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# MAORY: adaptive optics module for the E-ELT

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## ABSTRACT

MAORY is one of the four instruments for the E-ELT approved for construction. It is an adaptive optics module offering two compensation modes: multi-conjugate and single-conjugate adaptive optics. The project has recently entered its phase B. A system-level overview of the current status of the project is given in this paper.

**Keywords:** Extremely Large Telescopes, E-ELT, Multi-Conjugate Adaptive Optics, Laser Guide Stars

## 1. INTRODUCTION

MAORY[1] is one of the four first-light instruments[2] for the European Extremely Large Telescope[3][4] (E-ELT). It is an adaptive optics (AO) module offering two AO modes: multi-conjugate adaptive optics (MCAO) and single-conjugate adaptive optics (SCAO).

The MCAO mode is designed for high-quality adaptive optics compensation with uniform point spread function (PSF) over a relatively large scientific field of view; thanks to the use laser guide stars (LGS), the MCAO mode offers high coverage of the observable sky. Primary science cases in MCAO mode are astrometry and deep photometry with very high relative accuracy. The SCAO mode is intended to achieve even higher peak performance than the MCAO mode on a smaller field of view when a bright natural guide star (NGS) is available nearby the scientific target.

The primary client instrument of MAORY is MICADO[5], the E-ELT near-infrared high-angular resolution imager. MAORY has to provide also a second exit port for an instrument as yet undefined.

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The SCAO mode is a joint development between the MAORY consortium and the MICADO consortium[6].

The MAORY instrument is designed and built by a Consortium including INAF (Italy) and INSU IPAG (France). ESO, in addition to its role of customer, is also actively involved in the project.

The MAORY instrument project entered its phase B in February 2016. Consolidation of the baseline design is underway, taking into account scientific performance requirements, interface constraints and technology readiness of crucial hardware components.

# 2. INSTRUMENT REQUIREMENTS

## 2.1 General requirements and interfaces

MAORY has to be installed on the E-ELT Nasmyth platform at the telescope straight-through focus.

It has to provide two adaptive optics modes to support science observations with 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 adaptive quaternary mirror M4 of the telescope, the other is integrated in MAORY; provision for a second deformable mirror in MAORY shall be ensured;
- SCAO mode, in which wavefront compensation is performed using M4 only.

MAORY has to relay the telescope focal plane, re-imaging it at the client instrument port. As a design goal, the exit port optical interface should be 1:1 to the telescope optical interface, although a change is acceptable for MICADO provided the field curvature is not too strong.

The exit port for MICADO has to be gravity-invariant.

MAORY has to provide a second port for an instrument as yet undefined.

MAORY shall permit observations of non-sidereal objects also in MCAO mode.

## 2.2 Performance requirements

In MCAO mode, MAORY will have to provide Strehl Ratio SR $\geq$ 0.3 at $\lambda$ = 2.2 μm under median atmospheric conditions. This requirement is intended as average value over the MICADO field of view (~1 arcmin diameter) for observations close to zenith. The requirement has to be achieved over at least 50% of the observable sky at the telescope. The performance goal is SR = 0.5 at $\lambda$ = 2.2 μm: this performance level may be achievable with a second deformable mirror inside MAORY. Performance values will be consolidated in the project phase B.

Relative astrometric accuracy is one of the science drivers of the MCAO mode. MAORY will have to permit observations with MICADO such that the relative position on the sky of an unresolved, unconfused source of optimal brightness with respect to an optimal set of reference sources is reproducible to within 50 μas (goal 10 μas) over a central field of 20 arcsec diameter – and across the entire MICADO field as a goal – over timescales in the range of 1 hour to 5 years.

Concerning relative photometric accuracy, MAORY will have to permit observations with MICADO such that the relative flux of an unresolved, unconfused source of optimal brightness with respect to an optimal set of reference sources is reproducible to within 0.02 mag (goal: 0.01 mag) across the MICADO field of view over timescales in the range of 1 hour to 5 years.

