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MAORY : the adaptive optics module for the Extremely Large Telescope (ELT)

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ABSTRACT

MAORY is a post-focal adaptive optics module that forms part of the first light instrument suite for the ELT. The main function of MAORY is to relay the light beam from the ELT focal plane to the client instrument while compensating the effects of the atmospheric turbulence and other disturbances affecting the wavefront from the scientific sources of interest.

Keywords: Adatptive Optics, Astronomical Instruments

1. INTRODUCTION

MAORY[1] will provide the ELT with two adaptive optics modes : a very high correction over a small FoV (diameter ~10 arcsec, with performances rapidly degrading with distance from the bright natural star used to probe the wavefront – Single-Conjugate Adaptive Optics, SCAO mode) and a moderate correction over a wide FoV (diameter ~60 arcsec, with pretty homogeneous performances over the whole FoV – Multi-Conjugate Adaptive Optics, MCAO mode).

MAORY is not a scientific instrument in itself, as it does not produce scientific data on its own. It is designed to support two different instruments, both with the same optical quality and with a gravity invariant port. One of these two instruments will be the MICADO near infrared camera while the second one has yet to be defined.

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

2. MAIN MAORY TECHNICAL SPECIFICATIONS

The MAORY design has been developed in order to satisfy the following fundamental requirements:

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- MAORY has to provide two adaptive optics modes to support MICADO:
    - MCAO mode, in which at least two deformable mirrors are conjugated to different altitudes in the atmosphere; one of these deformable mirrors is the telescope M4;
    - SCAO mode, in which wavefront compensation is performed using M4 only. In this configuration the post focal deformable mirror(s) are kept rigid.
- The MCAO mode has to be available at first light with at least one deformable mirror in MAORY, with provision for a second deformable mirror as an upgrade, implying that MAORY has to be designed for two deformable mirrors from the beginning, with one deformable mirror being possibly replaced by a rigid mirror.
- The MCAO mode of MAORY is based on the use of 6 Laser Guide stars (LGS). Natural guide star wave-front sensors (3 in the baseline design) are also required to complement LGS measurements.
- MAORY shall provide two exit ports : one for MICADO and one for a second instrument to be defined.
- All the performance requirements assume a baseline for MAORY with one post-focal deformable mirror (used in conjunction with the telescope M4). The goal reflects the possible performance with a post-focal second DM.
- Under median conditions the MAORY system (including the telescope) shall deliver a Strehl Ratio of 0.3 at 2.2 micron wavelength with a goal of 0.5. This requirement is assumed to be met under median seeing conditions, as close to the zenith permitted by the zenith avoidance zone and over 1 arcmin diameter FoV
- MAORY shall be able to deliver the required performance over the sky observable by the ELT with 50% probability unless otherwise specified

3. HIGH LEVEL PRODUCT TREE

Following the requirements described in Section 2, the MAORY design has been developed starting from 4 different modules each containing different work packages:

- The MAORY Hardware module including the following WPs: Main Structure, Optomechanics (Post-focal relay optics(PFRO) and optical mounts) Deformable Mirrors, Calibration Unit, Test Unit
- The NGS WFS module, including the LOR WFS WP
- The LGS WFS module, including the LGS WFS WP
- The Control and Software module including the following WPs: Instrument Control Software, Instrument Control Hardware, Thermal Control System, Real Time Computer, End2End Simulations

This structure is reflected in the MAORY Product Tree reported in Figure 1.

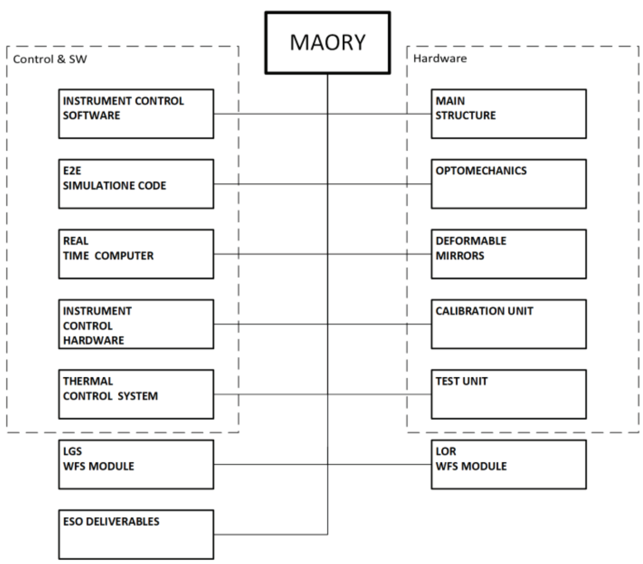


Figure 1. MAORY Product Tree arranged in different modules: Control and Software, Hardware, LGS WFS, LOR WFS and ESO deliverables.

