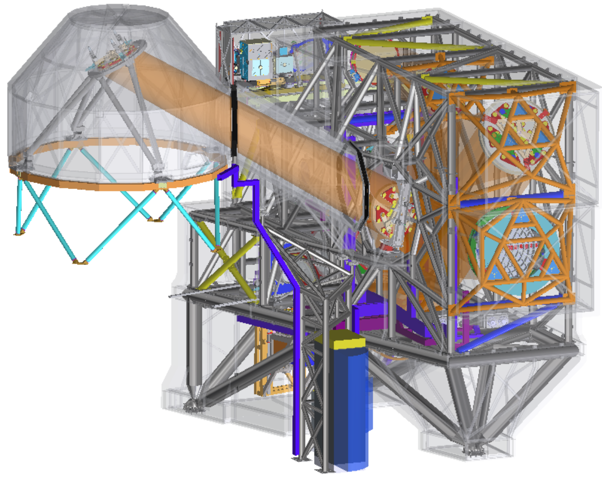

Figure 3: General Overview of the MORFEO Main Structure

## 3.2 OPTICAL DESIGN

The final MORFEO main path optics baseline (see overview in Figure 4) passed the Optical Final Design Review with ESO. It will include two optical paths:

- **the MPO (Main Path Optics)[7] that will focus IR light at the MICADO entrance focal plane** (blue rays in Figure 4). It has a total of 8 reflections. Following Figure 14, the F/17.75 beam coming from the ELT focal surface initially passes through the CPM. Following the path, there is the first flat mirror, M6M, folding the beam down to the first aspherical concave mirror, M7M. The beam is reflected up to the second aspherical concave mirror, M8M and then down again towards the first DM, M9M, having a spherical surface. This mirror is the only convex surface on the main path. After that, the beam is reflected by the second DM, M10M, which is concave and spherical. After M10M, the pupil's image is formed, and just after this image, the science and NGS light is separated from the LGS light by a dichroic filter. The LGS light (589 nm) is transmitted, while science and NGS light (600 nm - 2400 nm) are reflected. The reflected light then reaches M11M, a flat flip mirror that allows the selection of the MICADO path or of the second instrument path through a rotational axis. Finally, the light is reflected by a flat mirror, M12M (or M12M bis), installed over MICADO (or over a future second instrument) and comes to a focus at the gravity invariant entrance focal surface of the instruments.
- **the LGSO (Laser Guide Stars Objective)[8], which must draw laser wavelength (589nm) from the MPO and focus it at the entrance of the wavefront sensor** (green rays in Figure 4). The LGS Objective (LGSO) reduces the LGS beam F/# at wavelength 589 nm to 5 at the LGS WFS module entrance focal surface. It is composed of 4 silica spherical lenses (LGSO-L1, LGSO-L2, LGSO-L3 and LGSO-L4) and 3 fold mirrors (LGSO-FM1, LGSO-FM2 and LGSO-FM3). The third mirror allows feeding the LGS WFS module with a gravity invariant and telecentric focus.

The boundary between the two systems will be represented by a one-meter diameter class diameter dichroic[9], placed after all the MPO elements with power and reflecting the correct wavelength toward the LGSO (see Figure 4).

Finally, regarding the two deformable mirrors M9M(DM1) and M10M(DM2), their preliminary characteristic are available in [10] and [11] while their final design is under development in the framework of the commercial contract signed in December 2023 with Adoptica. The Final Design Review for the two deformable mirrors is foreseen by the end of 2024.