# 3. ADAPTIVE OPTICS SYSTEM ARCHITECTURE

## 3.1 MCAO mode

The MCAO mode of MAORY is based on the use of 6 LGS wavefront sensors. NGS wavefront sensors – 3 in the baseline design – are also required to supplement the LGS measurements.

The instrument sub-systems in the baseline design and their inter-relations in MCAO mode are shown in the block diagram in Figure 1.



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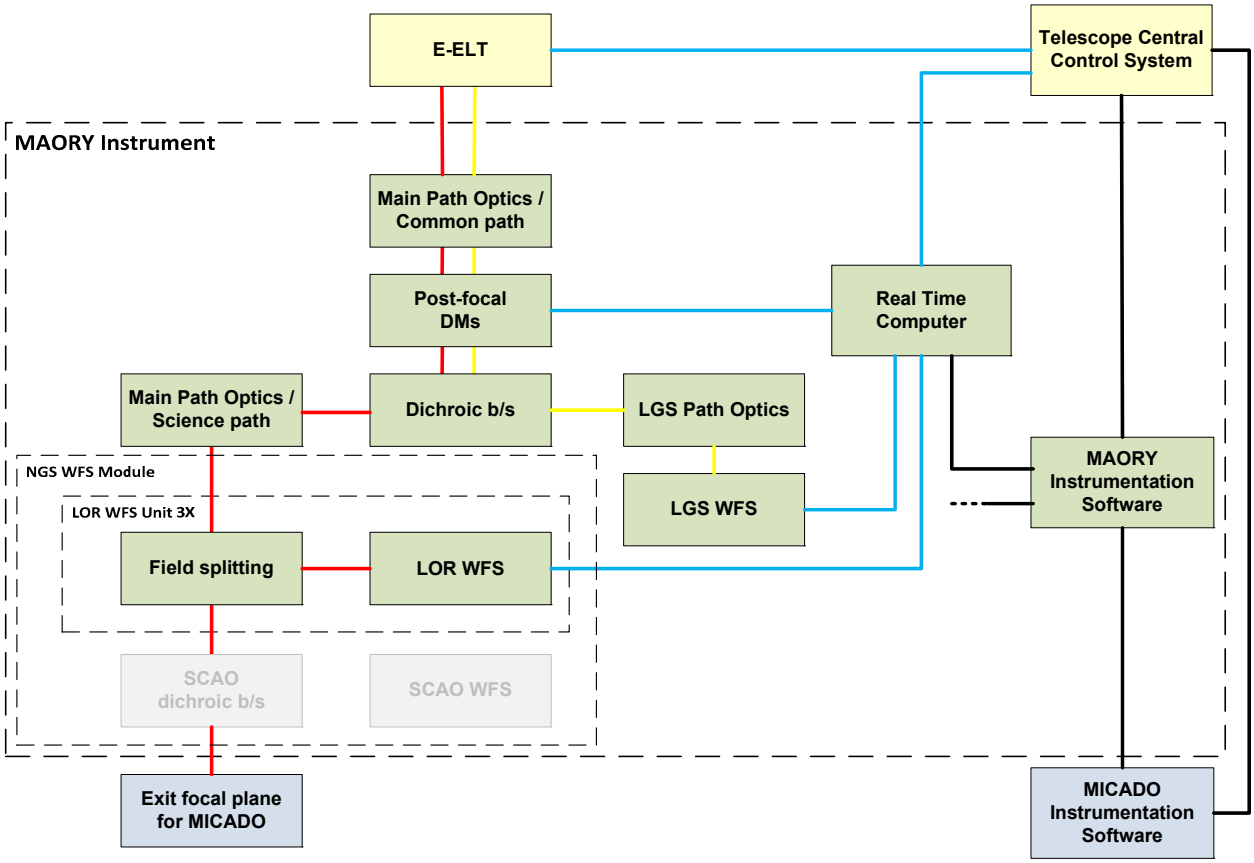



Figure 1. MCAO functional block diagram. Red lines: light path. Yellow lines: LGS light path. Blue lines: real-time signals. Black lines: non real-time signals. Light-grey blocks are not used in MCAO mode.

