MAORY/MORFEO@ELT: general overview up to the preliminary design and a look towards the final design

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ABSTRACT

MORFEO (formerly known as MAORY) is a post-focal adaptive optics module that forms part of the first light instrument suite for the Extreme Large Telescope (ELT). The project passed the Preliminary Design Review in two stages in April and July 2021 and is now entering the Final Design Phase. In this paper we report the status of the project.

Keywords: Adatptive Optics, Astronomical Instruments

1. INTRODUCTION

MORFEO (Multiconjugate adaptive Optics Relay For ELT Observations), as first generation ELT instrument, will help to compensate for the distortion of light caused by turbulence in the Earth's atmosphere which makes astronomical images blurry. It is a Multi-Conjugate Adaptive Optics (MCAO) module which will provide spatially uniform adaptive optics compensation over a large field of view (of about 1 arcmin^2) with high sky coverage. Wavefront sensing is performed using six Laser Guide Stars (LGS) and up to three Natural Guide Stars (NGS), for the measurement of high and low-order wavefront perturbation respectively. Finally, the wavefront error compensation is performed by two adaptive post focal Deformable Mirrors (DMs) located inside MORFEO. These two post focal DMs, which are in fact the core of the instrument, work together with the telescope's adaptive and tip-tilp mirrors M4 and M5, respectively. The MORFEO MCAO mode has to be available at the first light with at least one deformable mirror (DM), with provision for a second DM as an upgrade. This implies that MORFEO, although funded for only one DM, has to be designed for two DMs from the beginning, with one deformable mirror being possibly replaced by a rigid mirror.

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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 a detailed description of all sub-systems is given in this conference by several papers.

MORFEO is being designed and built by a consortium of partners in Italy (INAF is the lead Institute), France and Ireland, together with ESO.

2. STATUS OF THE PROJECT

The MORFEO project recently passed the Preliminary Design Review (PDR), whose formal closure is expected by early next October. Subsequently, the Project will enter the final design phase (12-18 months duration), followed by the manufacture and test phase in Europe. The first light at the ELT Nasmyth platform is expected by the end of 2028.

3. GENERAL ARCHITECTURE

A general overview of the MORFEO global architecture and a functional overview, as presented at the PDR are illustrated in Figure 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].

