Programme: **E-ELT**

Project: **ELT MCAO Construction - MAORY**

1

MAORY System Overview

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2021-04-30	6.5, 6.6,8.6	Section 6.5 : Clarification about the use of NACO DM in MAORY Test Unit. Figure 17 updated with new CU/TU overview. New Figure 17.1 with CU/TU mounted on MAORY main structure Section 6.6 Figure 18 updated with new LGS WFS module overview Section 8.6. New section with MAORY Performances with different atmospheric profiles	2

3 Contents

4 Introduction

4.1 Scope

This document provides a general overview of the MAORY system with a description of the general architecture and the main characteristics of all sub-systems. A short description of the performance expected is also provided. A more detailed description of the MAORY design is available in the document MAORY Design Report (RD1) while for all the AO related aspects of MAORY the reader is referred to the MAORY AO Design and Analysis Report (RD3). This document can be viewed, together with the Executive Summary and the MAORY System Design Report, as an introductory reading to understand the MAORY instrument.

4.2 Definitions, Acronyms and Abbreviations

AD	Applicable Document
AO	Adaptive Optics
CNRS	Centre National de la Recherche Scientifique
DM	Deformable Mirror
ESO	European Southern Observatory
FoV	Field of View

ICSS	Instrumentation Control System Software
INAF	Istituto Nazionale di Astro Fisica
INAF-OAA	INAF - Osservatorio Astrofisico Arcetri
INAF-OAAB	INAF - Osservatorio Astronomico d' Abruzzo
INAF-OAB	INAF - Osservatorio Astronomico Brera
INAF-OACN	INAF - Osservatorio Astronomico Capodimonte Napoli
INAF-OAPD	INAF - Osservatorio Astronomico di Padova
INAF-OAS	INAF - Osservatorio di Astrofisica e Scienza dello Spazio di Bologna
INSU	Institut National des Sciences de l'Univers
LGS	Laser Guide Star
MAORY	Multi conjugate Adaptive Optics RelaY

NGS	Natura Guide Star
NUIG	School of Physics at the National University of Ireland Galway
PAC	Preliminary Acceptance Chile
PAE	Preliminary Acceptance Europe
PFS	Pre Focal Station
PT	Product Tree
SGP	South Galactic Pole
SR	Strehl Ratio
VCM	Voice Coil Motor
WBS	Work Breakdown Structure
WP	Work Packages

4.3 Related Documents

4.3.1 Applicable Documents

The following applicable documents form a part of the present document to the extent specified herein. In the event of conflict between applicable documents and the content of the present document, the content of the present document shall be taken as superseding.

AD1	Agreement for the design, construction and commissioning of the MAORY Instrument on the European Extremely Large Telescope (E-ELT) Number 65221/ESO/15/67001/JSC
AD2	MAORY STATEMENT OF WORK ESO-257875 Version 1
AD3	MAORY (E-ELT MCAO) Technical Specification ESO-254311 Version 2
AD4	MAORY Project Management Plan E-MAO-000-INA-PLA-001 Version 4
AD5	Relevant Atmospheric Parameters for E-ELT AO Analysis and Simulations; ESO-258292 Version 2

AD6	Common ICD between the E-ELT Nasmyth Instruments and the Rest of the E-ELT System ESO-253082, Version 3

4.3.2 Reference Documents

The following documents, of the exact version shown herein, are listed as background references only. They are not to be construed as a binding complement to the present document.

RD1	MAORY SYSTEM DESIGN REPORT E-MAO-SE0-INA-DER-001 Version 1
RD2	MAORY SYSTEM ANALYSIS REPORT E-MAO-SE0-INA-ANR-001 Version 1
RD3	MAORY AO DESIGN AND ANALYSIS REPORT E-MAO-SA0-INA-DER-001 Version 1
RD4	ESO CRE ET-951 MAORY second port technical requirements specifications Version 1
RD5	MAORY Reply to ESO CRE ET-951 E-MAO-000-INA-CRE-001 Version 1
RD6	MAORY SYSTEM OPTICAL DESIGN REPORT E-MAO-SF0-INA-DER-001 Version 1

RD7	MAORY DEFORMABLE MIRRORS DESIGN REPORT E-MAO-PD0-INA-DER-001 Version 1D1
RD8	MAORY OPTOMECHANICS DESIGN REPORT E-MAO-PF0-INA-DER-001 Version 1D3
RD9	MAORY MAIN STRUCTURE DESIGN REPORT E-MAO-PM0-INA-DER-001 Version 1D1
RD10	MAORY THERMAL CONTROL DESIGN REPORT E-MAO-PT0-INA-DER-001 Version 1D3
RD11	MAORY CALIBRATION UNIT DESIGN REPORT E-MAO-PU0-INA-DER-001 Version 1D1
RD12	MAORY TEST UNIT DESIGN REPORT E-MAO-PV0-NUI-DER-001 Version 1
RD13	MAORY LGS WFS MODULE DESIGN REPORT E-MAO-PL0-IPA-DER-001 Version 1D13
RD14	MAORY LOR WFS MODULE DESIGN REPORT E-MAO-PN0-INA-DER-001 Version 1D9
RD15	MAORY INSTRUMENTATION SOFTWARE FUNCTIONAL SPECIFICATION E-MAO-PS0-INA-SPE-003
RD16	MAORY ICH DESIGN REPORT E-MAO-PH0-INA-DER-001 Version 1D4
RD17	MAORY REAL TIME COMPUTER DESIGN REPORT E-MAO-PR0-INA-DER-001 Version 1

RD18	Plantet et a. 2018, "*LO WFS of MAORY: performance and sky coverage assessment*" in *Adaptive Optics System IV* , 10703, 1141, SPIE 2018
RD19	Agapito G., Puglisi A. and Esposito S., "P*ASSATA: object oriented numerical simulation software for adaptive optics*", Proc SPIE 9909, SPIE 2016
RD20	MAORY ADAPTIVE OPTICS SIMULATION ANALYSIS REPORT E-MAO-PC0-INA-ANR-001 Version 1
RD21	MAORY AIV Plan Europe E-MAO-000-INA-PLA-010 Version 1
RD22	Comparison of the LGS WFS cameras detector E-MAO-000-INA-TNO-009 Version 1
RD23	MAORY INSTRUMENT SOFTWARE USER REQUIREMENTS SPECIFICATIONS E-MAO-PS0-INA-SPE-002
RD24	Ferreira, F, et al, "Hard real-time core software of the AO RTC COSMIC platform: Architecture and performance" Proc. SPIE 11448, Adaptive Optics Systems VII, 11448-172 (2020)
RD25	Gratadour, D., "The COSMIC RTC platform," RTC4AO5, https://indico.obspm.fr/event/57/contributions/327/ (2018)
RD26	Kerley, D. A., et. al., "HEART for all types of AO systems," Proc. SPIE 11448, Adaptive Optics Systems VII, 11448-175 (2020).
RD27	Crane, J., et. al., "NFIRAOS adaptive optics for the Thirty Meter Telescope," Proc. SPIE 10703, 107033V (2018).
RD28	Rakich, A. and Rogers, R.J., "A Maxwellian "Ideal Imager" optical relay suitable for AO application, Proc SPIE 11451, Advances in Optical and Mechanical Technologies for Telescope and Instrumentation IV, 2020

RD29	Rakich, A. and Rogers, R.J., "Aberration theory-based approaches to optical design", Proc SPIE 11548, Optical Design and Testing X, 2020
RD30	Request for Deviation for the MAORY LGS WFS Detectors E-MAO-000-INA-RFD-001 Version 1
RD31	MAORY Calibration Units User Requirements E-MAO-000-ESO-TNO-002 Version 2
RD32	MAORY CALIBRATION PLAN E-MAO-SC0-ESO-PLA-001_01 Version 1
RD33	A. Tokovinin and S. Heathcote 2006 *PASP* **118** 1165
RD34	Relevant Atmospheric Parameters for E-ELT AO Analysis and Simulations ESO-258292, version 2
RD35	Osborn et al., "Optical turbulence profiling with Stereo-SCIDAR for VLT and ELT", MNRAS, 478(1), 825-834 (2018)
RD36	MAORY Science merit function for the one vs two post focal DMs configurations E-MAO-SS0-INA-TNO-003 Version 1D2
RD37	MAORT trade-off study: Octopus End-to-End simulations, E_MAO-I00_ESO-TNO-001, 1D5

5 General Architecture

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.

5.1 Main Technical Specifications

The MAORY design has been developed in order to satisfy the following fundamental requirements given in the Technical Specification (AD2) :

- 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.

- 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 LGS. Natural guide star wavefront 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. When the original Technical Requirements specifications were written, little was known on the instrument to be hosted at the second port of MAORY. Nevertheless, in order to proceed with the design, several technical specifications for the second port (some marked as TBC) have been included in the MAORY Technical Specification documents (AD3). On the basis of all requirements related to the second port in AD3 (INFO-MAO-4, INFO-MAO-45, INFO-MAO-59, R-MAO-61, R-MAO-62, R-MAO-63, R-MAO-91, R-MAO-92, R-MAO-93) we did not have contractual bindings regarding the position where the second port will be delivered.

  Starting from March 2019 a discussion with ESO began on the possible characteristics of the instrument to be used in the second port. The first informal written request from ESO with the desired second port technical specification was received by the MAORY Consortium via email on 16 October 2019. The most impacting among the new requests was to have a gravity invariant focus with a back focal distance of at least 1m (ideally as much as possible close to 1.8m as for MICADO). According to these new requests, all the previous designs developed (including the baseline as it was in October 2019) were not compliant.

On July 6, 2020, we received the formal change request CRE ET-951 (RD4) from ESO. This CRE clarifies the new requirements for the second port of MAORY. It modifies and expands the MAORY technical requirements specification document (AD3). The CRE ET-951 has been accepted by the MAORY Consortium with a dedicated document (RD5).

On the basis of the new requirements, also the exit port for the second instrument has to be gravity invariant.

- 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 condition (from AD5) 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 condition, 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

5.2 High Level Product Tree

Following these requirements, the MAORY design has been developed starting from 4 different modules each containing different work packages :

- ❖ The MAORY Main Path module including the following WPs: Main Structure, Optomechanics (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

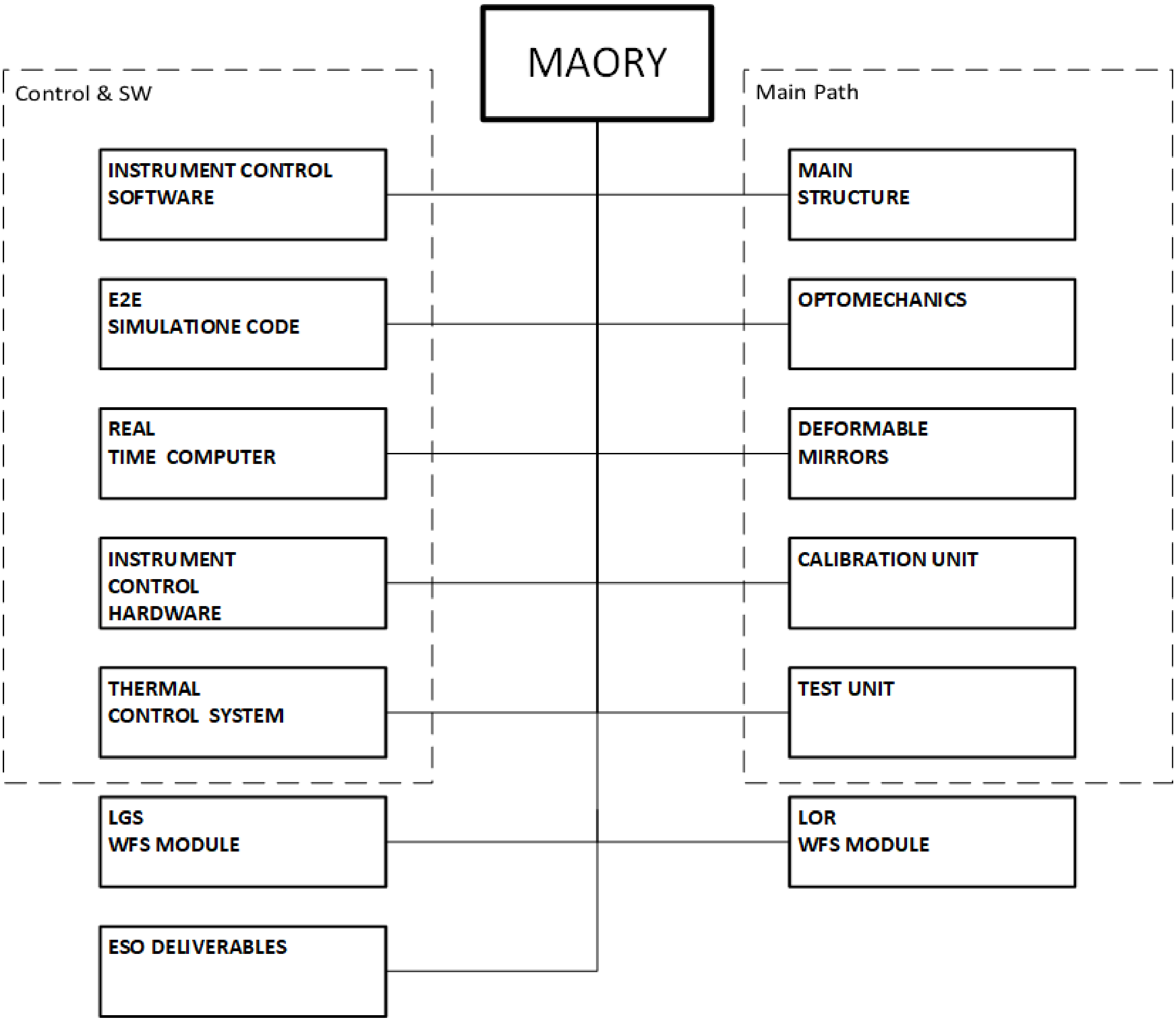

Figure 1 : *MAORY Product Tree arranged in different modules: Control and Software, Main Path, LGS WFS, LOR WFS and ESO deliverables.*

The activities of each WP are coordinated at the system level by dedicated WPs for management and system activities. It has to be noted that the WP PE0 (ESO Deliverables) is considered as an external activity, not subject to MAORY control. The deliverables of this WP are only the cameras to be used in MAORY, treated as Customer Furnished Items. No documentation is expected. For this reason this WP is not described in the MAORY PDR documentation.