The light from the E-ELT enters MAORY through the main path optics (common path). Upon wavefront compensation by the post-focal deformable mirror(s), which follow the telescope's M4/M5, the light is split by a dichroic beam-splitter, which forms part of the main path optics.

The LGS light propagates from the dichroic beam-splitter to the LGS path optics and then to the LGS wavefront sensor. The dichroic beam-splitter response curve may be a low-pass filter, with cut-off at about 600 nm, or a notch filter centred at the LGS wavelength. The trade-off is in progress. In any case, the LGS light is transmitted through the beam-splitter in the current baseline architecture.

The light reflected by the beam-splitter propagates through the last segment of the main path optics (science path) to the exit port. At the exit port the MAORY exit focal plane is delivered to MICADO. The light of the 3 NGSs is picked off by the low-order & reference (LOR) wavefront sensor units in the NGS wavefront sensor module. The LOR wavefront sensor serves different functions, among which: i) measuring the low-order modes (tip-tilt, but also focus and astigmatism) which are not reliably measured by the laser guide stars due to the well-known tilt indetermination problem and to fast sodium layer instabilities; ii) providing a way to "de-trend" the low/medium order modes, other than tip-tilt, focus and astigmatism, which are affected by sodium layer temporal variations coupled to instrumental effects in the LGS wavefront sensor such as spot truncation[7][8].

The wavefront measurements performed by the LGS and LOR wavefront sensors in the MCAO mode are processed by the MAORY real time computer[9], which drives in closed loop the MAORY post-focal deformable mirrors and, through the telescope central control system, the actuators in the telescope, including the adaptive quaternary mirror M4 and the tip-tilt mirror M5.

All instrument operations are controlled by the MAORY instrumentation software, which also provides interfaces to the telescope central control system and to the MICADO (or other) client instrument instrumentation software.



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### 3.2 SCAO mode

The SCAO mode is described in the block diagram in Figure 2.

Laser guide stars are not used in SCAO mode. The light path is essentially the same as in the MCAO mode, with the exception of the exit port. Here the light of a NGS nearby the scientific target of interest is selected in wavelength by a dichroic beam-splitter close to the exit focal plane. This dichroic beam-splitter transmits the science wavelength to MICADO. Signals from the SCAO wavefront sensor in the NGS wavefront sensor module are sent to the MAORY real time computer, which drives the actuators in the telescope, through the telescope central control system.

Control schemes for the post-focal deformable mirrors in SCAO mode are under investigation.