4. GENERAL ARCHITECTURE

4.1 OPTICAL DESIGN

The first step in the definition of the global architecture has been the development of an optical design able to satisfy all the requirements. In the early phase of the MAORY Phase-B, the design has been developed and optimized to fully support the MICADO instrument, leaving the port for the second instrument in a less favorable position (not gravity invariant). In early 2020, after a trade off study and in agreement with ESO, the optical baseline design was changed in order to also provide a gravity invariant port for the second instrument. The performances guaranteed to MICADO were maintained and extended also to the second instrument.

The final MAORY main path optics baseline[2] 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 (side and top view) is shown in Figure 2 where, in the bottom panel, the second port focal plane, the LGS module area envelope and the MICADO envelope are also shown. 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 2) while the second concave DM (M10 DM2 in Figure 2) is replaced by a rigid mirror.

An aspheric correcting plate[3] near the telescope focal surface allows the optical relay to simultaneously produce stigmatic images of the telescope focus and of laser guide stars over the full range of object distances. The plate correction also improves the image quality of system pupils and meta-pupils. In the presented optical configurations, the plates are about 350 mm after the focal plane.

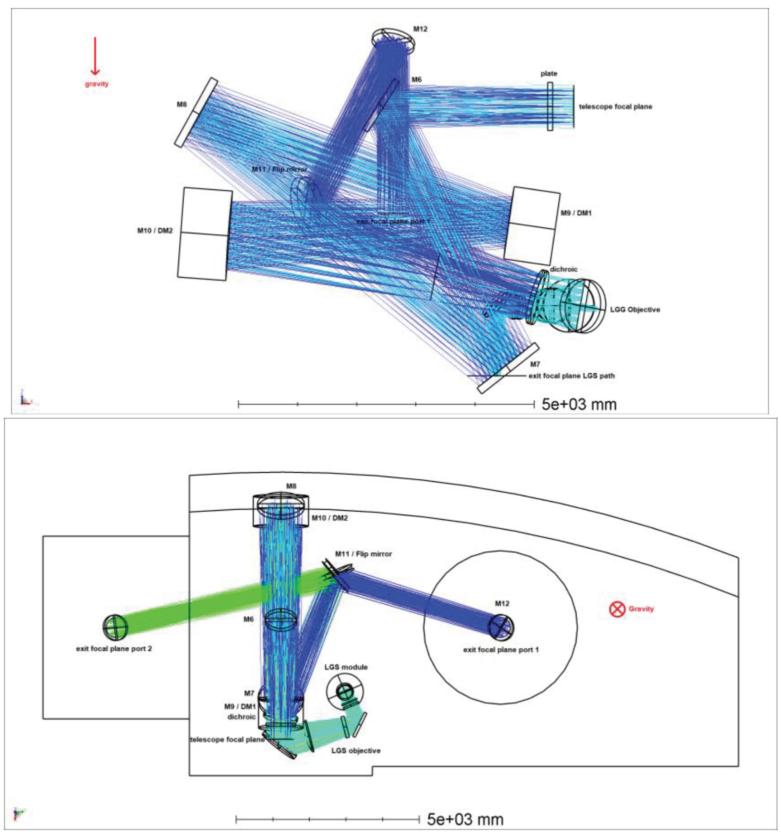


Figure 2 : Post-Focal Relay Optics baseline side way layout (top) and top view layout (bottom). Blue rays: optical beam from telescope focal plane to the exit port for MICADO. Green rays: differential path to exit port for second instrument. Light Blue rays: LGS path

4.2 MAIN STRUCTURE

Starting from the optical design developed in three dimensions, the mechanical design has been completely revised since February 2020. The MAORY main structure[4] is now based on a latticework tower made of standard structural steel truss-beam shaped pipes, welded/bolted with different section properties. The truss is connected to the Nasmyth platform through 10 legs that merge into 3 points. The overall design has been constrained to be able to fit with the three legs concept, in order to null the distortion induced by the Nasmyth displacements out of a rigid body motion.