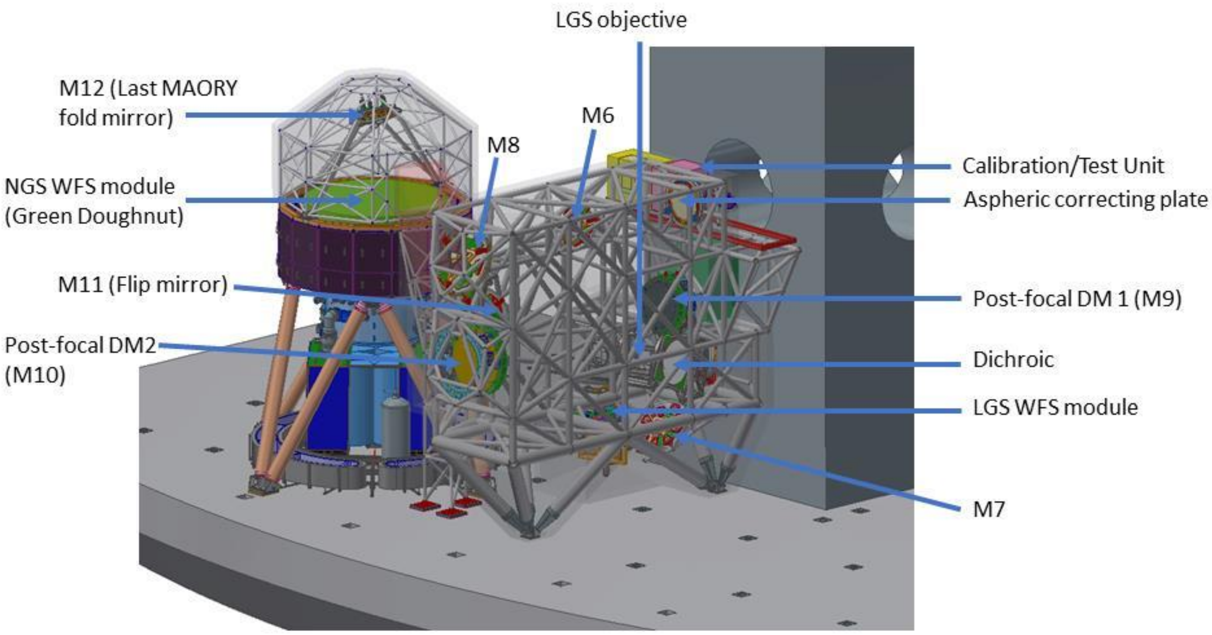

Figure 1. General overview of the MORFEO instrument (thermal cover in transparency) installed on the Nasmyth platform with MICADO.

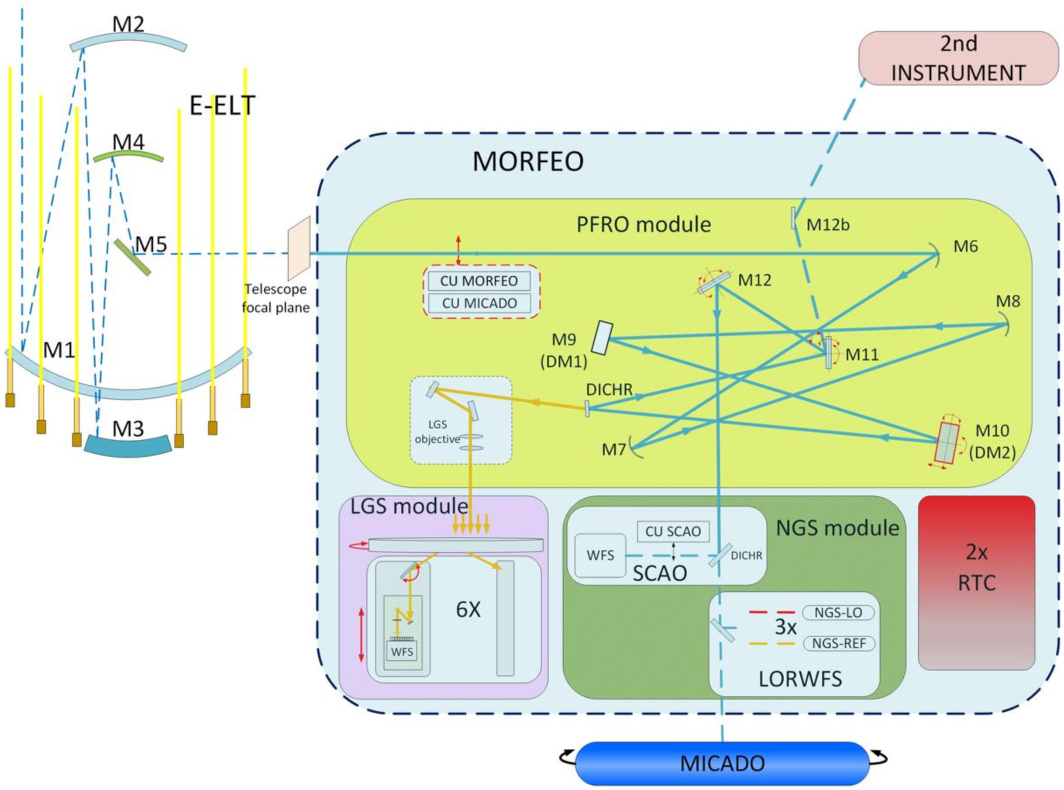

Figure 2. Functional overview of the MORFEO module in the context of the ELT and MICADO client instruments