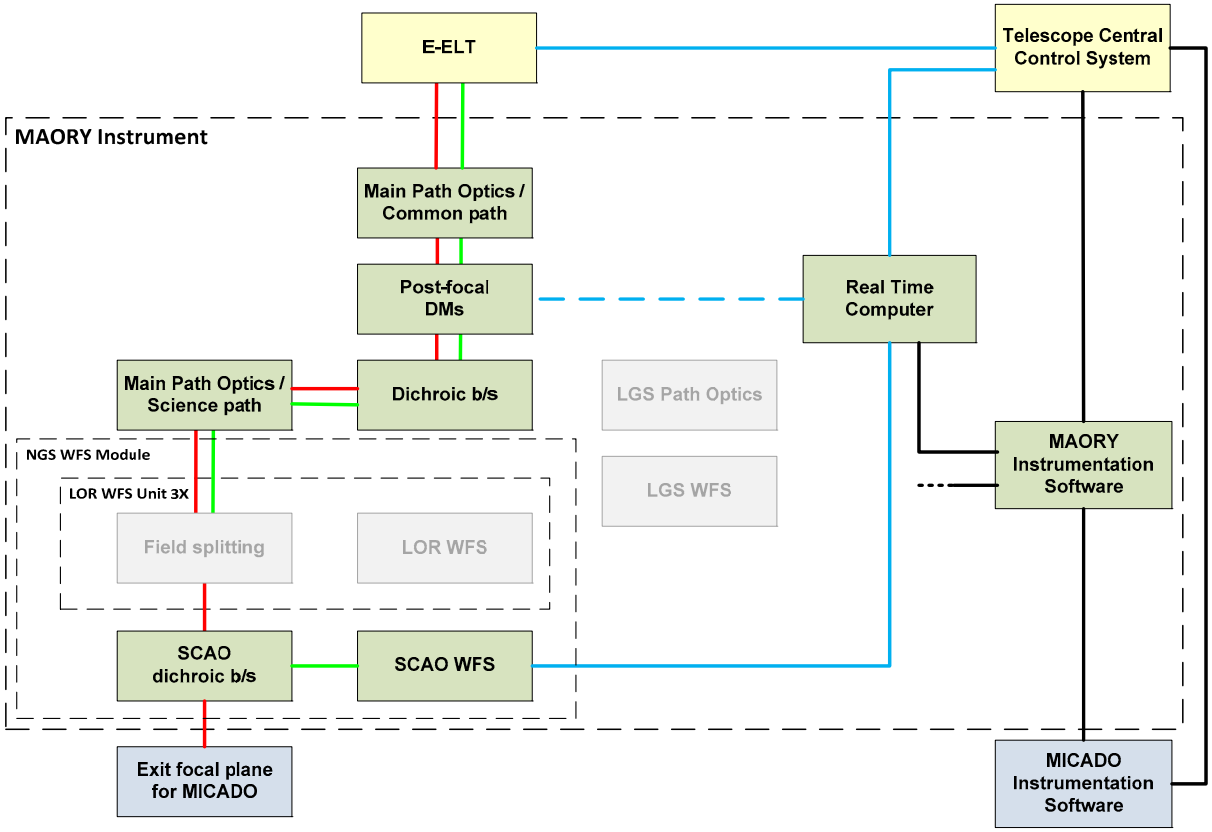



Figure 2. SCAO functional block diagram. Red and green lines: light path. Blue lines: real-time signals. Black lines: non real-time signals. Light grey blocks are not used in SCAO mode. The dashed blue line corresponds to the possible post-focal deformable mirrors control in the SCAO mode.

## 4. OPTICAL AND MECHANICAL DESIGN

The MAORY optical relay has to re-image the telescope focal plane at the exit port for MICADO. A second port for an instrument as yet undefined has to be provided.

The main path optics are an all-reflective design. A dichroic beam-splitter is used for separation of the LGS light from the science path light, the former being reflected on the dichroic surface: thanks to this choice, the beam-splitter substrate material may be plain optical glass.

Three optical design concepts of MAORY have been considered in early phase B, respectively with 7 mirrors, 6 mirrors and 5 mirrors. The 7-mirror design fulfils the 1:1 relay condition, which is a design goal for MAORY. On the other hand, the second instrument port would be in a quite inconvenient location on the Nasmyth platform, posing interface and accessibility problems. The 6-mirror and the 5-mirror designs change the optical interface on the exit port of MAORY.



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On other hand fewer mirrors imply increased throughput and reduced thermal background. The 6-mirror design, in particular, provides optimal accessibility to MICADO and to the second instrument port, being the two client instruments on opposite sides of the MAORY bench. At the moment of writing, the 6-mirror design has been chosen as the reference design to be developed.

The optical relay is mounted on a bench which stands on a hexapod support structure. Other approaches have been tried, but with unsatisfactory performance. Stiffness of the overall mechanical structure is a crucial aspect: considering that the design is in a preliminary stage of development, a minimum eigen-frequency of ≈ 20 Hz for the mechanical structure has been adopted as a target, which is larger than the requirement set by telescope interfaces.

Two mechanical concepts have been considered in early phase B, corresponding to different mounting schemes for MICADO: MICADO on its own stand-alone support structure (detached mounting scheme) and MICADO attached to MAORY (coupled mounting scheme). The detached mounting scheme provides better accessibility to MICADO and simplifies maintenance operations. In this scheme the MAORY NGS wavefront sensor module has to be mounted onto the MICADO cryostat, in order to measure the same tip-tilt disturbances experienced by MICADO itself. The coupled scheme implies more complex mounting and maintenance operations, but it might improve the relative mechanical stability between the two instruments. This might be an added value of the coupled mounting scheme, considering the tight requirements applicable to MAORY and MICADO, related in particular to astrometry. In any case active and adaptive compensation is expected to be needed to achieve the required performance. Although the detached mounting scheme has obvious advantages, the relative stability issue is still under investigation and a fall-back solution is being investigated, based on the coupled mounting scheme.