A general overview of the MAORY global architecture is illustrated in Figure 3. The main hardware subsystems indicated in the figure are complemented by the electronics[5] at system and sub-systems level, instrument control software and real time computer[6].

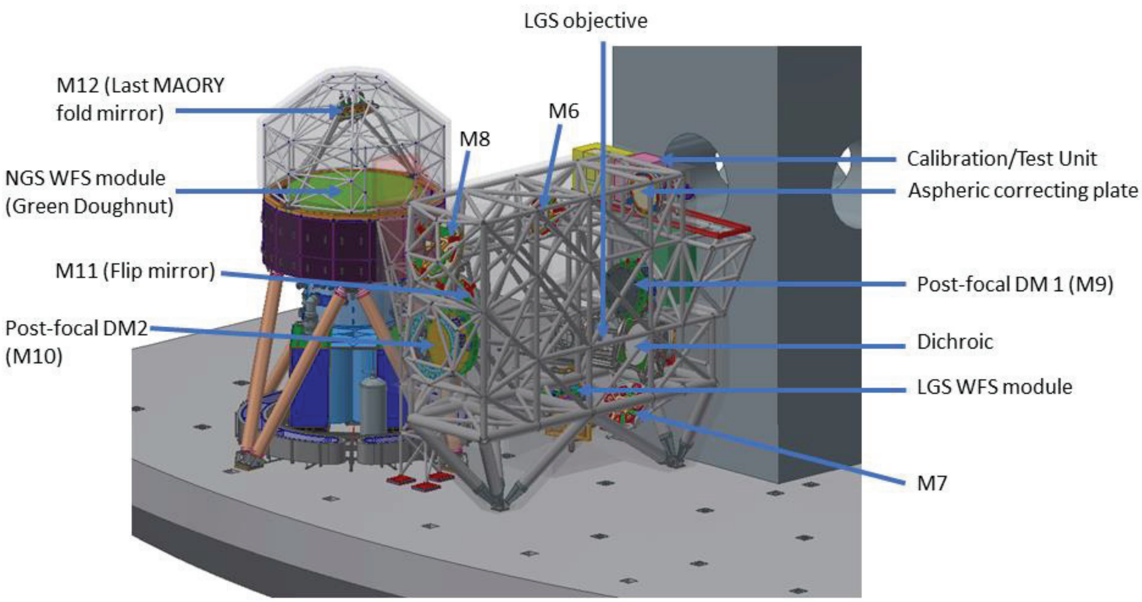


Figure 3 : General overview of the MAORY instrument (thermal cover in transparency) installed on the Nasmyth platform with MICADO

4.3 WAVEFRONT SENSOR MODULES

The MCAO mode in MAORY is based on the use of two wave-front sensor (WFS) modules: an LGS WFS module with 6 beacons (upgradable for 8) arranged in a 45" asterism, an NGS WFS module with 3 low order sensors and 3 reference sensors patrolling a technical field of 160 arcses.

The LGS WFS module is a device dedicated to measurement of the wavefront aberrations due to atmospheric turbulence and other effects. In Figure 4 we show an overall view of the full LGS WFS assembly.

The LGS WFS module contains 6 wavefront sensor units to measure wavefront distortion on the laser guide stars. It is attached below the MAORY main structure (see Figure3) 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