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 Optical Design and deformable mirrors

The final MORFEO main path optics baseline[4] has 8 reflections: 2 aspheric concave mirrors, 2 spherical deformable mirrors (one convex and one concave), 1 dichroic and 3 fold mirrors. The optical layout is shown in Figure 3. In the current configuration, according to the technical specification, the MAORY baseline provides for the presence of only one DM (convex shape with an optical diameter of 880 mm, M9 DM1 in Figure 3) while the second concave DM (M10 DM2 in Figure 3) is replaced by a rigid mirror.

The sub-system contains the following channels:

- Main path optics, which relay the telescope focal plane to the exit port for the science instruments
- LGS Objective, which creates an image plane for the laser guide stars, used by the LGS WFS sub-system to measure the high order wavefront aberrations for the MCAO mode of MORFEO in real time.

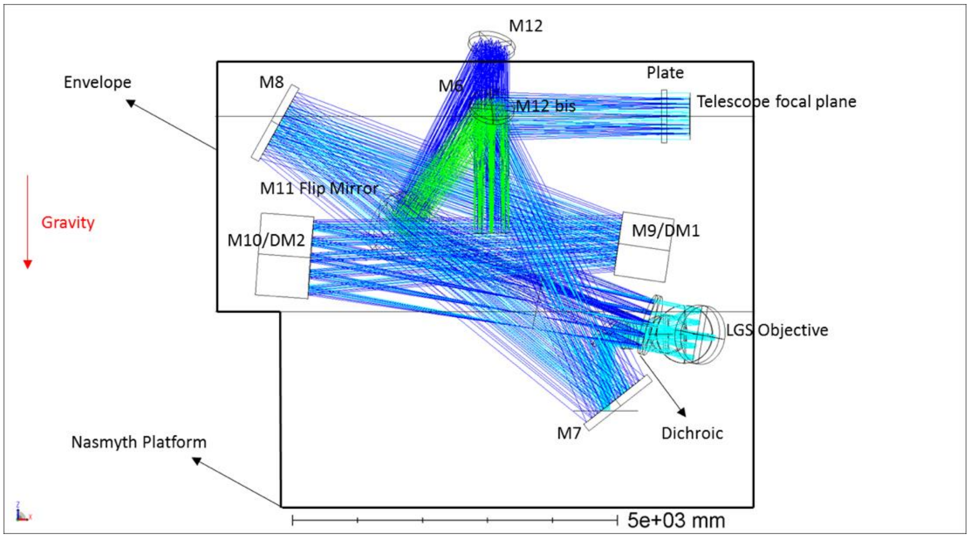

Figure 3 : MORFEO Optical Layout

Inside the optical path, two clear planes are created, optically conjugate to two different ranges from the telescope entrance pupil, allowing the insertion of up two DMs (conjugated at 6-12 km and 17-20 km, respectively). The optical design study and the adaptive optics preliminary simulation performed during the preliminary design phase study, allowed us to release a first set of performance specifications for the two DMs as reported in Table 1.

	DM1/M9	DM2/M10
Shape	Convex	Concave
RoC (mm)	-15785	15258.49
Clear Aperture (mm)	880	1160
Optical Aperture (mm)	928	1225
Settling Time (Hz)	>500	>500
Number of actuators inside CA	>700	>1500
Fitting errors 1.5” seeing RMS (nm)	40	40

Table 1: Deformable mirror technical specification summary

Starting from the technical specifications reported in Table 1, a preliminary study for the two DMs has been performed. The result of this preliminary design presented at the MORFEO PDR is a DM1 with 1026 actuators, equally spaced on a 928 mm diameter projected circle and 918 modes available for active shape correction. For DM2 the suggested solution is a deformable mirror with 1147 actuators, equally spaced on a 1225mm projected circle and 1027 modes available for active shape correction. A detailed description of the MORFEO deformable mirrors is available in a separate paper[5].