The MAORY layout has been significantly changed since phase A. The instrument design volume is now on the telescope straight-through focus, which is a convenient location in term of space and available field of view.

A possible opto-mechanical layout of MAORY on the Nasmyth platform is shown in Figure 3 and in Figure 4.

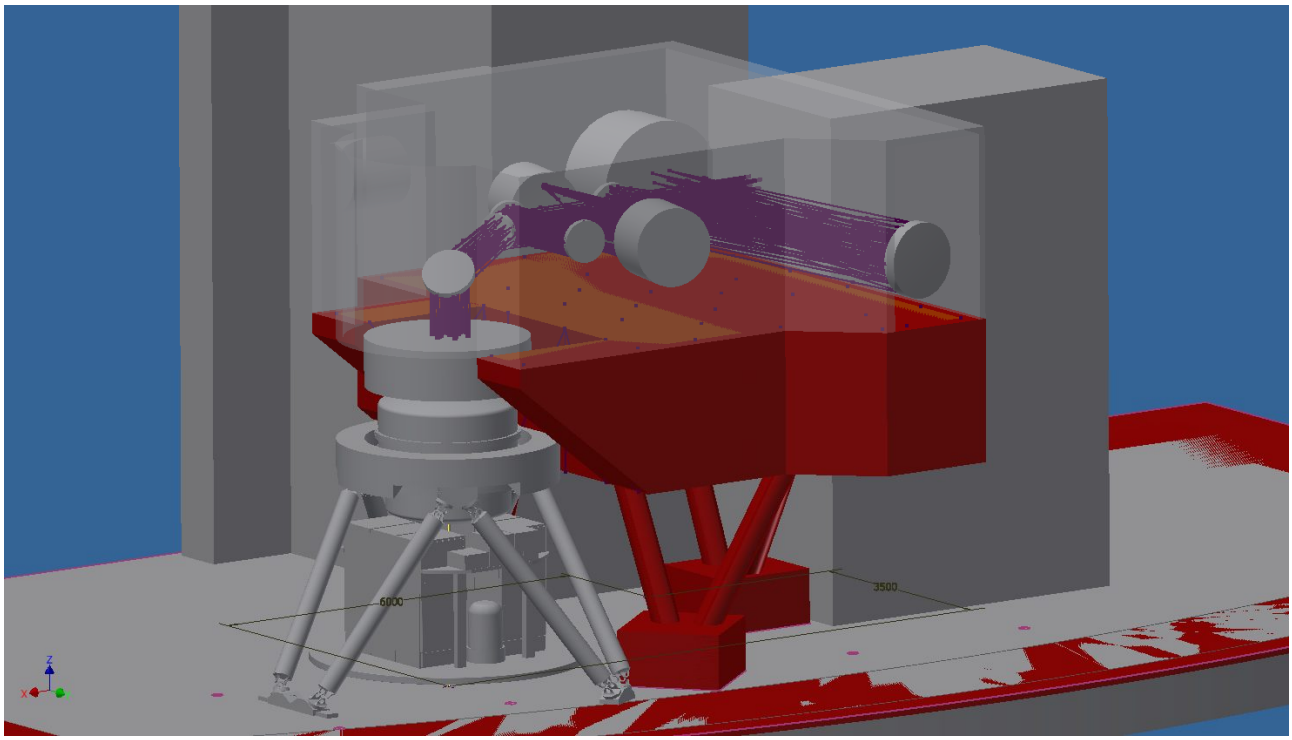



Figure 3. Preliminary MAORY layout on the E-ELT Nasmyth platform. The light-grey structure on the left is MICADO, standing on its own support system in this configuration.