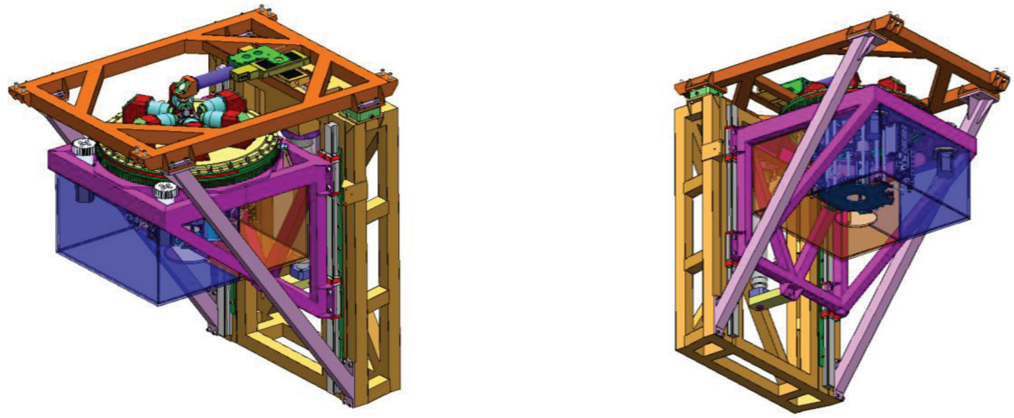


Figure 4 : overall view of the full LGS WFS assembly

The Low Order and Reference (LOR) Module implements the Natural Guide Star wavefront sensing functionalities needed by MAORY 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.

Figure 3 gives an overview of the position of the LOR WFS modules in the environment of the Nasmyth platform (it is located on the top of MICADO) while Figure 5 gives a close up view of the hardware implemented within the LOR WFS.

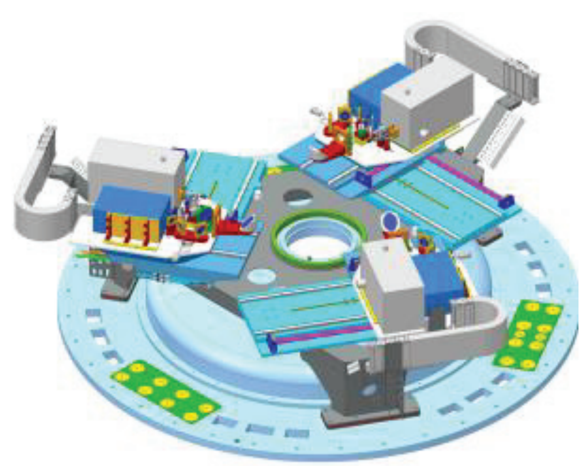


Figure 5 : Detail of the hardware implemented within the LOR WFS module.

4.4 CALIBRATION AND TEST UNIT

The MAORY Calibration[7] and Test[8] unit is an independent optical system fixed on the MAORY 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)

An overall view of the CU/TU module is shown in Figure 6 while a detailed description of the optical design can be found in [7] for the CU and in [8] for the TU.

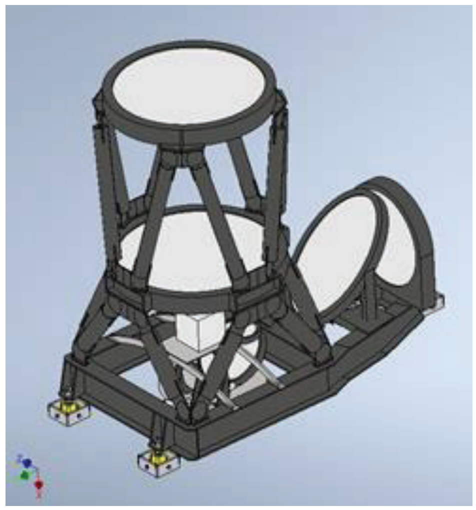


Figure 6 : Calibration/Test Unit overall view

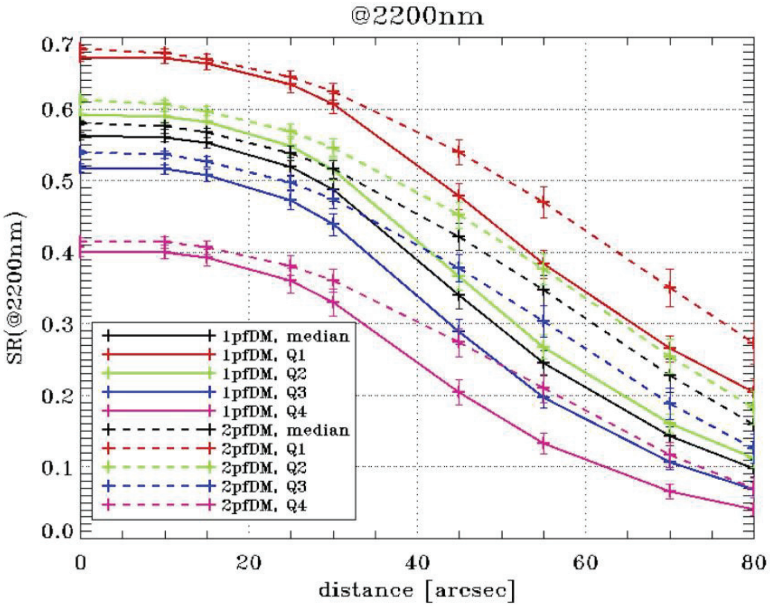
The TU mode is activated through insertion of a DM that reflects the light coming from the star mask towards the telescope focal plane while in CU mode the DM is replaced by a flat static mirror