3.2 Adaptive Optics Control

A general overview of the MORFEO AO control is reported in Figure 4.

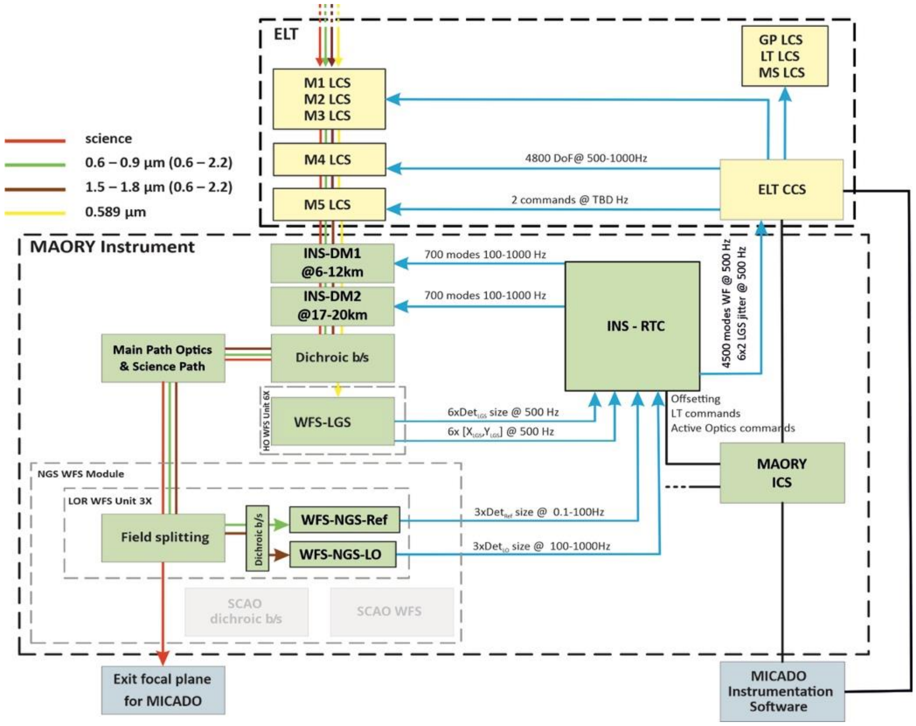

Figure 4**:** General Overview of the MORFEO AO control in MCAO mode. Red lines mark the science path, green lines the NGS visible light path, brown lines the NGS infrared light path and yellow lines the LGS light path. Real time command paths are marked with light blue lines, non-real time ones are in black. Devices belonging to MORFEO are colored in green, while ELT devices are represented by yellow boxes. The greyed-out SCAO boxes are not in use in MCAO mode. Finally, the two grey boxes at the bottom represent MICADO subsystems

With reference to Figure 4, light collected by the telescope enters the MORFEO Common Path Optics, which include the two Post-Focal Deformable Mirrors (INS-DM1/2 in the Figure). At this point, light is split by a dichroic: the light of wavelength shorter than 600 nm goes to the LGS Wavefront Sensors, while the light of longer wavelength goes to the direction of the science path. The light required for the NGS (Low-Order and Reference, LOR) Wavefront Sensors is picked up outside the science field of view (“Field splitting” in the Figure) and is split by a dichroic inside each WFS: visible wavelengths are directed to the Reference WFS, while infrared ones to the Low-Order WFS.

Pixel data collected by LGS and LOR Wavefront sensors are sent to the RTC, which drives in closed loop the MORFEO (Post-Focal DMs) and Telescope real-time actuators. The latter include the adaptive quaternary mirror M4, tip-tilt mirror M5 (both seen as one single unit by the RTC) and the Laser Launch Telescopes Jitter Mirror. A thorough description of the MORFEO AO system is given in a separate paper[6].