A detailed description of the MAORY WBS is reported in AD4.

5.3 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. During the Phase-B several Trade Offs between different optical designs have been carried out in order to optimize the design in terms of performance, minimization of optical elements, compactness of the main path optics, manufacturability and optical alignment. According to AD2, all the different optical designs investigated assumed the presence of two post focal DMs although in the baseline it is foreseen the presence of only one DM with the second one replaced by a rigid mirror. AO simulations (RD3) show that in presence of only one post focal DM, the optimal conjugation altitude for the DM is in the range 17-20 Km above the telescope. In the case of two post focal DMs, the mid-altitude optimal range is 6-12 Km.

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 (no gravity invariant). In early 2020, after a trade off study and in agreement with ESO, the optical baseline design was changed in order to provide also for the second instrument a gravity invariant port. The performances guaranteed to MICADO were maintained and extended also to the second instrument. A summary of all optical trade off performed is reported in RD2.

The final MAORY main path optics baseline has 8 reflections: 2 aspheric concave mirrors, 2 spherical deformable mirrors (one convex and one concave), 1 dichroic and 3 fold mirrors. A detailed description of the optical design is available in RD6 while a detailed description of the deformable mirrors is available in RD7. The optical layout (side and top view) is shown in Figure 2 where, in the bottom panel, the second port focal plane is also shown, as well as the LGS module area envelope and the MICADO envelope. In the current configuration, according to the technical specification, the MAORY baseline provides for the presence of only one DM (a 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 (RD28, RD29) 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 the system pupils and meta-pupils. In the presented optical configurations, the plates are at about 350 mm after the focal plane.

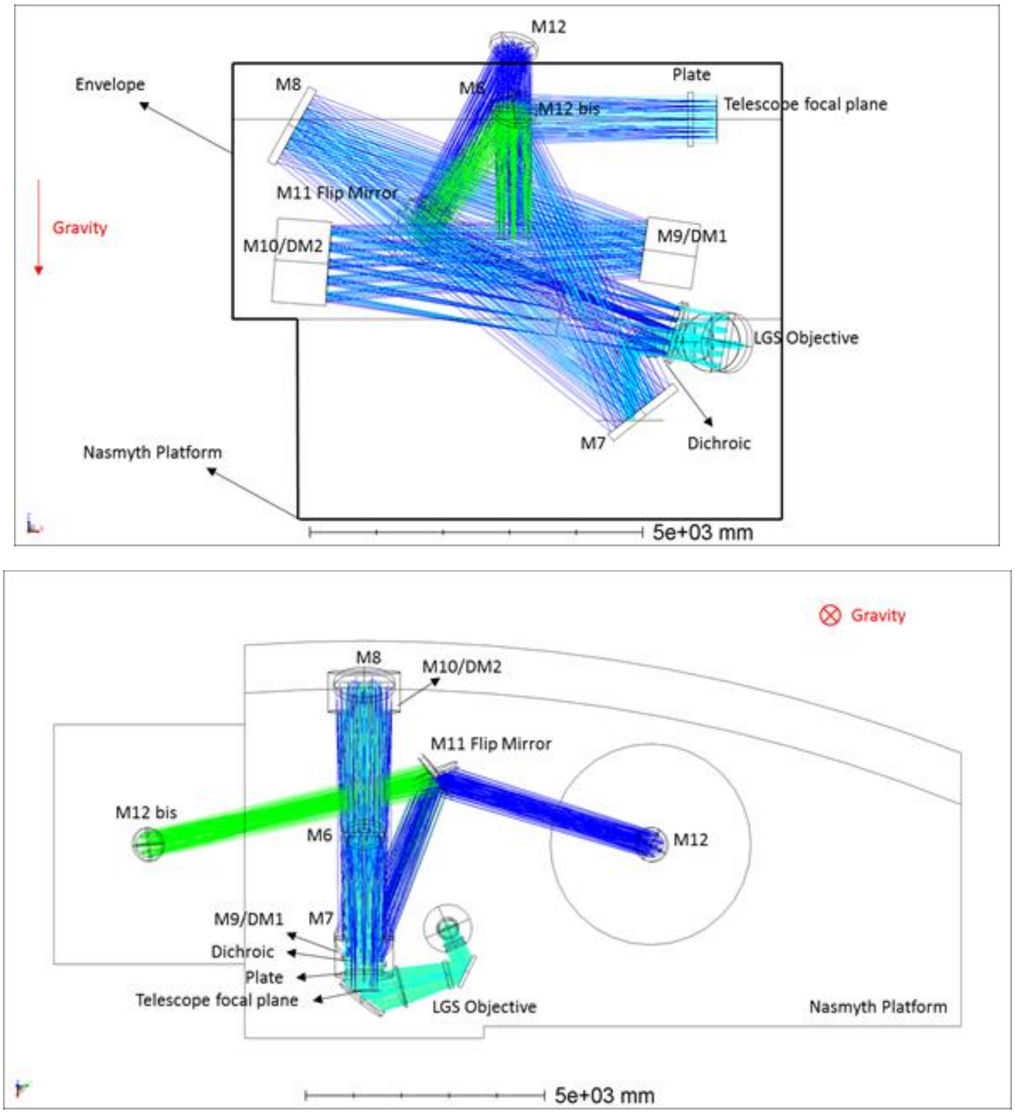

Figure 2 : *Post-Focal Relay Optics baseline sideways layout (top) and top view layout (bottom). Blue rays: optical beam from the telescope focal plane to the exit port for MICADO. Green rays: the differential path to the exit port for the second instrument. Light Blue rays: LGS path*

5.4 Global architecture and Functional Diagram

On the basis of the baseline optical design and considering all the requirements in AD2 the global architecture illustrated in Figure 3 and the functional diagram reported in Figure 4 have been adopted.

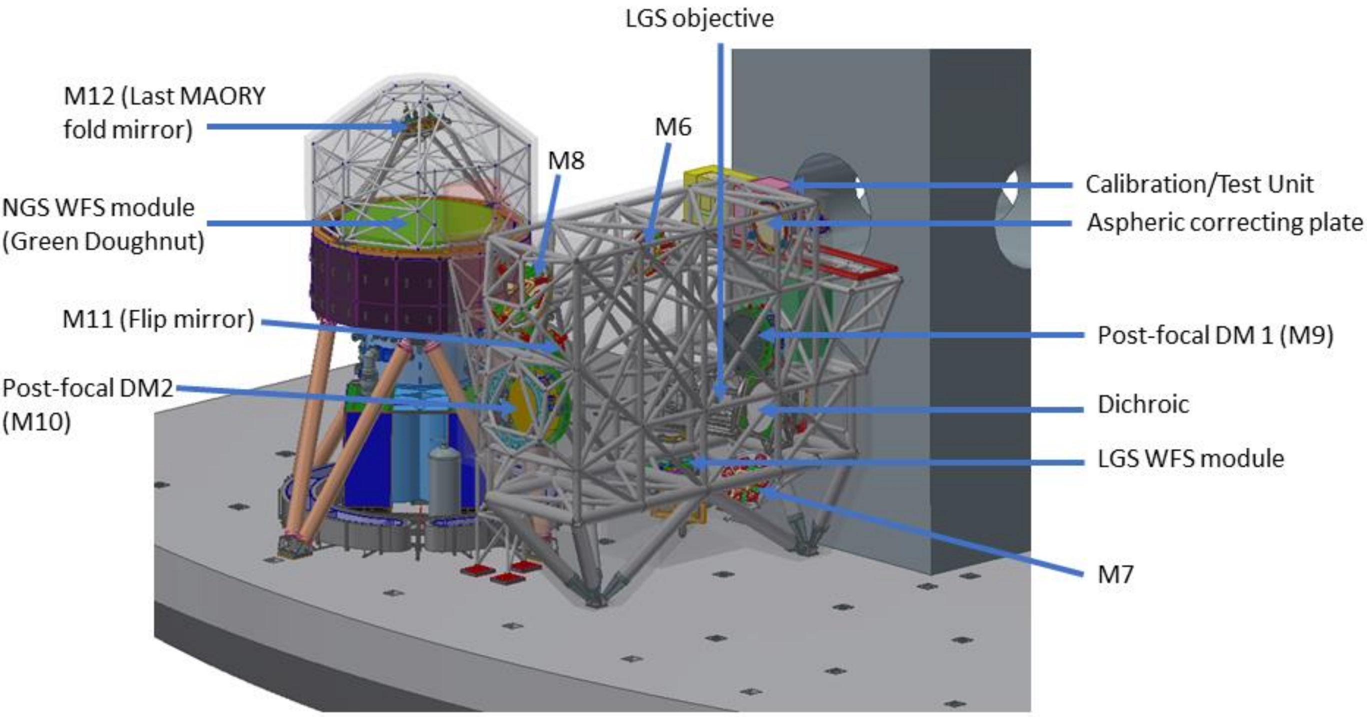

Figure 3: *General overview of the MAORY instrument (thermal cover in transparency) installed on the Nasmyth platform with MICADO*

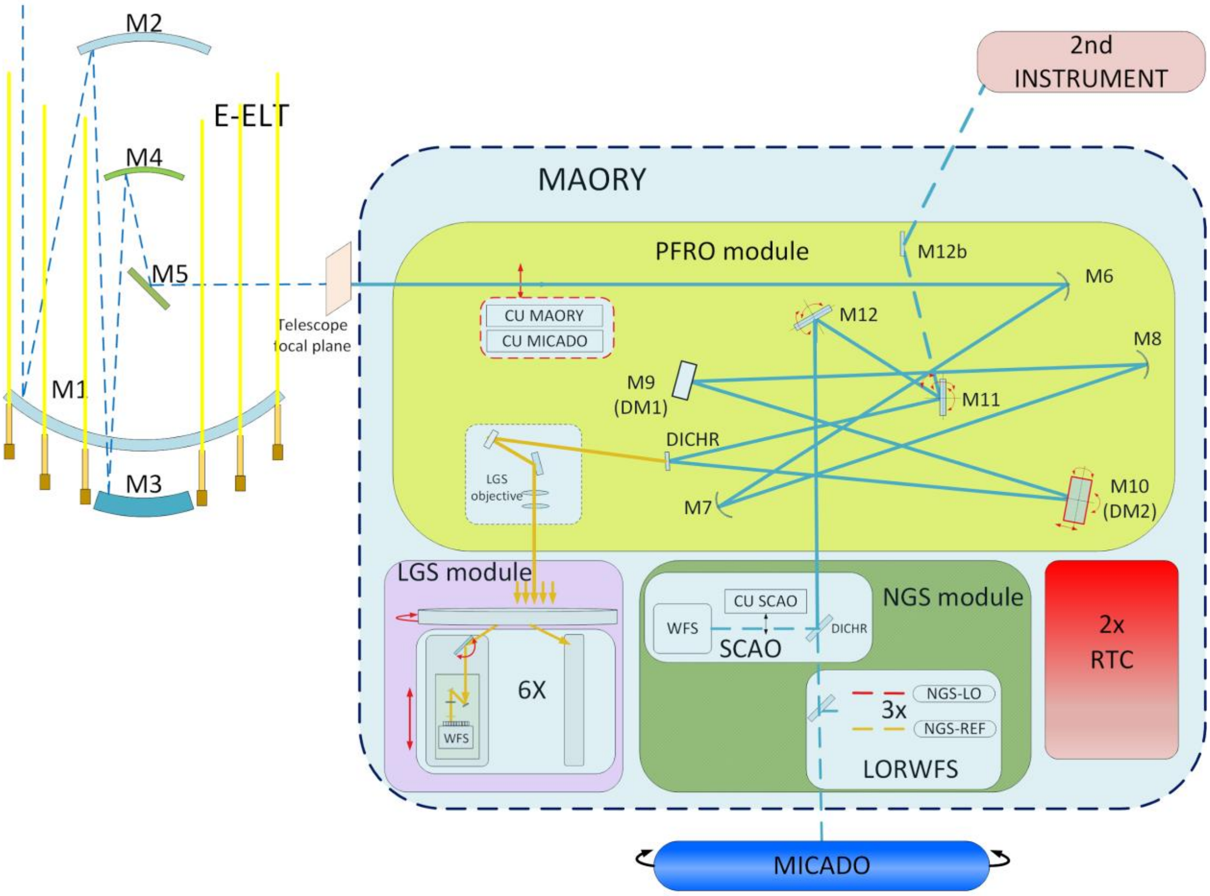

Figure 4: *Functional overview of the ELT, MAORY and MICADO.*

Both the 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 MAORY Real Time Computer, which drives the deformable mirrors, i.e. the telescope's M4/M5 adaptive/tip-tilt mirrors and two post-DMs inside MAORY itself. All the wavefront sensors in MAORY are placed downstream of the deformable mirrors ensuring optical feedback.

5.5 Adaptive Optics Control

A general overview of the MAORY AO control is reported in Figure 5.

With reference to Figure 5, light collected by the telescope enters the MAORY 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 in 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 MAORY (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.

In the next section, a short overview of the sub-systems is given, while a detailed description at system and sub-system level is available in the various System and Sub-system Design and Analysis Reports.