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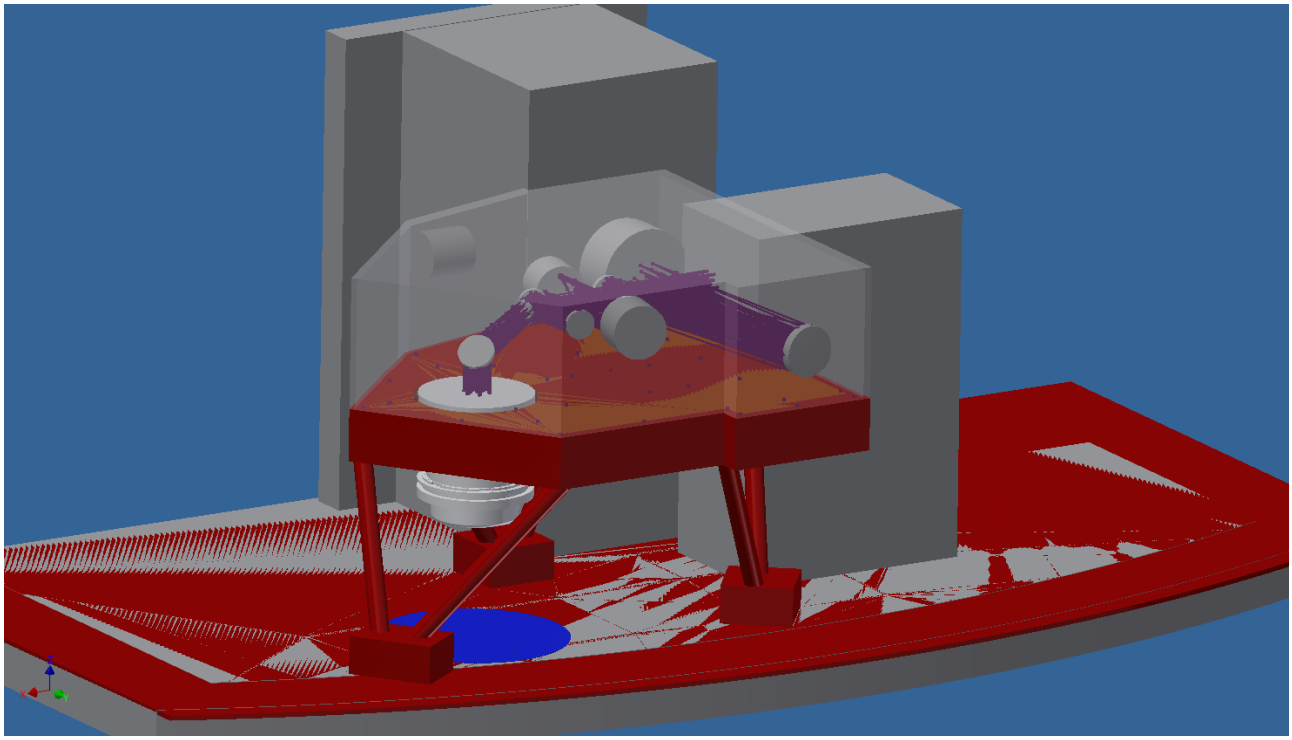


Figure 4. Preliminary MAORY layout on the E-ELT Nasmyth platform. Alternate version. The MICADO cryostat (light grey) is appended to the MAORY bench in this configuration.

## 5. CONCLUSIONS

The phase B of the project for the design and construction of the MAORY instrument for the E-ELT has been recently launched.

Significant changes of requirements have been made since the MAORY project phase A. The instrument location on the Nasmyth platform has been changed from a folded focus to the straight-through focus of the telescope, which is more convenient in terms of space and field of view. A SCAO mode has been included in the MAORY baseline, to be developed in collaboration with the MICADO instrument consortium.

Consolidation of interfaces to the telescope, to MICADO and to the second science instrument is in progress at the moment of writing. The instrument architecture and the expected performance of its adaptive optics system[11] are under consolidation, in preparation for the forthcoming system requirements review.

## ACKNOWLEDGMENTS

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