3.3 Main Structure

The MORFEO main structure is based on a latticework tower, made of standard structural steel truss- beam shaped with different section properties. The structure is connected to the Nasmyth platform through 10 legs that will be joint into the three mounting support points on the ESO ELT Nasmyth platform A. The overall design has been constrained to fit with the three support points concept, in order to have an ideal interface plane. This strategy eliminates the distortion induced by the Nasmyth platform displacements out of a rigid body motion. The present configuration of the mechanical design for the MORFEO main structure is shown in Figure 5.

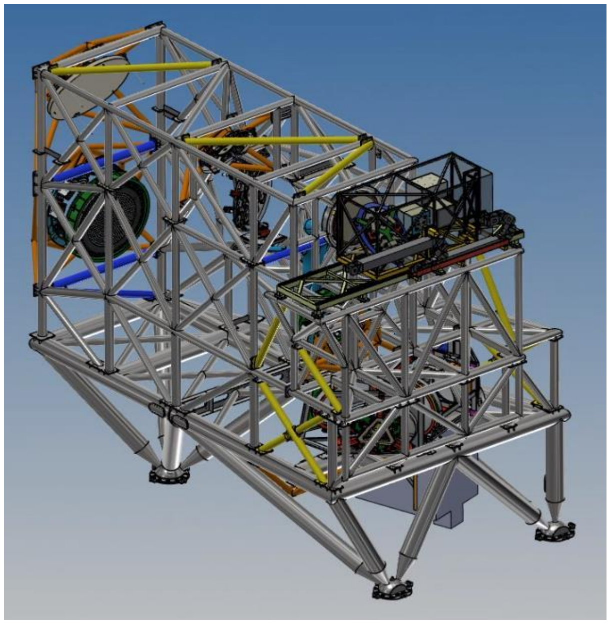

Figure 5: Mechanical design for the MORFEO main structure

The Main Support Structure Assembly is composed of: Main Support Structure (MSS) that holds up all optomechanical elements and their Optomechanical Support Structures themselves (see Figures 6). The main purpose of the Main Support Structure is to provide a very stable opto-mechanical reference and a support for all the opto-mechanical elements and sub-assemblies components weighing on it. This structure, shown in the Figure 6, will be split up in several (welded) parts connected to each other with bolts. Reference pins will be also used in order to have an accurate mounting/dismounting for the various provisional phases (number of final parts is under evaluation). A detailed description of the MORFEO main structure and optomechanical elements are available in separate papers[7],[8].