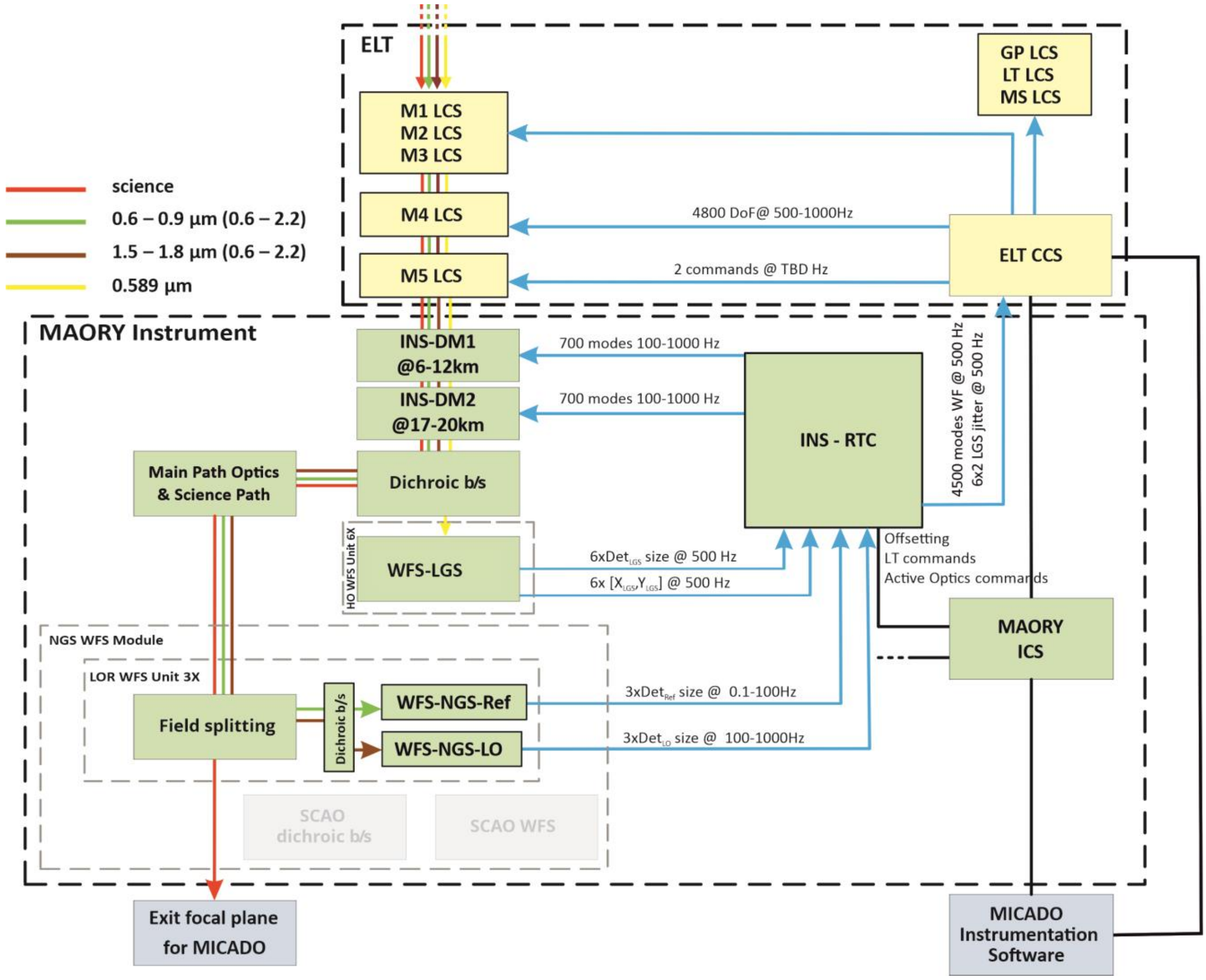

Figure 5: General Overview of the MAORY AO control in MCAO mode. Red lines mark the science path, green lines the NGS visible light path, brown lines the NGS infrared light path and yellow lines the LGS light path. Real time command paths are marked with light blue lines, non-real time ones are in black. Devices belonging to MAORY 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.

6 Sub-systems

The following sections describe the main characteristics of each sub-system. For a detailed description of each sub-system, the reader is referred to the various Sub-system Design and Analysis reports.

6.1 Deformable mirrors

The current optical design has been developed assuming the presence of two post focal DMs although in the baseline the presence of only one DM is foreseen with the second one replaced by a rigid mirror. According to the AO simulations (RD3) the optimal conjugation for these two DMs is in the range 17-20 Km for the first one and in the range 6-12 for the second one.

In the baseline design the two mirrors are spherical shell with a thickness of 1.6 mm made of Zerodur with the following parameters :

	M9-DM1	**M10-DM2**
Shape	Convex	Concave
Outer Optical Diameter (mm)	880	1160
Total actuators number	1026	1147
Conjugation Altitude (Km)	17.5	6.5

In the current configuration, the MAORY baseline provides the presence of only M9-DM1 while M10-DM2 is replaced by a rigid mirror.

The MAORY deformable mirror units consist of several sub-systems, namely :

- The Deformable Mirror made of
  - the shell, that is the subunit physically providing wavefront corrections; it includes the mirror, the mirror support system, force actuation mechanisms (VCM actuators), and capacitive sensors needed to set the shape of the mirror.
  - the Reference Body, that is the subunit providing a stable reference for the first armature of the capacitive sensors used to measure the position of the mirror,
  - the coldplate the mechanical structure to hold the actuators and the related electronics

- the electronics, which comprises the embedded Control Electronics and the Supply and Operation Electronics
- the cooling system, serving both the DM and the electronics crate
- a kinematic mount that connects the cold plate to the bench

A 3D layout of the two MAORY DM is shown in Figure 6.

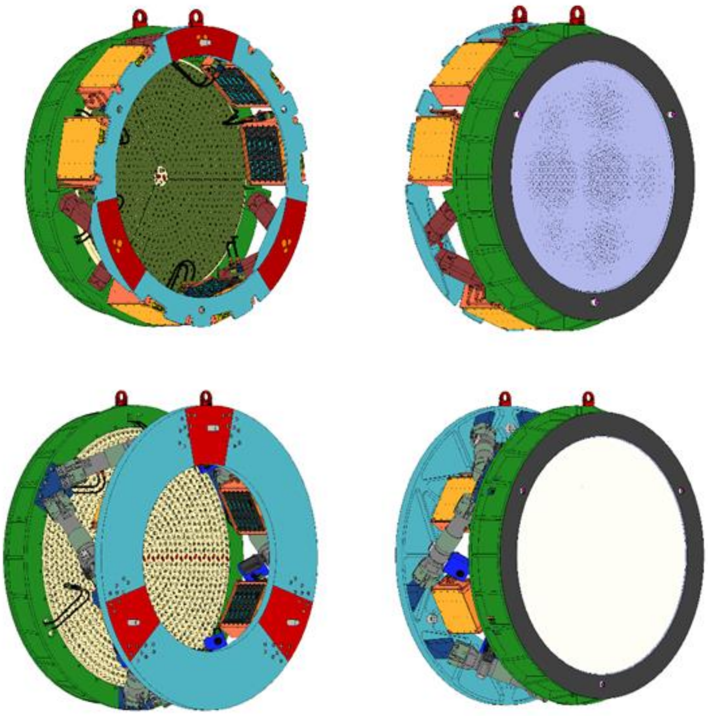

Figure 6: *3D Layout of the M9-DM1 unit (top panel) and of the M10-DM2 unit (bottom pane)*

The detailed feasibility study performed on the MAORY DMs allow us to state that both the deformable mirrors can be realized on the basis of the existing technology, with no need for very specific additional development. This has a very positive impact in terms of schedule, risks and cost. Finally, it has been demonstrated that in the case where two DMs are adopted, those can share the same design and most of the line replaceable units (LRU), which is a great benefit in terms of calibration, maintenance and costs.

A detailed description of the MAORY Deformable mirrors is available in RD7

6.2 Optical Mounts

The main purpose of the optical mounts is to keep the optics in position fixed onto the MAORY bench. The overall optomechanical architecture has been conceived in order to be modular, if not identical, among all the components besides the DMs, whose mounts have been developed together with the DMs themselves.

After discussing with the manufacturing companies, the design has been tuned to propose a LW solution where all the mirrors have a thickness that is 1/20 of the semi-major axis. This solution implies less stiffness provided from the glasses itself and also for manufacturability reasons is better to keep the optomechanics using a Whiffle Tree (WT) solution.

The WT is designed in order to have 27 connection points on the optical elements, with three levels of flexure. The three levels of the WT define the tip/tilt/focus position, while the central membrane defines the decenter. The WT dimensions vary according to the related mirror, while the flexure components are identical (per-level). Those structures are connected to the main structure with three kinematic connections apart from M11, M12, the structure that holds the LGSo and the DC that are pinned to the main structure.

An example of a whiffle tree solution for M11, M8 and M12 is shown in Figure 7.

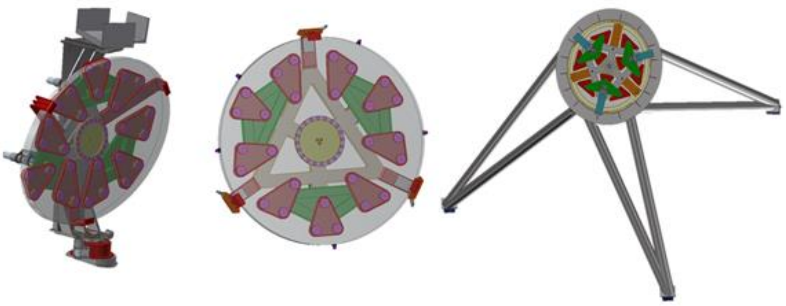

Figure 7 : *Example of WT solution for M11 M8 and M12*

A detailed description of each of the optical mounts is available in RD8

6.3 Main Structure

The “MAORY Main Structure” is a part of the whole MAORY module that includes in the current baseline configuration:

- MAORY Main Support Structure (MAORY_MSS)
- Thermal Enclosure – MAORY side.
- Support Structure between MAORY & MICADO for the thermal duct.
- Thermal duct between MAORY & MICADO.
- Support Structure for MICADO Thermal Enclosure.
- Thermal Enclosure – MICADO side.
- CU Selector for MAORY Folding Mirror (Folding Mirror_CU) and MICADO Calibration Assembly (MCA).

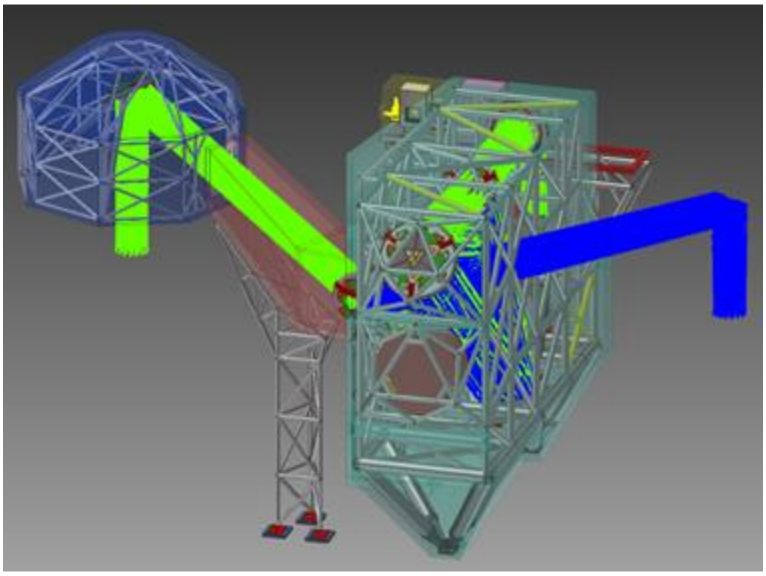

Figure 8 : *Preliminary CAD model of the MAORY Main Support Structure*

The MAORY Main Support Structure (MAORY_MSS) will require to be fixed through three main support points on the grid of Nasmyth Platform. In addition to these points, other (probably three) additional points will be required to fix the Support Structure for the thermal duct, between MAORY & MICADO, that connects MAORY thermal enclosure to MICADO thermal enclosure.

A detailed description of the main structure is available in RD9

6.3.1 MAORY Main Support Structure - DESIGN OVERVIEW

The MAORY MSS (Main Support 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 joined 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 mechanical design for MAORY_MSS is shown in Figure 8.

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 9, 10 and 11).

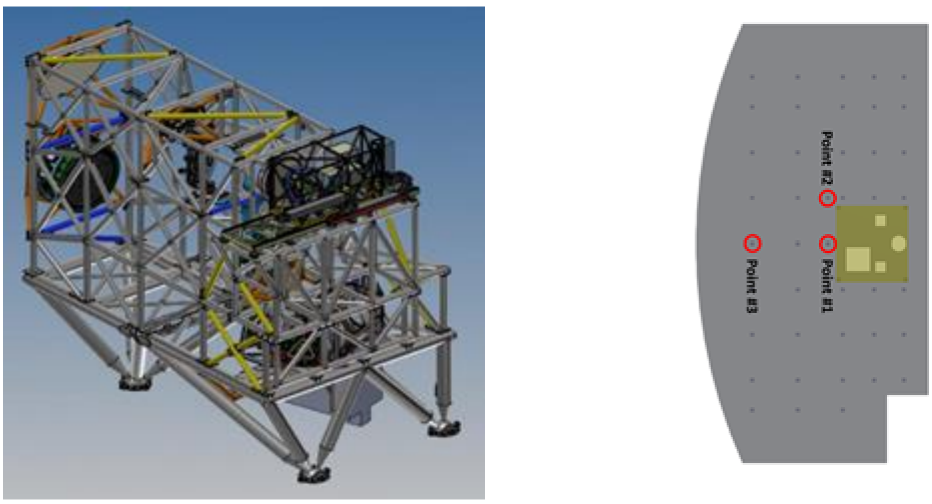

Figure 9 : *MAORY Main Support Structure (left side) and Nasmyth Platform with the choised main attachment point (right side)*

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 10, will be split up in several (welded) parts connected to each other with bolts and using, also, reference pins in order to have an accurate mounting/dismounting for the various provisional phases (see Figure 10). The accessibility to all opto-mechanical components and sub-assemblies (for mounting/dismounting/maintenance operations) is ensured by the possibility of the temporary disassembly of some sub-assembly elements or beams from the MAORY_MSS (depicted in yellow in the Figures 9 and 10). Electrical harness inside the MSS allows all maintenance operations.