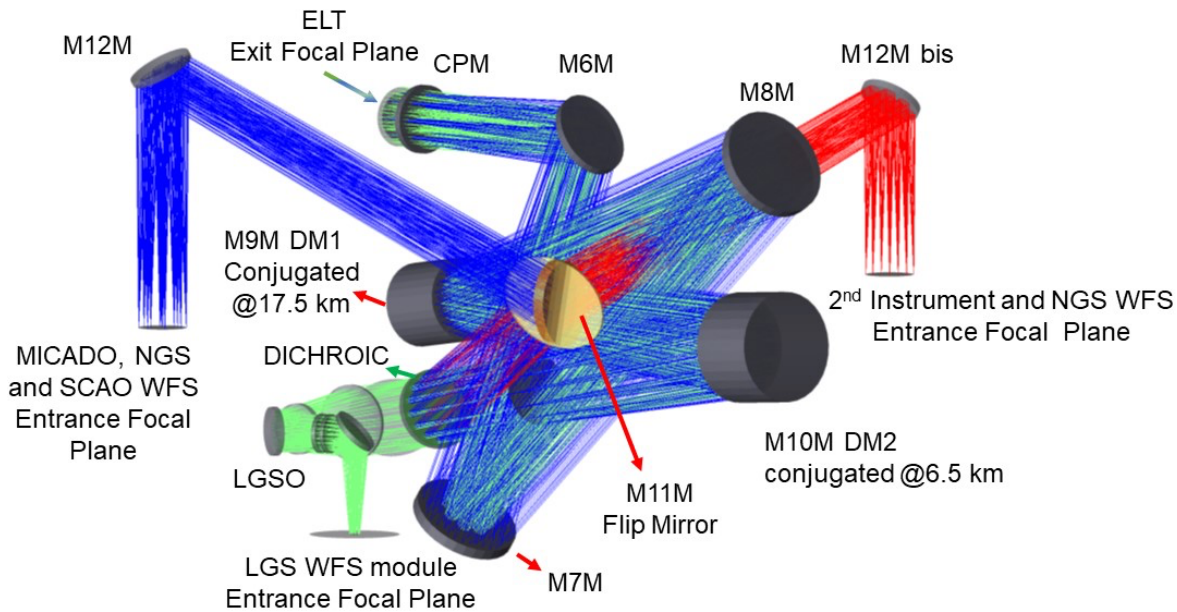


Figure 4; Overview of the MORFEO optical path

## 3.3 REAL TIME COMPUTER

According to the ELT architecture, the Real Time Computer (RTC) consists of a Hard Real-Time Core (HRTC) and a Soft Real-Time Cluster (SRTC). The former is in charge of acquiring data from the wavefront sensors and controlling the deformable mirrors and jitter mirrors, while the latter performs all the supervisory and monitoring tasks, in addition to the auxiliary loops for optimization of correction. A detailed description of the recent update of the MORFEO RTC is available in [4].

## 3.4 WAVEFRONT SENSORS

The system makes use of the 6 laser guide stars provided by the ELT and of 3 natural guide stars for low-order modes correction and truth sensing. The corresponding wavefront sensors are grouped in an LGS WFS module and in a Low Order and Reference (LOR) WFS unit, field-derotated by MICADO itself.

### 3.4.1 Laser Guide Star Module

The LGS WFS module is gravity invariant, and it can be divided into three main units: the wave-front sensor probes, which pick off the MORFEO beam after the LGSO in an LGS focal plane and sample the ELT pupil to measure the wavefront aberrations (there are 6 such probes for 6 laser launch telescopes, see right part of Fig. 5), the support structure that holds the 6 probes and aligns them in the MORFEO beam (left part of Fig. 5) and the module control electronics, cabling, power and cooling lines.

Each WFS has a 68 × 68 lenslet array positioned after a pupil imaging collimator and a folding mirror, and then, an optical relay re-images the LGS spots onto the camera detector. As a detector chip, we selected the Sony IMX 425, and one of the key points that encouraged us to make this choice is the clear advantage of a global shutter detector for our specific application[12]. The pick-off mirror in each WFS is mounted on a 2-axis piezo stack and allows to recenter the pupil image onto the lenslet array to compensate for possible shifts of the pupil.

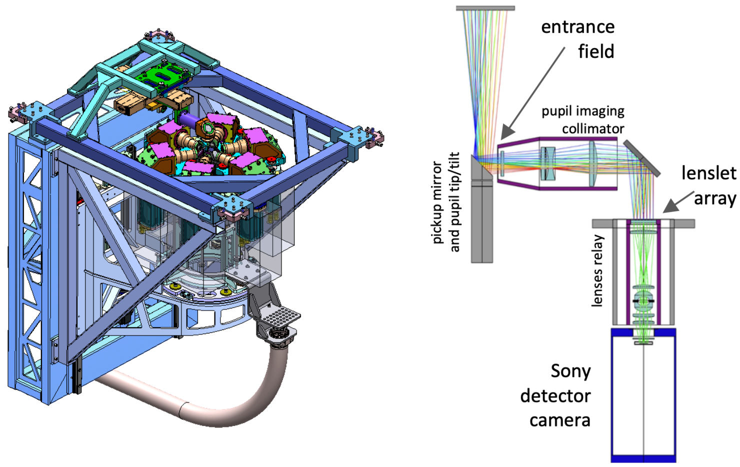


Figure 5: Laser guide star wavefront sensor (LGS WFS). Left, 3D model of the assembly of the 6 units in the mechanical structure with derotator and focus actuator, right, schematic of a single unit showing the optics and detector.