5. EXPECTED PERFORMANCE

Assessing the MAORY performance and sensitivity to parameter variations during the design phases is a fundamental step for the engineering of such a complex system. The simulation software has been used not only to estimate to MAORY performance, but also to help the system engineering in the selection of many parameters including the technical field of view, the LGS asterism, the number of the sub-apertures in the LGS wavefront sensor and NGS wavefront sensor and the post focal DM pitch.

The MAORY expected performances[9] are summarized in Figure 4. In the top panel we report the Strehl Ratio (SR) as a function of the radial distance (arcsec) from the field center for different atmospheric conditions (different colors) considering only one post focal DM (the baseline configuration, solid lines) and two post focal DMs (dashed lines). In the bottom panel we report the sky coverage as a function of the SR again for different atmospheric conditions with 1 DM (solid lines) and 2 DMs (dashed lines). To calculate the sky coverage we make use of the statistical approach to estimate the fractional occurrence of the performance on a simulated field at the South Galactic Pole (SGP). The performance that we quote at 50% Sky Coverage should be understood as "the median performance obtained for a large set of random pointings at the SGP" which is indeed conservative with respect to the MAORY requirement that refers to have 30% SR (goal 50% with 2 DM) over 50% of the observable sky.

As shown in the Figure, a system with a single DM is capable of delivering a SR above 40% with 50% sky coverage, well above the requirement, while including a second DM is fundamental to push the system toward maximal performance.



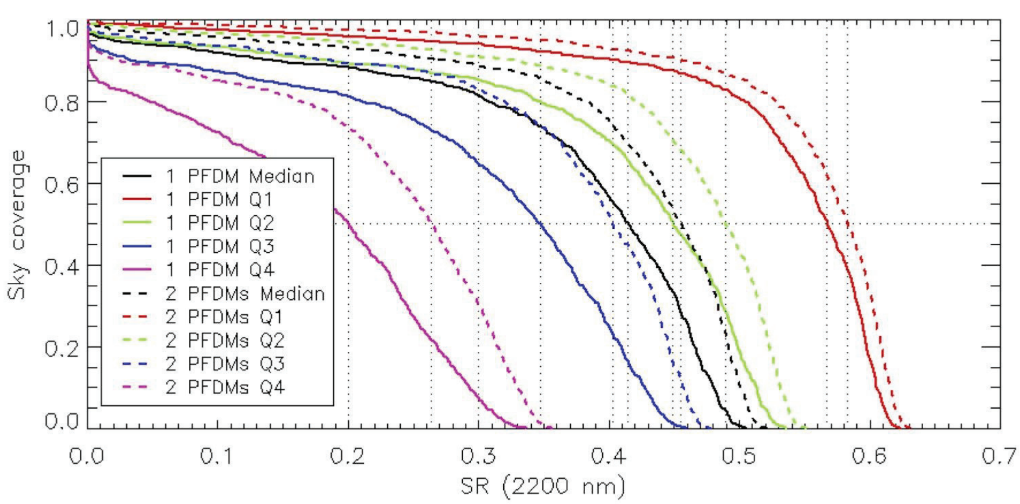


Figure 4: Summary of the MAORY performance. Top panel: SR as function of the radial distance for different atmospheric conditions and 1 or 2 post-focal DMs. Bottom panel: Sky coverage as a function of the SR for different atmospheric conditions and 1 or 2 post-focal DMs.

6. CONCLUSION

The MAORY Project is approaching the end of the Phase-B design stage with the preliminary design review foreseen (in two stages) for April and July 2021. The instrument has been designed to provide two gravity invariant exit ports : one for MICADO and one for a second instrument that is yet to be defined. The simulations performed show that the MAORY instrument with only one post focal DM is able to provide performance well above the requirement. However it is also evident that a second post focal DM is mandatory to push the system toward maximal performance.

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