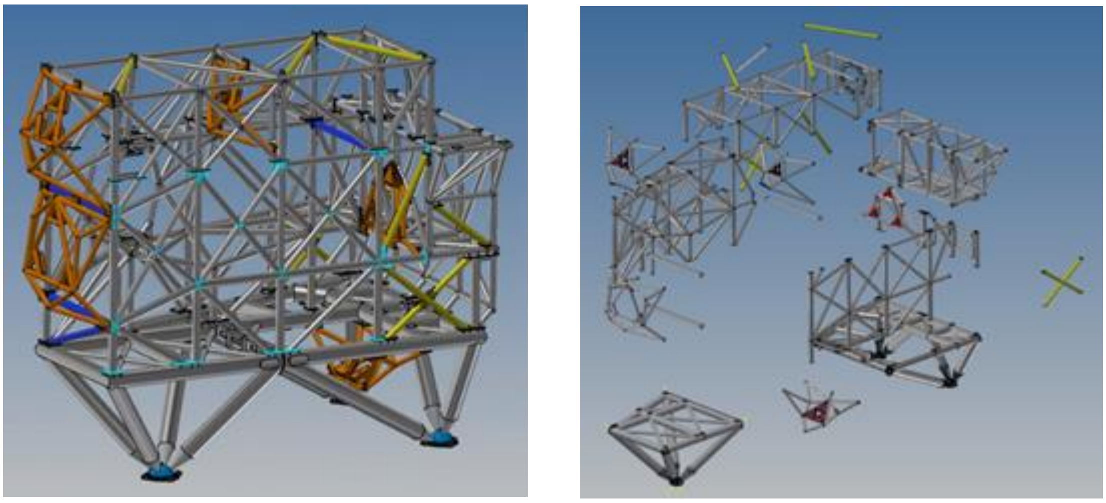

Figure 10 : *MAORY MSS (left side) and splitting strategy for the MSS (right side)*

6.3.2 Optomechanical Support Structure

The Optomechanical Support Structures (OSS - orange structures highlighted in the Figure 10) will be used in order to accommodate accurately the optical and optomechanical elements installed on the MAORY module. The optical elements hosted are: SP, M6, M7, M8, M9/DM1, M10/DM2. The structure of these sub-assemblies are made of structural steel pipes and interface steel plates with the cinematic supports for the Optomechs. The optomechanical support structures of M8 (left side) and M7 (right side) are shown in Figure 11.

Figure 11 : *Optomechanical Support Structures of M8 (left side) and M7 (right side).*

6.3.3 MAORY and MICADO calibration units selector

The calibration selector is a linear stage that deploys the MAORY FM_CU (Folding Mirror for MAORY Calibration Unit) and the MCA (MICADO Calibration Assembly), or clears the path for the light coming from the telescope

Figure 12 : Mechanical model for the Calibration Units selector

6.3.4 Support Structure between MAORY & MICADO

The Support Structure between MAORY & MICADO is the mechanical structure shown below in the Figure 13. On the top part of this support structure the thermal duct (red tube on the right panel in the Figure 13) between MAORY and MICADO enclosures will be installed. The installation of this support structure will be possible using additional support points on the grid of the Nasmyth Platform.

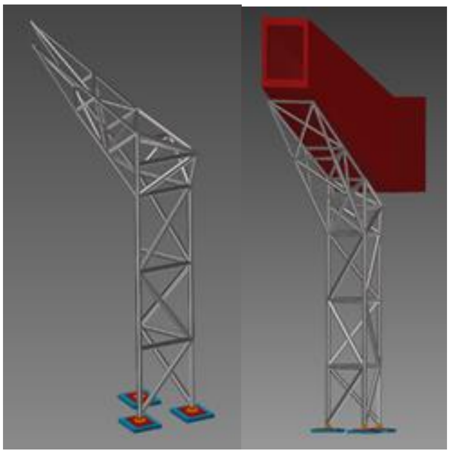

Figure 13 : *CAD model of the Support Structure between MAORY and MICADO*

6.3.5 Support Structure for MICADO Thermal Enclosure

The structure for MICADO Thermal Enclosure is made with standard structural aluminum pipes and welded panels. The preliminary mechanical design is shown in the next Figure 14 (right side). This support structure holds up the thermal enclosure of MICADO and is installed directly on this instrument. The four interface flanges on MICADO top bench are shown below in Figure 14 (left side) and are highlighted with yellow circles.

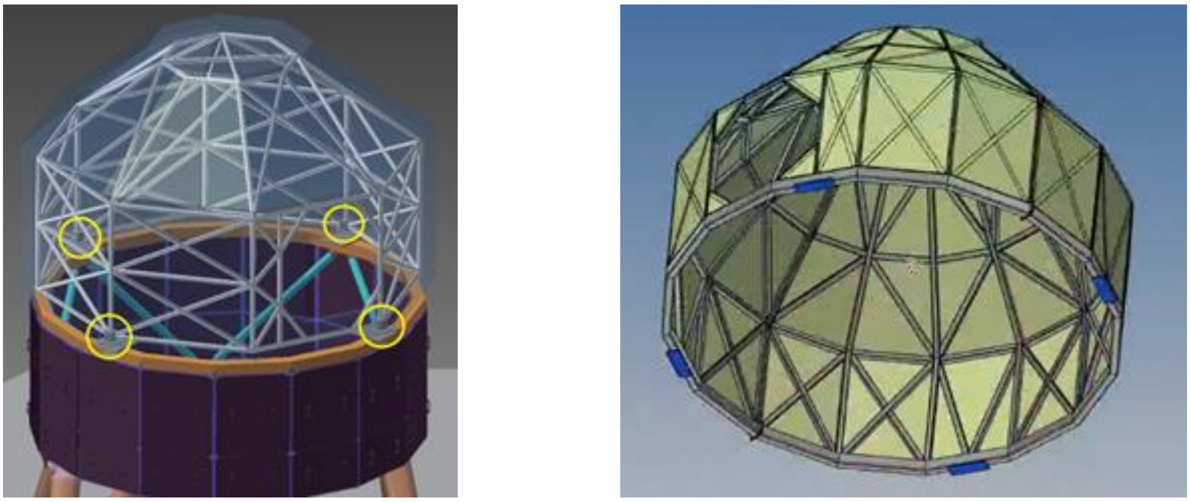

Figure 14 : *CAD model Support Structure for MICADO Thermal Enclosure.*

6.4 Thermal Cover

The main goal of the thermal cover is to ensure the required thermal homogeneity between the optical bench structure and the environment during non-operational daytime and between the subsystems, the internal surface of the panels, and the optical bench structure during night-time periods.

A passive insulation cover has been selected after trading off with an active insulation cover (see RD10 for more details). The panels are composed of a 70mm thick PIR panel (density around 34kg/m3 and thermal conductivity 0.022W/(m*K)) with an inner plate of aluminium 1100 1mm thick.

The system has a value of tau (time constant) of approximately 8 hours and, therefore, the temperature variations are limited (and compatible with the optical requirements) during the night. In Figure 15 we show the simulated temperature variation outside (blue line) and inside (red line) the MAORY instrument over a period of time of ten hours.

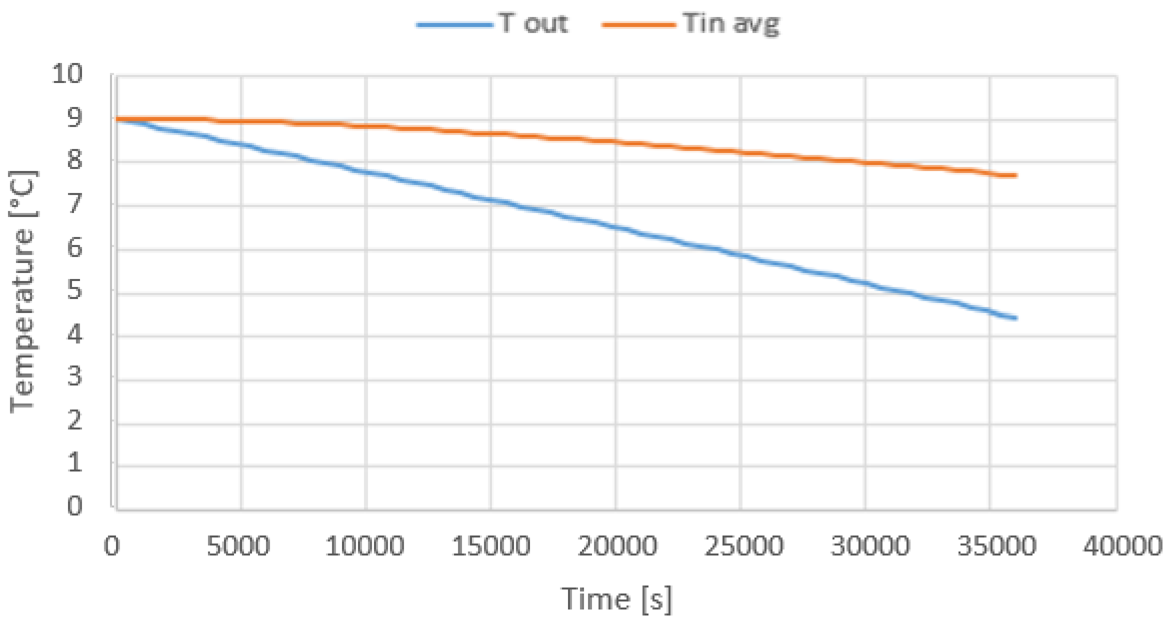

Figure 15: *Temperature variation outside (blue line) and inside (red line) MAORY as function of time*

An overview of MAORY with the thermal cover is shown in Figure 16

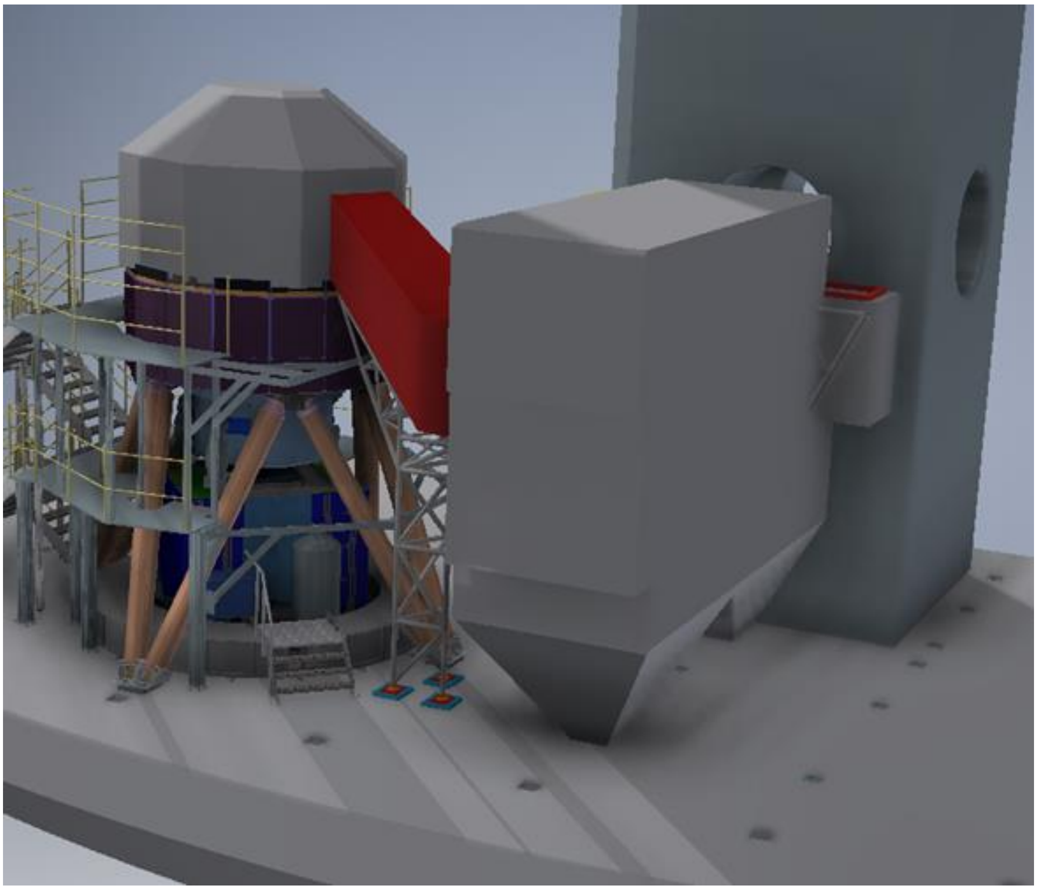

Figure 16: Overall view of MAORY with the thermal cover

A detailed description of the thermal cover is available in RD10.

6.5 Calibration and Test Unit

The Calibration and Test unit is an independent optical system fixed on the MAORY main structure adjacent to the PFS (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 and its optical design is shown in Figure 17.