### 3.4.2 Low Order and Reference Module

The LOR WFS Module[13] implements the functionalities required by the NGS-based reconstruction of atmospheric turbulence. Three identical WFS are foreseen in the subsystem, each one is made of a fast Low-Order WFS and a slow Reference WFS, acting as a truth sensor. Each LOR WFS Unit is equipped with a Low-Order WFS and a Reference WFS sharing the light from the same NGS. The Low-Order (LO) WFS configuration is a Shack-Hartmann sensor with 2x2 sub-apertures operating in the H band. The design of the first WFS, the low-order one, considers the usage of the FREDA cameras[14] while the design of the Reference WFS (R WFS) makes use of ALICE cameras[15].

The Reference WFS acts as a "truth" sensor to de-trend LGS wavefront estimates and measure pseudo-static aberrations of the telescope and of the post-focal relay optics. The whole opto-mechanical assembly of the LOR WFS is rigidly connected and supported by the MICADO rotator that allows for field de-rotation (see Figure 1 anf Figure 6). The LOR WFS also implements dedicated control electronics that are hosted in the co-rotating cabinets below the MICADO dewar.

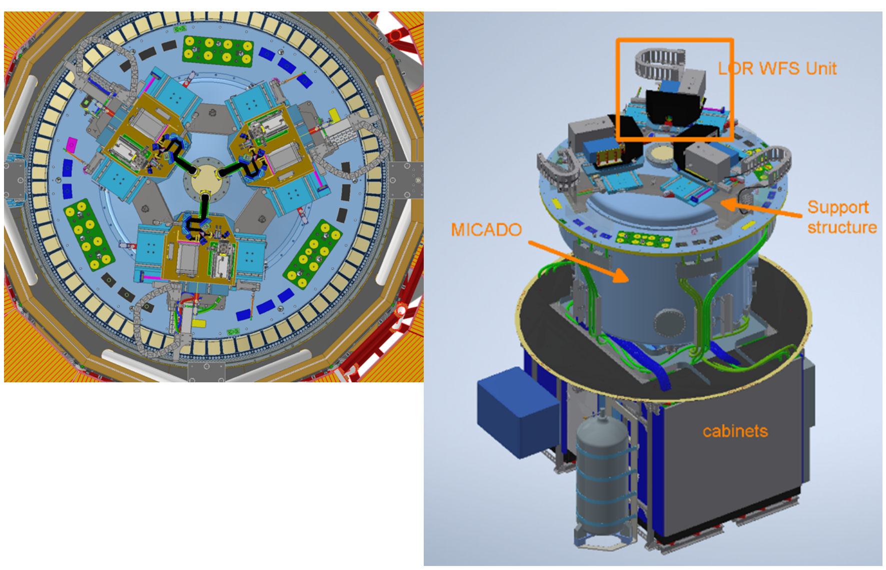


Figure 6: Overview of the LOR WFS module on top of the MICADO cryostat

## 4. OPERATIONS

The control strategy of MORFEO deals with the main closed loop operations, which include slope computation, wavefront reconstruction and control, and auxiliary loops that update the system depending on external conditions variation in order to provide a stable correction during the observations. All this is managed by the Instrument Control System Software (ICSS)[2]. ICSS will control almost 100 functions and will interface with RTC and two different instruments (MICADO and the future second port instrument). A more detailed description of the AO control and the foreseen operation is available in [11] and [16].

## 5. CALIBRATION and TEST UNIT

MORFEO is a complex system that requires a wide range of calibrations to function as intended, and several test procedures will be performed to verify its functionality and performance. The calibrations range from the data required by the detectors, such as the conversion gain factor and bias level per readout channel, to the adjustment of geometric parameters, such as the relative displacement between the sub-aperture array and the DM actuator grid, and also include the estimation of field distortion and non-common aberrations between WFS and science path. MORFEO is thus equipped with a calibration plan that concatenates all the calibration tasks that are required for MORFEO to perform and achieve its specifications The configuration of MORFEO excludes the possibility of placing calibration sources on the ELT conjugated focal planes; therefore, the CU is an optical relay that provides emulated sources at three conjugated focal planes infinity for NGS, 104 km and 150 km for LGS.