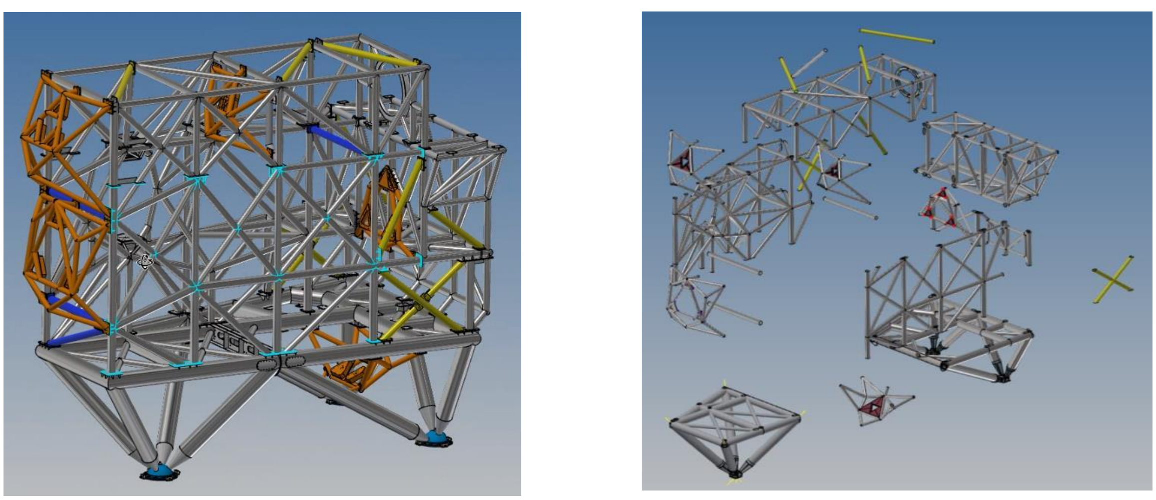

Figure 6: MORFEO main support structure (left side) and spitting strategy (right side). The optomechanical support structures are highlighted in orange while in yellow are shown the sub-assembly elements or beams that can be temporally disassembled for mounting/dismounting and maintenance operations of all opto-mechanical components.

3.4 Wavefront Sensor Modules

The MCAO mode in MORFEO is based on the use of two wave-front sensor (WFS) modules: an LGS WFS module with 6 beacons arranged in a 45" asterism, and an NGS WFS module which includes 3 low order sensors and 3 reference sensors patrolling a technical field of 160 arcsec.

The LGS WFS module is a device dedicated to measurement of the wavefront aberrations due to atmospheric turbulence and other effects. The LGS WFS module contains 6 wavefront sensor units to measure wavefront distortion on the laser guide stars. It is attached below the MORFEO main structure in a gravity invariant configuration. The light of wavelength shorter than about 600 nm is propagated from the Dichroic beam-splitter through the LGS Path Optics and then to the LGS Wavefront Sensor module. The light enters each probe, where it is collected by a WFS camera

The Low Order and Reference (LOR)[9] Module implements the Natural Guide Star wavefront sensing functionalities needed by MORFEO in the MCAO mode. The LOR WFS Module is downstream of the Post Focal Relay Optics (PFRO), and the LOR WFS benefits from the MCAO correction, of course in a way that depends on the off-axis distance of the NGS. It consists of 3 identical LOR WFS units to sense the aberrations in the direction of 3 NGSs chosen in a technical field having an outer radius of 80 arcsec. 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 Reference WFS act as "truth" sensor to de-trend LGS wavefront estimates and measure pseudo-static aberrations of the telescope and of the post focal relay optics

3.5 Calibration and Test Unit

The MORFEO Calibration and Test unit is an independent optical system fixed on the MORFEO main structure adjacent the pre focal station (see Figure 3) that simulates:

- Natural Guide Stars and Laser Guide Stars before the focal plane (Calibration Unit, CU)
- the Telescope Deformable Mirror M4 and atmospheric turbulence (Test Unit, TU)

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. The underlying motivation for the need of the CU is therefore to minimize the time spent calibrating on sky, by performing most of the daily or periodic calibrations, verifications and checks with this unit.

The CU sources are grouped into four typologies, according to their wavelengths and corresponding WFS: LGS sources (589 nm) feeding the LGS WFS, NGS-REF sources (R-band) feeding the Reference WFS, NGS-LO sources (H-band) feeding the Low Order WFS and NGS-MIC sources (H-band) feeding MICADO.

The CU optical and mechanical designs are shown in Figure 7 while a detailed description of the CU is available in separate papers[10][11].