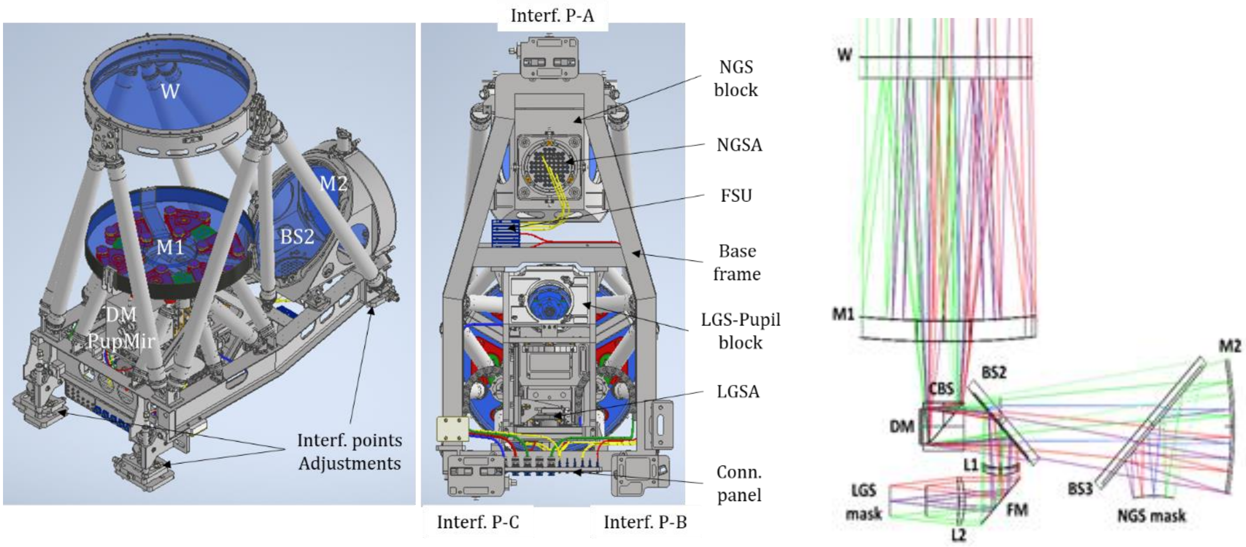

Figure 17: *Calibration Unit overall view and Optical layout (see RD12 for more details)*

TEST UNIT

The TU mode is activated through the insertion of a small DM that bends the light coming from the star mask upwards to the "telescope" while in CU mode the small DM is replaced by a flat static mirror. The TU will be used during the MAIV phase in Europe and in particular during the PAE to simulate the presence of the Telescope. The TU DM will be used to insert controlled optical disturbances to facilitate testing of the MAORY subsystems and the overall MAORY operation. A Test Camera/WFS will be installed at the focus of the corrected beam exiting MAORY and used for the final alignment and PAE of MAORY.

In the current design for the DM we will use the NACO piezo-based CILAS DM with 17x17 actuators and 7 mm pitch. We know that the NACO CILAS DM is an old device and the MTBF could be an issue. For the moment we will keep this device in our baseline for the Test Unit because its use is foreseen only in Europe and helps us to keep cost low.

However, as soon as will be possible to have this device in one of our labs in Europe, it will be tested and verified. As risk mitigation we are investigating the possibility to use a COTS device.

A detailed description of the Test Unit is available in RD12

CALIBRATION UNIT

The Calibration Unit (CU) is needed to run calibration templates, such as WFS calibrations, NCPA calibration and tomographic reconstructor calibration, as well as verification and test procedures (essentially system health checks).

These operations can be done independently from other activities involving the telescope, both in daytime or night-time at the Nasmyth platform (standalone mode). This modality will reduce the amount of required night-time spent on sky, a fundamental resource at the ELT. The underlying motivation for the need of the CU is therefore to keep the time spent on sky for essential activities, while performing all other daily or periodic calibrations, verifications and checks with this unit. The CU is needed to perform the following operations described RD31 and RD32 :

- AIV
    - **Test and verification**: Functional verification of the system during daytime, validation of new algorithms to be used during the night, verification of Hardware behavior after installation and after maintenance
    - **Alignment** verification and fine tuning
- Calibration and recalibration
    - **MAIT in Europe:** Calibration of initial configuration and development of calibration templates
    - **AIV in Chile:** Run templates to calibrate the system “as aligned” in the final environment

    - During the **life of the instrument**, e.g. after maintenance of subsystems (PFDMs, Cameras, recoating), displacement of the bench to access neighboring systems (PFS, other INS), earthquakes, etc …
- Preventive maintenance diagnosis:
    - Daytime **performance trending**
    - **Ageing and malfunction identification** and tracking
    - **Alignment verification** and realignment
- Future Upgrades (HW or SW):
    - Functional verification during daytime before offering the change

In Figure 17.1 the CU is shown mounted on the MAORY main structure together the MICADO Calibration. The CU Folding Mirror (CUFM) and the Calibration Units Selector are also shown.

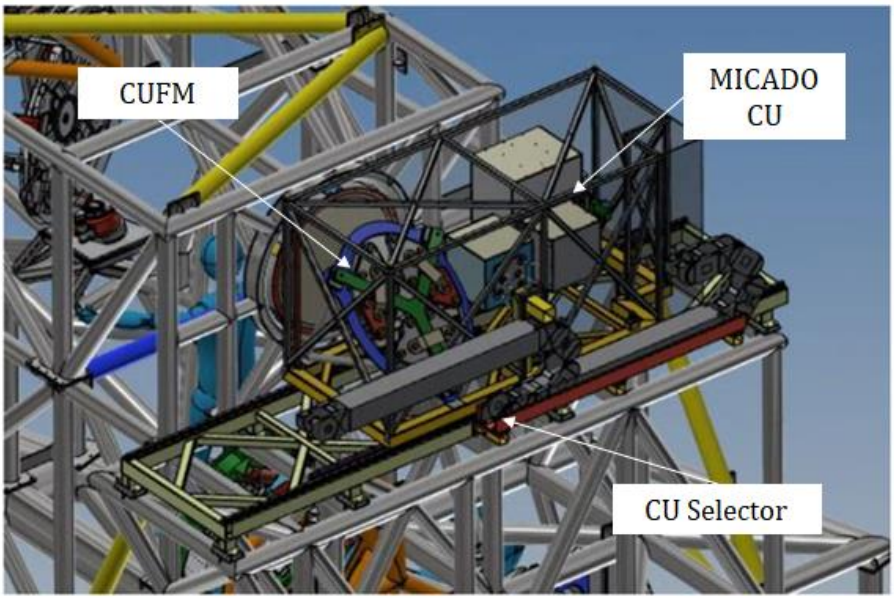

Figure 17.1: Calibration Units Selector and CU Folding Mirrors mounted on the MAORY main structure.

A detailed description of the Calibration Unit is available in RD11.

6.6 LGS WFS Module

The LGS WFS module is a device dedicated to the measurements of the wavefront aberrations due to atmospheric turbulence and other effects. In Figure 18 we show an overall view of the full LGS WFS assembly.

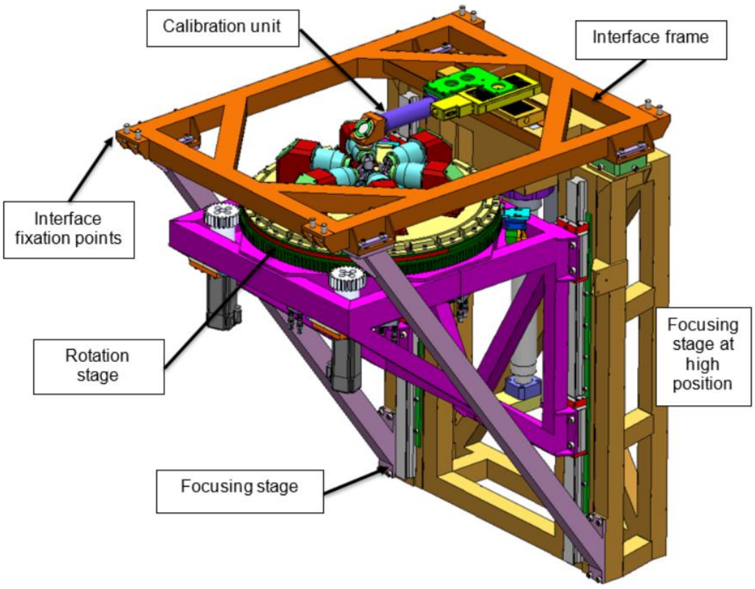

Figure 18 : *Overall view of the full LGS WFS assembly.*

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 is collected by a WFS camera.

6.6.1 LGS WFS cameras

As specified in AD1 the wavefront sensor cameras are ESO deliverables. From the beginning of Phase B, the LISA WFS camera equipped with an LVSM (Large adaptive optics Visible Sensor

Module) detector has been considered by ESO as the baseline camera for the LGS wavefront sensors. However, in 2018 the promising detector IMX425 with 1600x1100 pixels was made available by Sony Semiconductor Corporation for industrial applications. In June 2020 we prepared and delivered to ESO a document (RD22) with a comparison between the two detectors. On the basis of our analysis, our preferred choice for the MAORY LGS WFS is the SONY detector because it solves the issue related to the limited number of pixels that forces to compromise between spot sampling and spot truncation due to a too small FoV. This issue is widely considered to be the most critical aspect of the LGS WFS for extremely large telescopes and it represents a fundamental risk for the adaptive optics system. Any mitigation of this aspect is therefore to be pursued actively.

Moreover, the SONY IMX425 also presents another very attractive feature that is the global shutter, again removing the need for complicated analysis and reducing the risk associated with spatially-varying transfer functions.

The conclusion of our analysis was that we consider the SONY detector as the MAORY LGS WFS detector baseline and it has been used to finalize the PDR design and documents of the LGS WFS module.

A request for deviation for the use of the SONY detector has been submitted to ESO (RD30)

6.7 LOR WFS Module

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, depending, of course, 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”. The innermost limit for the NGS pickoff is set by the requirement to not vignette the MICADO science FoV and hence it will be limited by software to adapt to the observing mode selected by the instrument (or calibration mode). Depending on the observing mode and considering an avoidance zone of 15” on the radius, the innermost limits are 41.5” (large field mode), 25” (small field mode) and 22.5” (spectroscopic mode).

The patrolled field of each LOR WFS unit spans about half of the entire technical field, so it partially overlaps with the field of the other 2 LOR WFS units, to increase the number of NGS constellations accessible and the sky-coverage. 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 (Ref or R) WFS act as a “truth” sensor to de-trend LGS wavefront estimates and measure pseudo-static aberrations of the telescope and of the PFRO. They are required to measure 55 modes in the visible band (approx. 0.6 - 1.0 μm) with < 5s integration time on the same NGS used for Low-Order correction. Both the Low Order and Reference WFS are able to work in the magnitude range **9-21 mag H (Vega)** and R-H=2 mag (**R<23 mag**). We have verified that this is not limiting the sky coverage (see RD3). Brighter stars could saturate the LO detector (RD14).

Figure 3 gives an overview of the position of the LOR WFS module on the top of the MICADO instrument while Figure 19 gives an overview of the opt-mechanical implementation inside the Green Doughnut (GD), the structure hosting the SCAO and LOR WFS systems. Finally, in Figure 20 a detail of the LOR WFS support bench is reported.

A detailed description of the LOR WFS module is available in RD14.

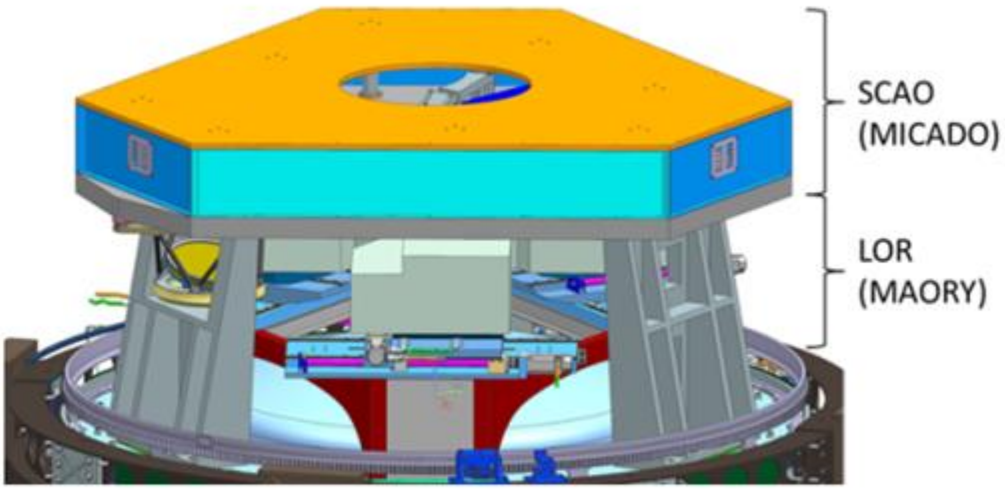

Figure 19. *Sketch of the opto-mechanical implementation of the Green Doughnut, hosting the SCAO system on top and the LOR WFS Module on the bottom.*

Figure 20. *Detail of the LOR WFS support bench.*

6.7.1 LOR WFS Cameras

The Reference sensor is a Shack-Hartmann sensor with 10x10 sub-apertures, using the ALICE camera provided by ESO with a field of view of about 4 arcsec. MAORY requires for a customized version of this camera since the lenslet array must be embedded within the camera housing.. The Low Order is a Shack-Hartmann sensor with 2x2 sub-apertures, using a FREDA detector also provided by ESO with a field of view of about 1 arcsec.

6.8 Instrument Control Software

The MAORY instrument control software will offer two AO modes to support the client instruments, the Multi Conjugated and the Single Conjugated one. Moreover, it foresees a simplified architecture to cover the SCAO mode for the MICADO stand-alone case. The SCAO mode is developed in collaboration with the MICADO consortium.

The MAORY ICSS (see RD15, RD23) will follow the architectural concepts defined by ESO and will be based on the ESO instrument control software framework for ELT.

The block diagram in Figure 21 shows the control perspective in the general MCAO case and can be used to illustrate the global architecture of the MAORY ICSS. Only one client instrument, MICADO, is shown on top (purple box). The MAORY ICSS environment (yellow box) is composed of two packages, one dedicated to SCAO mode (cyan) and the other to MCAO (green). This modularity choice allows separating as much as possible the control of the SCAO and MCAO functionalities so they can be developed almost independently.

Each package controls one or more Function Control System (FCS). They represent the ensemble of processes aimed to control the hardware functions and to monitor the output of the sensors. Each FCS includes a high-level Software, which runs in the instrument workstation, and a low-level Software, which runs in the Local Control System (LCS), which include the PLCs.

Both SCAO and MCAO packages include at least one Detector Control System (DCS), dedicated to control and monitor the AO WFS cameras.

All active interactions between MICADO and the Central Control Software (yellow, bottom), which controls the ELT's adaptive mirrors and laser launch telescopes, are controlled by MAORY, which also dispatch the commands to the RTC to open and close the involved AO loops and to trigger the required computations on the WFS frames. The MAORY ICSS indeed interfaces with two Real Time Computers (red), one dedicated to SCAO one dedicated to MCAO.