By providing suitable NGS and LGS light sources, the Calibration Unit will enable MORFEO to run calibration templates, such as WFS calibrations, Non-Common-Path Aberrations (NCPA) calibration and tomographic reconstructor calibration, as well as verification and test procedures, in standalone mode, drastically reducing the amount of required night-time for such operations. Therefore, the underlying motivation for the need of the CU is to minimize the time spent calibrating on the sky by performing most of the daily or periodic calibrations, verifications and checks with this unit during the daytime.

The CU optical and mechanical designs have been extensively revised after PDR. An overview of the CU is shown in Figure 7, while the new optomechanical design and performance analyses have already been presented and discussed in separate papers[17,18].

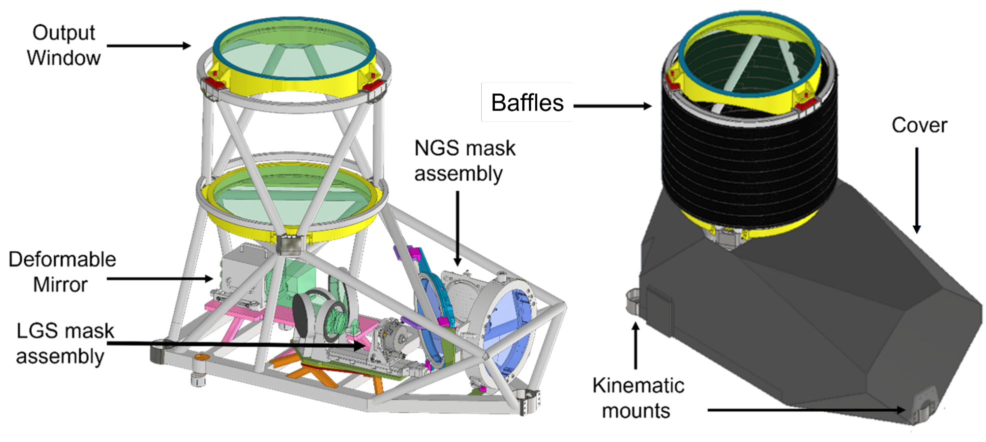


Figure 7: 3D model of the CU optomechanics (preliminary design).

# 6. PERFORMANCE

In this section, we present the main results related to the AO performance of MORFEO and their evolution from the preliminary design of the system[16,19]. We chose the word evolution because during the current (final) design phase, a number of changes that affect the performance of MORFEO are taking place, in particular:

- Telescope: the thickness of 5 arms of the spider was reduced, and their shadow went from 540 to 310 mm[20]. This has a positive impact on performance because it decreases the part of the pupil that is not seen by the LGS WFSs.
- MORFEO relay: the design of the coating of the optical elements and, in particular, the laser dichroic has been reviewed to improve throughput in the 600 – 1000 nm bandwidth where the reference WFSs operate. This opens the way to new control approaches: the consortium is investigating the possibility of using full-aperture infrared sensors for tip/tilt control[13] instead of 2×2 Shack-Hartmann sensors and asking the reference WFS to control fast focus in addition to the tomographic truth sensing[19].
- NGS loop: an extensive optimization of NGS loop parameters – framerate, gain and weighted CoG map size – was performed by a trial-and-error approach.
- Review of the error budget terms not included in the end-to-end simulations like design, manufacturing and alignment of the optical elements of the instrument, non-common path and field aberration[21], DMs fitting[10], calibration errors, dome and instrument seeing, etc. These terms that previously amounted to 180 nm RMS were reduced to 150 – 160 nm RMS (difference of 80 – 100 nm RMS) mainly due to a more accurate estimation of the local turbulence in the MORFEO optical relay. Note that a contingency term of 90 nm RMS is considered to provide some safety margins, as some terms, such as low wind effects, are not yet included.