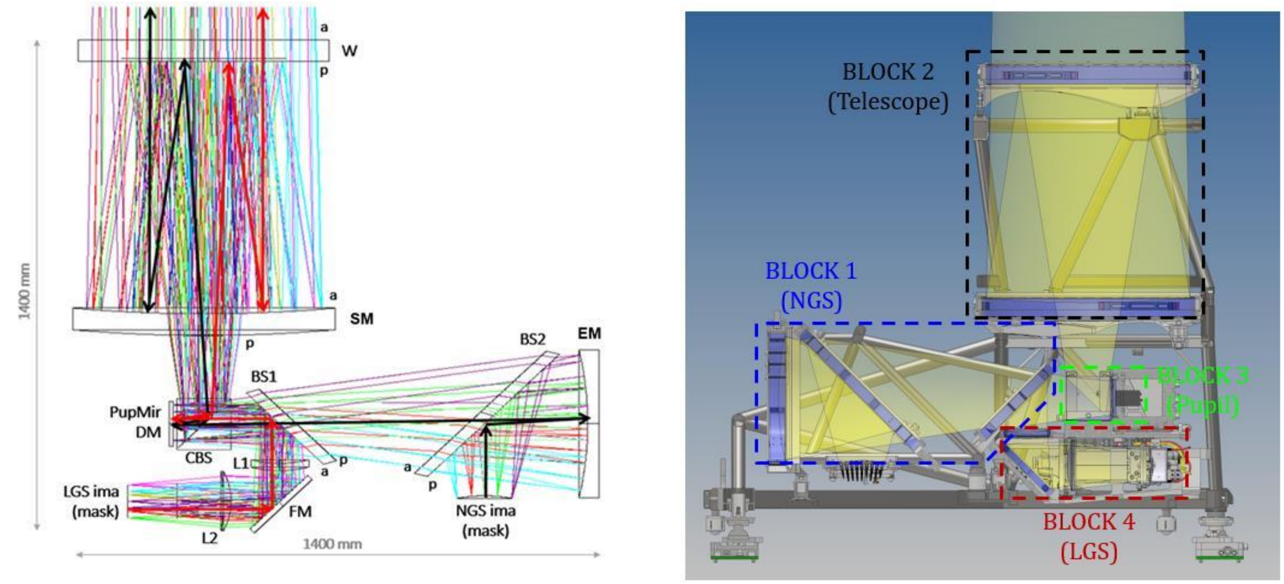

Figure 7: (left) The CU catadioptric relay. The colored arrows indicate the two optical paths: LGS path (red, with the mask planes conjugated to 104 km and 150 km) and NGS path (black). (right) CU Main Bench mechanical design with its blocks, needed to implement the alignment strategy. In both: the CU Folding Mirror (needed to inject the CU light into the MORFEO main path) is not shown, gravity goes from top to bottom. See [10] for more details.

4. PERFORMANCE : 1 POST FOCAL DM VS 2 POST FOCAL DMS

The studies performed during the preliminary phase design, clearly show that a system with a single post-focal (pf) DM (i.e. a system with two DMs considering also the telescope's deformable mirror M4), is capable of delivering a Strehl Ratio (SR) compliant with the requirements while the presence of the second post focal DM (bringing to three the number of the total DMs) is fundamental to push the system toward maximal performance.

In the framework of the post Preliminary Design Review (PDR) activities, an exhaustive analysis of the one post-focal DM versus two post-focal DM photometric, astrometric and sky coverage performances was carried out based on realistic atmospheric profiles that take into account a wide range of observing conditions[12]. The effect of the 2nd pfDM is to increase image quality and its stability under variations of atmospheric turbulence and seeing conditions, and more dramatically for bluer filters than for redder ones. The 2nd pfDM also significantly improves the spatial homogeneity of the point spread function, allowing for the restoration of the full 2 arcmin MORFEO field of view, with consequent impact on the natural reference stars's region and on the sky coverage.

In terms of scientific performances, this means:

- The sensitivity one can expect for a typical target in typical observing conditions will increase by about 1 mag in the K-band (or ~2 mag in the H-band and over ~3 mag in J-band). A 1 mag difference corresponds to a factor 6 reduction in telescope time to reach the same signal-to-noise on faint point sources. This is invaluable for deep integrations on faint targets, as well for as efficient use of telescope time.
- The fraction of targets for which a scientifically useful minimum Strehl ratio can be achieved (i.e., the sky coverage) will increase by a factor 2-6 in the K-band. This is invaluable for target selection as well as programme scheduling on the telescope.
- The astrometric accuracy over the (zoomed-in, reduced) MICADO FoV will be improved by 20% in high SNR conditions (>200) corresponding to the range baseline-goal of the MORFEO requirements.