An important architectural goal was to separate the control of the MICADO and MAORY systems as far as possible also from the user point of view, that is at template level. MICADO's Observation Blocks including acquisition, observation and calibration templates, will run in MICADO, which will interface to MAORY through a dedicated library provided by MAORY. In addition, MAORY calibrations that require MICADO functionalities will run in the MICADO environment. In this case MAORY will access MICADO through a similar library, provided by MICADO. In both cases the same library will cover both SCAO and MCAO cases, keeping therefore the interfaces to SCAO and MCAO as similar as possible. Finally, MAORY technical templates which do not need to access MICADO will run in the MAORY environment, but these templates are normally not offered to astronomers.

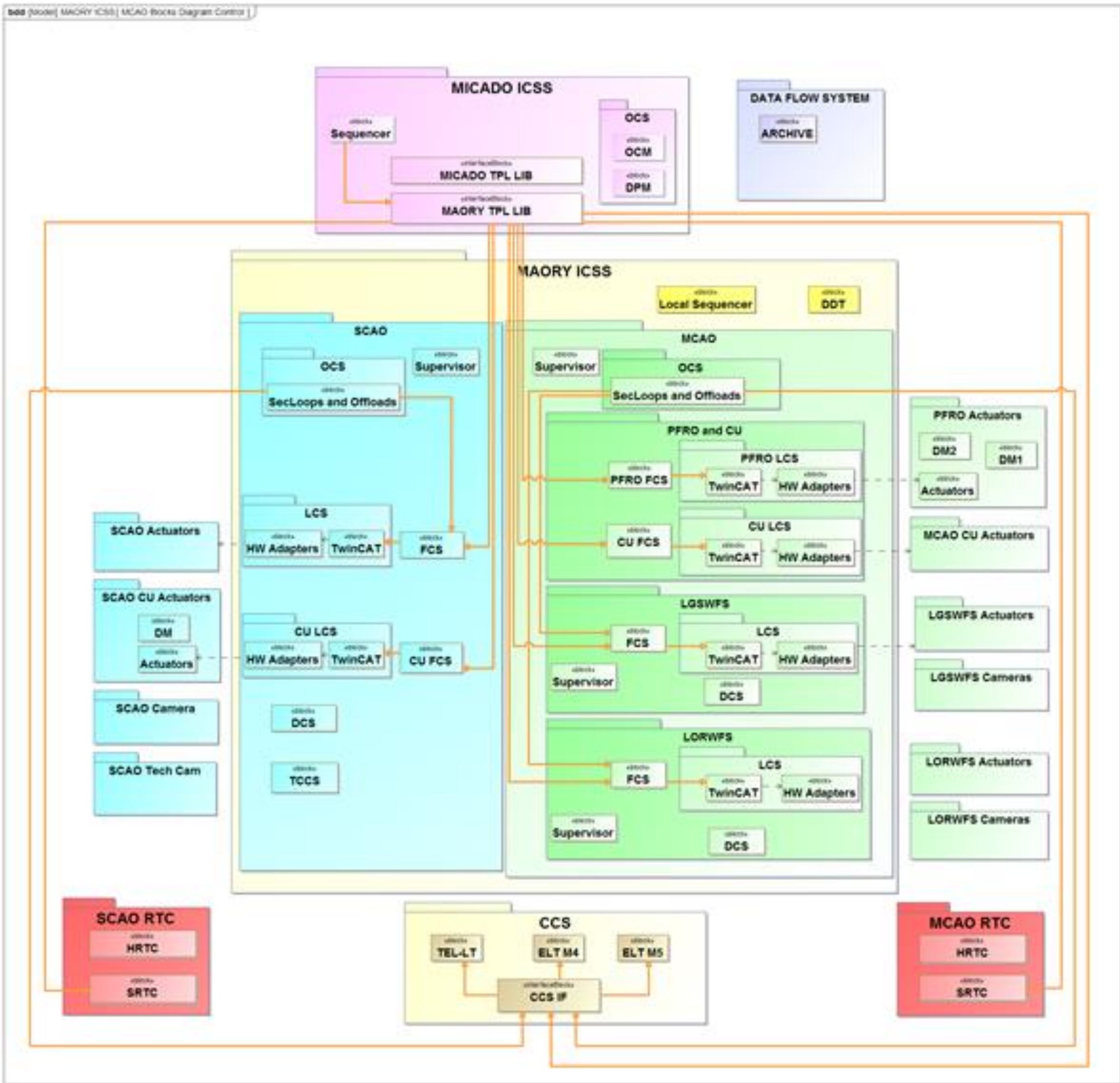

Figure 21 : *MAORY Instrument Control Software architecture for the general MCAO case.*

6.9 Instrument Control Hardware

The design of the MAORY control electronics is shared between the WPs.

In particular, the Instrument Control Hardware WP is responsible for the control electronics of the Post Focal Relay Optics motorized functions, the movement of the Calibration Unit selector, the harness to the MAORY Main Support Structure and for power distribution to the entire MAORY system. It also represents the interface point with ESO, and is responsible for compliance to ESO requirements and for harmonizing the overall MAORY control electronics design. Finally, the ICH WP provides general guidelines to the other subsystems, and parts of the design that are shared between them. To this purpose a document was released (E-MAO-PH0-INA-TNO-001 “Instrument Control Hardware Guidelines for MAORY Subsystems”).

The other subsystems, listed below, are in charge of their respective electronics:

- Calibration Unit
- Deformable Mirrors
- Thermal Control
- NGS WFS module
- LGS WFS module

The division into subsystems allows the independent design and testing of MAORY functions, helping parallel development and simplifying the interfaces, which are based on the essential services.

The architecture of the control system is based on the paradigm of decentralized functions and the extensive use of field buses, drawing on industrial standards. Each sub-system has dedicated PLC, CPU and terminals, in order to facilitate the independent integration and verification for every sub-system. The use of industrial standards and COTS elements allows for rapid development, lower cost for spare parts and a widespread understanding of architecture among specialized firms. In Figure 22 we show an overview of the instrument control hardware and the various subsystems cabinets.

A detailed description of the MAORY Instrument Control Hardware is available in RD16.

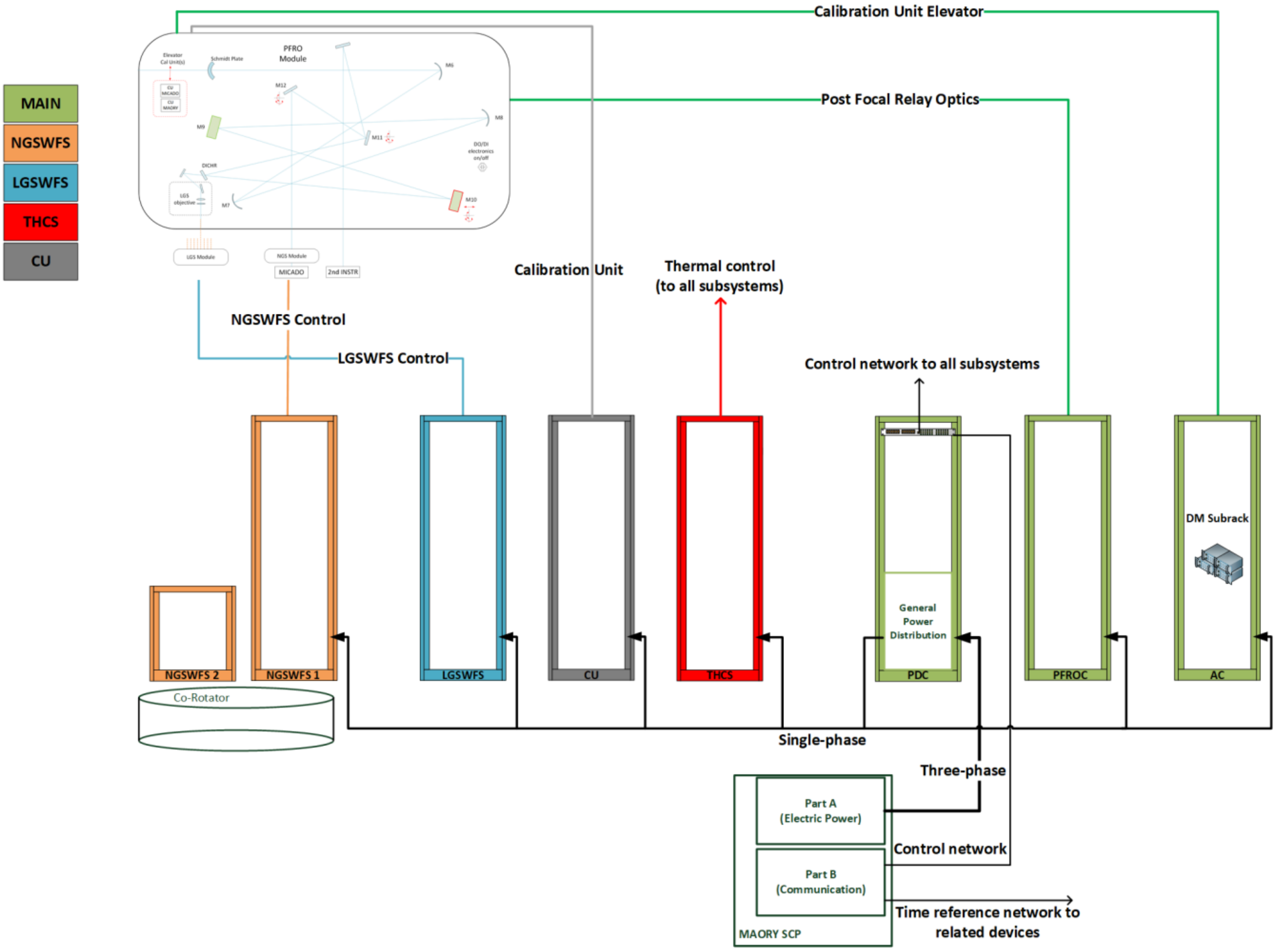

Figure 22 : *Overview of the control electronics for MAORY.*

6.10 Real Time Computer

Figure 23 illustrates the main control loops and task for the MCAO configuration. Pixel data from the WFS cameras will be processed to produce slopes. Pixels will be reordered as needed (depending on the readout scheme for each camera), calibrated and centroids will be computed for each sub-aperture.

The baseline control strategy is based on the Pseudo Open-Loop Control (POLC) algorithm. Three POLC loops are foreseen: **High Order** (HO) and **Low Order** (LO), that compute the split tomography and the real time correction of the wavefront distortion, and the **Reference** (REF) loop that measures and corrects slower wavefront distortion of low to medium order that are poorly sensed and/or corrected by the other loops.

The data produced by the cameras of the LGSWFS and of the NGS WFS are collected by the MAORY RTC, which drives the deformable mirrors, i.e. the telescope's M4/M5 adaptive/tip-tilt mirrors and two post-DMs inside MAORY itself. All the wavefront sensors in MAORY are placed downstream from the deformable mirrors ensuring optical feedback.

According to the ESO constraints on all RTCs for ELT instruments, the AO RTC shall be composed of a Hard Real-Time Core (HRTC), in charge of controlling the main AO loops, a Soft Real-Time Cluster (SRTC), in charge of the high-level supervision and optimization, and communication infrastructure, interconnecting the HRTC, the SRTC, the sensors and the actuators, and integrating the AO RTC into the ELT Communication Infrastructure. Moreover, there is no specific constraint on the architecture of the HRTC, in order to allow maximum flexibility in the choice of the solution which can cope with the highly-demanding hard real-time loops.

In the MAORY project, we decided to externally procure the HRTC and, in the course of Phase B, we commissioned two studies to verify the feasibility of realizing the HRTC for MAORY using two different technologies.

The first study has been performed by Microgate s.r.l., from Bolzano (Italy), who studied the possibility of realizing the MAORY HRTC using the COSMIC platform (RD24, RD25). The HRTC design proposed as a result of this study is composed of an off-the-shelf product, the NVIDIA DGX-1 workstation equipped with 8 Tesla VT100 GPUs connected with an ultra-high-speed NVLINK bus which allows direct and dedicated interconnection within the GPU cluster.

A second study has been conducted by the research team at the Herzberg Astronomy and Astrophysics Institute of the National Research Council Canada who developed the HEART framework (RD26) as part of the RTC design for NFIRAOS (RD27), the TMT first light AO system. The HRTC design, based on HEART, uses commercial-off the shelf (COTS) CPUs running standard Linux distributions (currently CentOS) with the real-time patch and Ethernet communication. HRTC functionalities are partitioned across different server roles.

Both the studies demonstrated the feasibility of the MAORY RTC. The final decision concerning the adopted architecture will be taken after the PDR, when a provider will be identified following a competitive selection procedure.

Finally, regarding the SRTC, the design strictly follows the guideline provided by ESO and the preliminary design foresees a total of five servers (possibly equipped with accelerators (GPUs) and a network switch to provide the necessary connection between the SRTC and high-level control software as well as between the SRTC and HRTC. One of the servers is devoted to data recording and is therefore configured with high storage capacity. The exact hardware configuration is still to be defined, but in order to support the fast collection of all telemetry data at loop rate, this machine might be equipped with a large RAM disk. This node will also run the tasks devoted to PSF Reconstruction data collection and publishing of disturbance data on a reliable communication channel.

A detailed description of the MAORY RTC is available in RD17.