These changes resulted in an improvement of a few percentage points of K band SR, however, as this process is not yet complete and the design has not yet been finalized, we have decided to quantify these uncertainties in the performance estimate: as you can see in Figure 8 the sky coverage curves (complementary cumulative distribution of the K band SR as a function of sky percentage) are not lines, but bands that account for variability of 110 nm RMS (a factor of about 0.91 for the K-band SR). For further information on the estimation of these curves we refer the interested reader to Ref. [22].

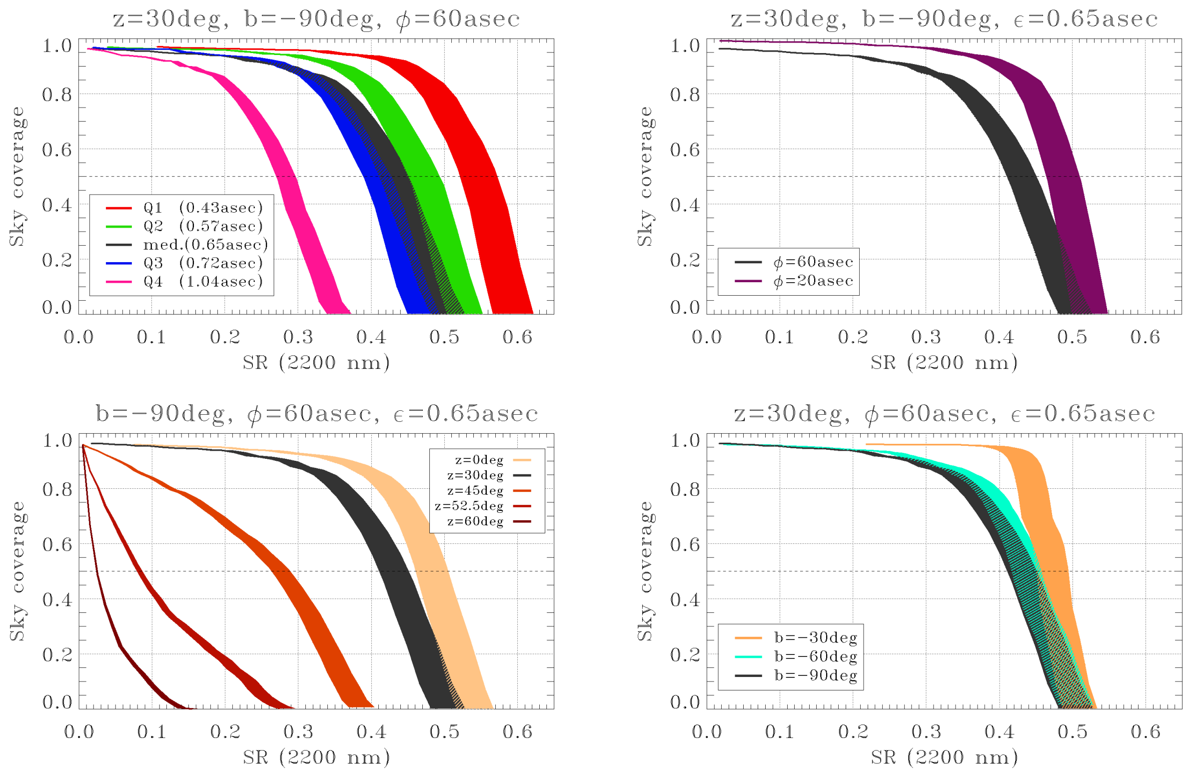


Figure 8. MORFEO complementary cumulative distribution of the K band SR as a function of sky percentage (known as sky coverage curves) in different conditions. Top-left: sky coverage for different atmospheric profiles[23], top-right, sky coverage for small and large MICADO FoV, bottom-left, sky coverage for different zenith angles and bottom-right, sky coverage for different galactic latitudes. The uncertainty, expressed as bands in the plots, is approximately 110 nm RMS or a factor of 0.91 at K-band SR, and it is due to the non-finalisation of the design and performance estimation process. The amount of error not directly included in the end-to-end simulations is 150 – 160 nm RMS (see the main text for further details). Where it is not specified, the atmospheric profile is the median one (seeing at zenith 0.65 asec), the zenith angle is 30 deg, the galactic latitude is -90 deg, the galactic longitude is -90 deg, and the MICADO FoV is the large version (size is 53×53 asec, $\phi \simeq 60$asec).

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