In order to provide an immediate visualization of the improvement provided by the introduction of the second post-focal DM, we plot in Figure 8, left panel, the K-band point-source sensitivity one can expect under different atmospheric conditions, while we show in Figure 8 (right panel) the fraction of targets for which one can achieve a minimal scientifically useful SR of 10% in K-band for different atmospheric conditions. The SR measures the intensity profile reached at the peak of the PSF and it is directly proportional to the energy concentration within the diffraction limited core.

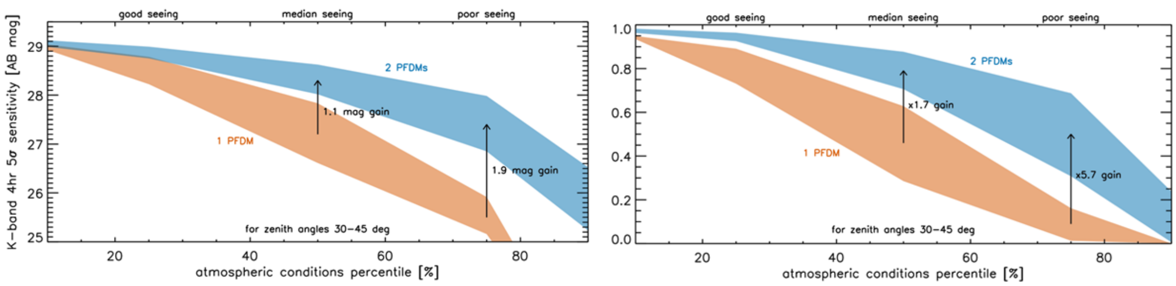

Figure 8: Comparison of performances with one pfDM (orange region) and with two pfFMs (blue region). Lefts panel: K-band point-source sensitivity for different atmospheric conditions (very good to very bad, from left to right). Right panel: fraction of targets for which one can achieve a Strehl ratio of 10% in K-band for different atmospheric conditions.

From Figure 8 is evident that in the best atmospheric conditions, the difference in performance and number of targets observable with SR>10% is rather small. However, the improvement increases rapidly with decreasing observing condition quality, and for typical atmospheric conditions the factor 2-3 gain in sensitivity corresponds to more than 1 mag; this increases to almost 2 mag in poor conditions because the performance with 1 post focal DM is very limited in this case. The scientific benefit of 1 mag gain in the K-band (and of 2 mag in the H-band) with the second post focal DM will have a great impact on all science cases where sensitivity is a key ingredient. Another way of looking at this is that any accepted programme aimed at detecting faint targets will be able to reach the specified depth in a factor 6 less observing time.

In terms of observable targets, the impact of having a second post focal DM increases dramatically their number. In median observing conditions, there are nearly twice as many targets available for any given programme; in poor atmospheric conditions this increases to almost a factor 6 more targets available for astrophysical selection. Equivalently, this means that observing time can be used more efficiently, because there will be more programmes in the queue that can be observed in a given set of ambient conditions. This will lead to an increase in the fraction of programmes that can be completed.

It is clear that all the effects described above will have a direct benefit on the scientific impact of the ELT. Indeed, without the second post focal DM there will be a significant loss for science cases about the dynamics of dense stellar systems and black holes in galaxies, while resolved stellar population, Galactic Centre, and galaxy evolution studies will be affected in a major way.

5. CONCLUSION

The MORFEO project recently passed the Preliminary Design Review, whose formal closure is expected by early next October. The design presented at the PDR, briefly described in this paper, showed that there are not theoretical showstoppers to the fulfillment of all the specifications. This is a fundamental step for the project and it opens the door for the next phases: the final design phase and then the manufacturing and test phase in Europe. The first light at the ELT Nasmyth platform is expected by the end 2028.

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