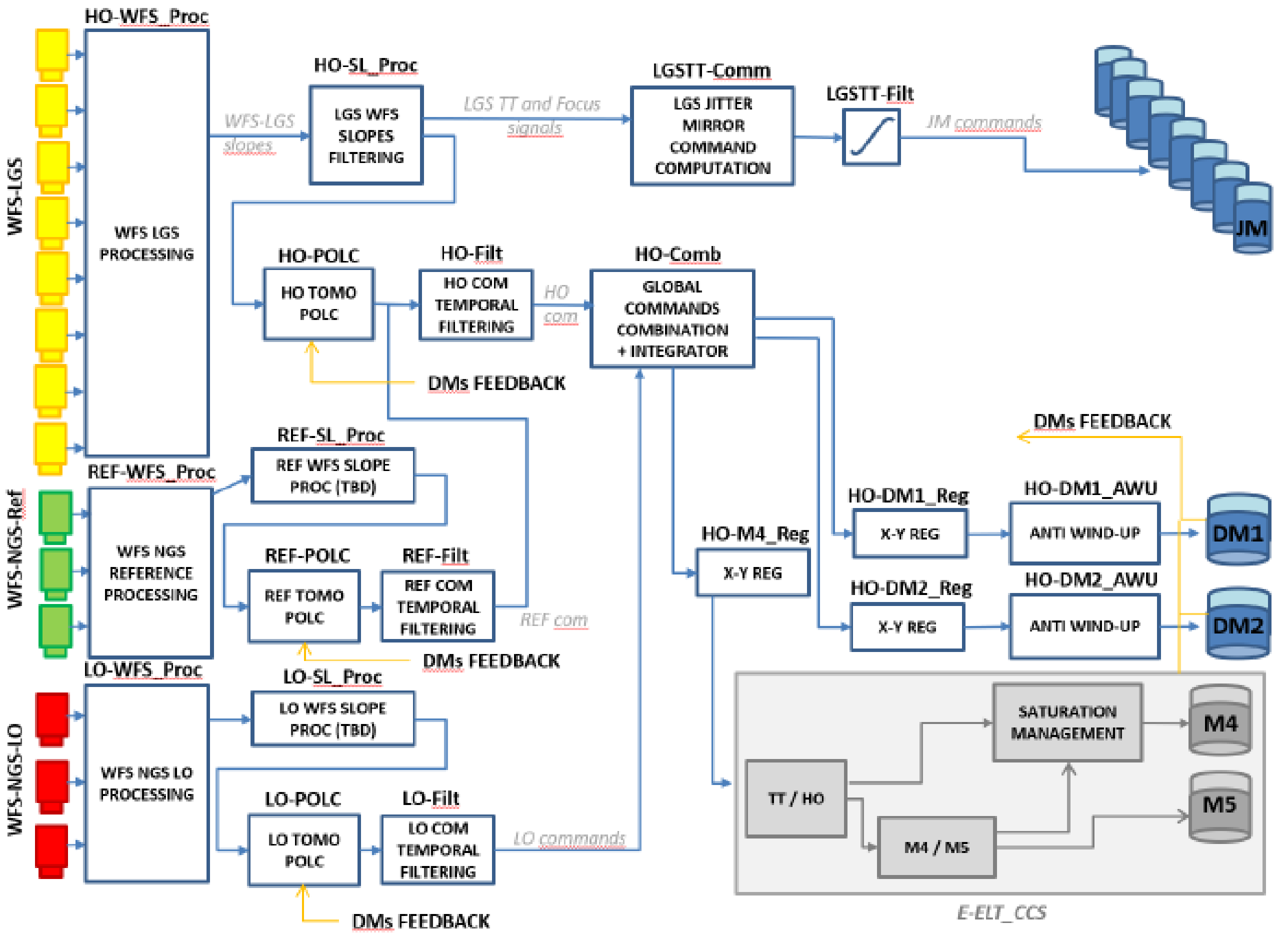

Figure 23 : MAORY control loops and tasks for the MCAO configurations.

7 AIV Concepts

The main steps from the MAORY design phase to a MAORY operating on the Nasmyth platform are :

- MAORY Assembly Integration and Verification in Europe (MAORY Phase-D)
- Preliminary Acceptance in Europe (PAE)
- MAORY de-integration for shipping preparation
- MAORY shipping to Chile
- MAORY unpacking and preparation in Chile
- MAORY Assembly Integration and Verification in the Telescope Assembly Integration Hall
- MAORY transfer from Telescope Assembly Integration Hall to Nasmyth Platform
- MAORY Installation on the Nasmyth Platform
- MAORY - MICADO installed together and first MAORY-MICADO test
- Commissioning
- MAORY Provisional Acceptance in Chile (PAC)

The integration facility in Europe is located in Bologna in the North of Italy at the premises of INAF-OAS.

The MAORY and MICADO instruments will not be together in Europe. However, the test in Europe should ensure that no major problems will be encountered when they are mounted together at the observatory. In particular, the MAORY MCAO capability must be tested during the PAE. Considering that in its final location the LOR WFS module will be mounted on the MICADO instrument, special equipment will be needed during the AIV phase in Bologna in order to compensate for the absence of the MICADO instrument as well as of the telescope. In particular, a dummy de-rotator and test camera are needed to simulate MICADO while the Test unit is devoted to simulating the telescope.

The baseline assembly, alignment and test strategy in Bologna consists of the following main steps:

- Assembly of the main structure and dummy de-rotator in the Bologna Integration Hall
- Bench Main Structure population with all the optics and references for the laser track alignment
- Placement of the optical elements with the laser tracker to residual positioning errors of about +/- 200 micron and +/- 30 arcsec
- Engagement of the Maory calibration unit to provide on-axis and off-axis point-like sources for the fine alignment process
- Imaging of on-axis and off-axis PSFs with the test and alignment camera
- Fine-tuning of the WFE acting on M10/DM2 tip/tilt and focus using defocused PSFs accordingly to the Donut technique (RD33)
- Fine-tuning of the exit focal plane position on the test camera by tip-tilting the last two flat mirrors, M11 and M12 (at PAE)

- Fine-tuning of exit pupil and the exit focal plane position by tip-tilting the last two flat mirrors, M11 and M12 when MICADO and MAORY come together at the Nasmyth platform (at PAC)
- System functional and performance tests

A similar sequence is foreseen in the Telescope Integration Hall in Chile where, however, the performance tests are not foreseen but will be performed when MAORY will be installed on the Nasmyth platform.

A detailed description of the integration and test plan is available in RD21.

8 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. During the Phase-B a huge amount of work has been devoted to develop the sky coverage estimation library (RD18) and to improve the end-to-end AO system simulator PASSATA (RD19).

The simulation software has been used not only to estimate the MAORY performance, but also to help the system engineering in the selection of many parameters such as the technical field of view, the LGS asterism (angular size and number of stars), the number of NGS WFS and “truth” sensor, the number of the sub-apertures in the LGS and NGS wavefront sensors and the post focal DM pitch.

Here we report the results obtained with all the specification profiles (Median, Q1, Q2,Q3 and Q4, see AD3 and RD34 for their definition) and 1 or 2 post focal DMs (PFDMs). Moreover, a huge amount of work has been done also with different atmospheric profiles (Stereo-Scidar profiles, RD35). The results with these different atmospheric profiles are available in RD20.

8.1 Strehl Ratio and Sky Coverage

The expected performance of the MAORY instruments is summarised in Figure 24. In the top panel, we report the Strehl Ratio (SR) value as a function of the radial distance (arcsec) from the field centre for different atmospheric conditions considering only one post focal DM (as it is in 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 value 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 performances that we quote at 50% Sky Coverage are hence to be meant as "the median performance obtained for a large set of random pointings at the SGP". These estimations are therefore conservative with respect to the MAORY requirement that refers to having 30% SR (goal 50% with 2 DM) over 50% of the whole observable sky, not at the SGP where the star density is lower than the rest of the sky.

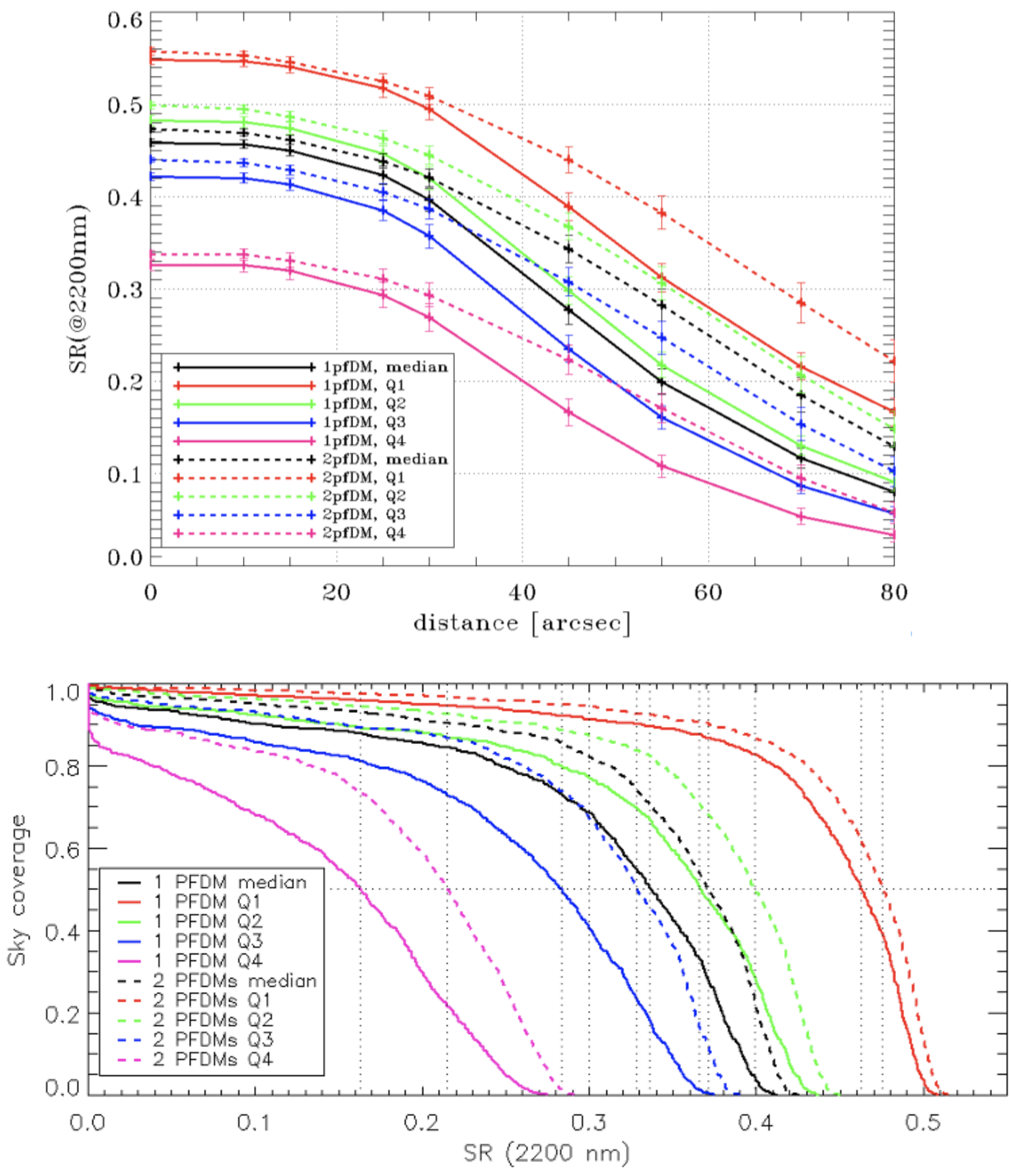

Figure 24: *Summary of the MAORY performance. Top panel: Average K band SR as function of the radial distance for a good NGS asterisms (NGSs are bright and close to the science field, i.e. 0% sky coverage), different atmospheric conditions and 1 or 2 post-focal DMs. Average values and error bars are computed over 5 different atmospheric and noise realizations. Bottom panel : Sky coverage as a function of the K band SR value for different atmospheric conditions and 1 or 2 post-focal DM over the large MICADO FoV (60" diameter).*

8.2 Uniformity

In Figure 25 we plot the non-uniformity in the scientific FoV of 60” for all the specification profiles and 1 or 2 PFDMs. The non uniformity is defined as the maximum SR difference to be expected in the FoV divided by the average SR. This is an indication on how stable the SR is with respect to different conditions.

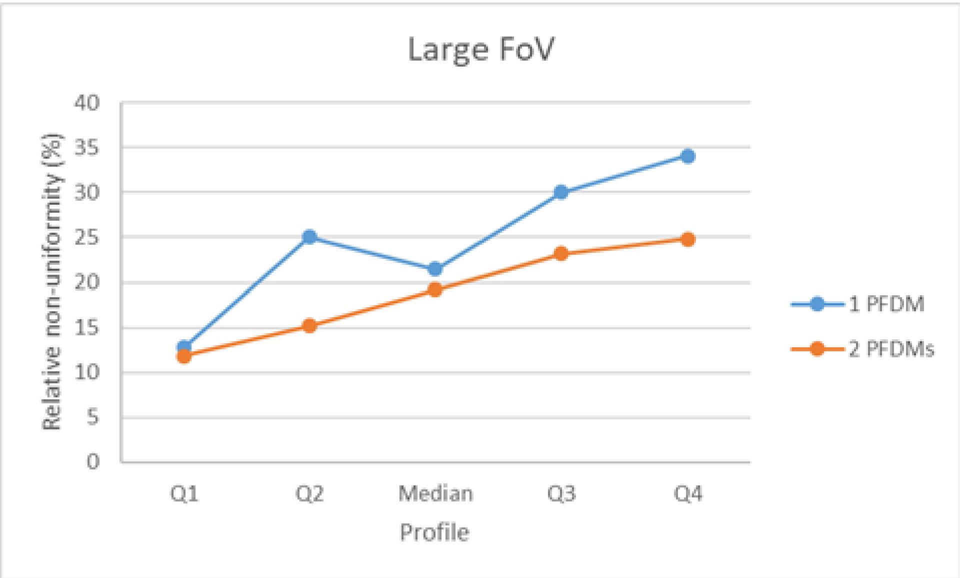

Figure 25 : *Non uniformity within the scientific field of view (60”) for 1 or 2 PFDM for different atmospheric profiles. The relative uniformity is defined as (SR_max-SR_min)/SR_average. SR is the Strehl Ratio in the K band.*

As shown in figure 25, we have a significantly better SR uniformity in the scientific FoV using 2 PFDMs.

8.3 Performance at different zenith angles.

Though our requirements are defined at a zenith angle of 30°, the system will of course perform at other – often larger – zenith angles. Figure 26 shows the sky coverage using the median profile for z = 30° (black lines), z = 10° (green lines), z = 45° (red lines) and for 1 and 2 PFDMs (solid and dashed lined). Using the second PFDM we have a significantly better SR at higher zenith angles.

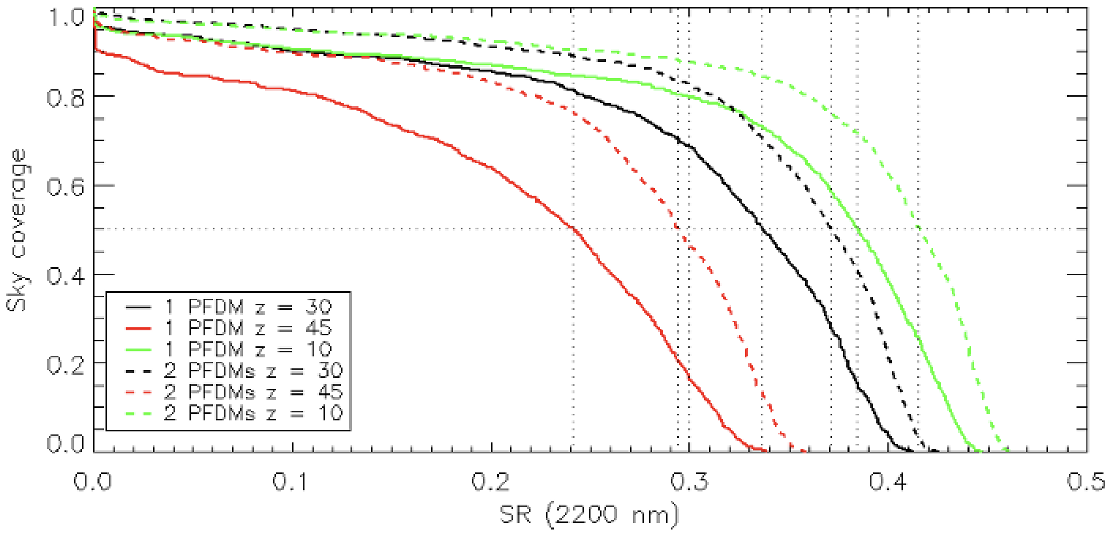

Figure 26 : *Sky coverage for the median profile with 1 or 2 PFDMs, at a zenith angle of 10°, 30° or 45° over a FoV of 60".*

As shown in all the figures in this section, a system with a single DM is capable of delivering a SR above the requirement (SR 30% over 50% of the whole observable sky) while the presence of the second DM is fundamental to push the system toward maximal performance, to ensure an higher robustness to varying atmospheric conditions (CN2 profiles, seeing) and better performance to varying observational conditions (zenith angles). A detailed description of the AO expected performance is available in RD20.

8.4 Astrometric accuracy

The shared interpretation of this requirement is that the MAORY and MICADO are aiming at relative astrometric observations where MICADO must be capable of measuring, through multiple epoch observations, the change in distance between two targets separated by 1" with an accuracy of 50 microarcsec.

We have performed a series of analysis aimed at quantifying the astrometric accuracy obtainable by MAORY. In some of them, we are facing the difficulty related to the lack of design details that are needed as input to the study e.g. in the cases concerning the optical design, where details about polishing surface errors or long term evolution of NCPAs and calibrations are still missing.

In the AO-related analysis we are facing the issue of simulating effects evolving on long time periods. Therefore a supplement of analysis is required in the future. So far, the astrometric requirement within its interpretation given at the beginning of this section is satisfied.

8.5 SimCADO simulations

To combine all the above effects we simulate a series of faint (25-32 magnitude) isolated point sources in the I and H bands using the SimCADO software. We used these simulations to estimate:

- the magnitude limits reachable with different configurations and conditions
- for a given magnitude limit the open shutter time that can be saved using 2 PFDMs rather than 1 PFDMs

In Figure 27 and Figure 28 we show the point source limiting (S/N=5) magnitude in the I and H band for the best atmospheric profile and an NGS configuration producing the best performance (SR=0.38 (0.41 for 2 PFDMs) in H band, Figure 27) and for median atmospheric profile and an NGS configuration producing non optimal performance (SR=0.13 (0.16 for 2 PFDMs) in H band, Figure 28). For comparison in Figure 27 we also show the magnitude limits obtained with two different exposure time calculators : ELT ETC available at ESO and AETC available at INAF Padova.

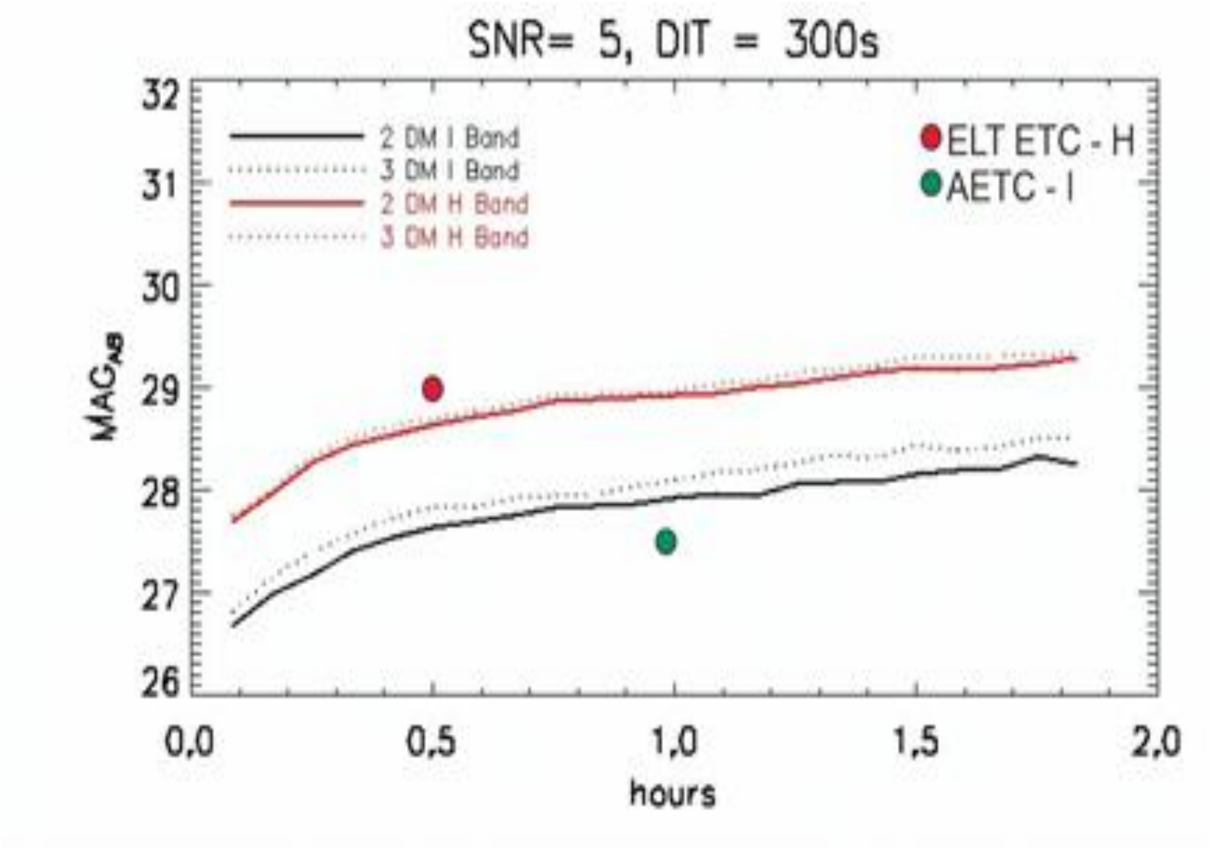

Figure 27: *Point source limiting (S/N=5) magnitude in the I (black lines) and H (red lines) bands for the median atmospheric profile and optimal guide star configuration. 30deg Zenith distance. SR=0.38 (0.41 for 2 PFDMs) in H. Solid lines show performance with 1 PFDMs (2 DMs in total considering also M4) while dashed lines show performance with 2 PFDMs (3 DMs in total considering also M4).*

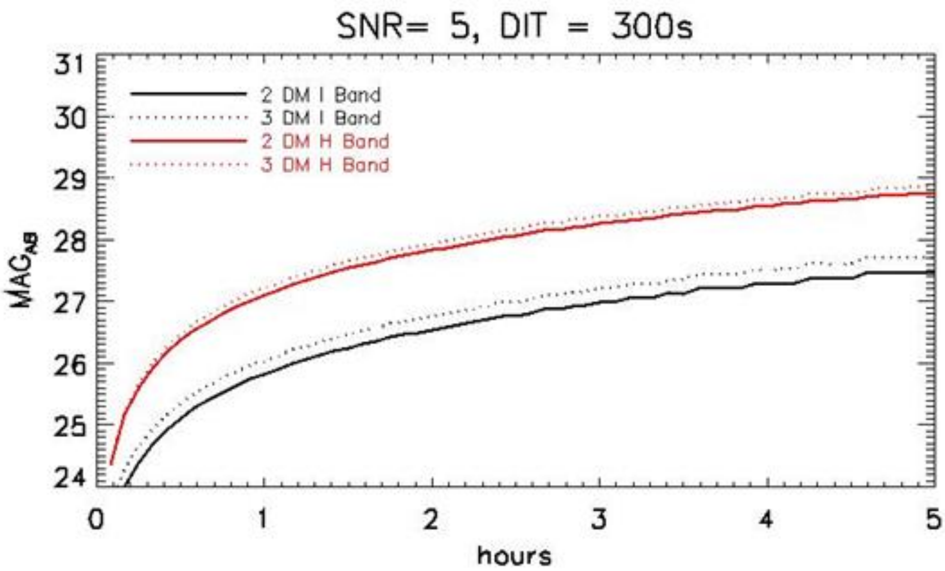

Figure 28 : *Point source limiting (S/N=5) magnitude in the I (black lines) and H (red lines) bands for median atmospheric profile and an NGS configuration producing non optimal performance (SR=0.13 (0.16 for 2 PFDMs) in H band).*

Considering Figure 27 (best atmospheric profile and performance) a point source of magnitude I=28.2 reaches SNR 5 in 1h20min with the 3 DM configuration while it needs 1h50min in the 2 DM configuration. Such time difference is larger for more moderate SR as confirmed in Figure 29 where we plot, for median atmospheric profile and non optimal performance (as in Figure 28), the fraction of open shutter time saved using the 3DM configuration rather than 2DM configuration.

With the second post focal DM, it is possible to save about 20% and 10% of the observing time respectively in the I and H band.

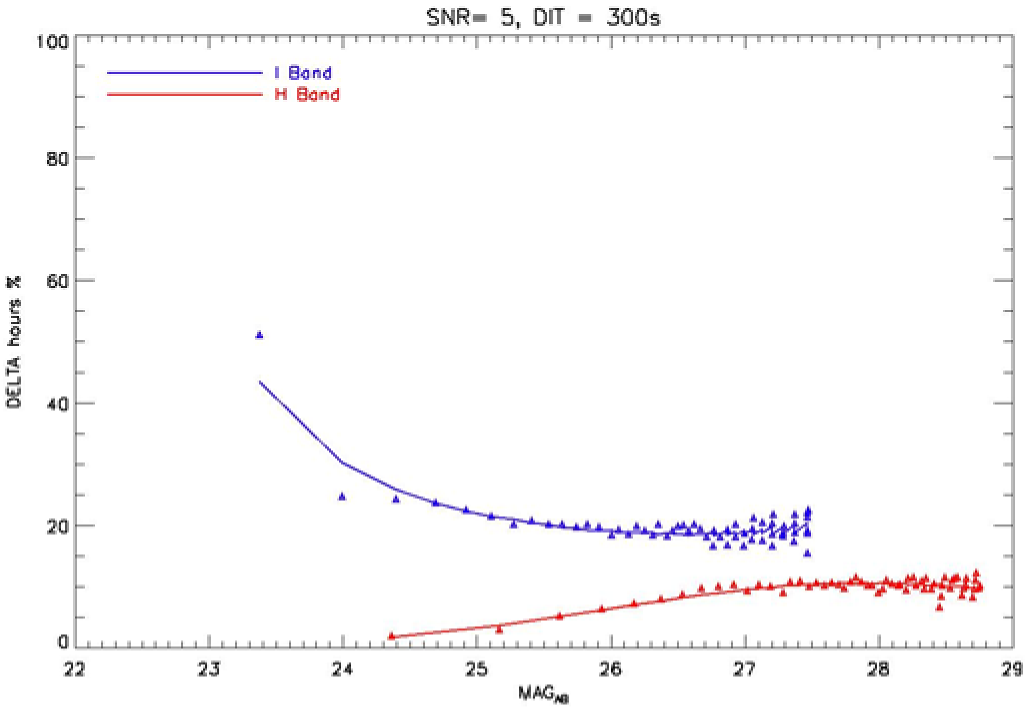

Figure 29 : *The two curves show the percentage of observing time that it is possible to save using 3DMs (2PFDMs) rather than 2DMs(1 PFDMs): about 20% and 10% of the open shutter time, respectively in the I and H band (blue and red symbols respectively). The solid lines interpolate the simulated measurements.*

A detailed description of the SimCADO simulations and the results obtained is available in RD36

8.6 Performances with different atmospheric profiles

The performance shown in the previous section has been obtained with all the specification profiles (Median, Q1, Q2,Q3 and Q4, see AD3 and RD34 for their definition). In order to test the stability of the system with different atmospheric condition and different turbulence profiles, we analyzed the variability of the performances with respect to the stereo-scidar profiles (RD37). The specification profiles median, Q1, Q2, Q3 and Q4 do not cover the range of variability of the vertical distribution observable in the stereo-scidar dataset. A set of 5 profiles (P10,P25,P50,P75,P90), derived from approximately 10,000 measurements profiles at Paranal, has been selected representing a probability of occurrence of a lower performance. For example 75% of the profiles have performance lower than the ones obtained for the P75 profile.

In Table 1 we report the SR values corresponding to the 50% sky coverage for J,H, and K bands using the 5 stereo-scidar profiles (P10,P25.P50.P75 and P90) and for comparison the technical specification median profiles (last column). For each band we list the SR values and the relative gain by using the 2 post focal (2PDM) configuration instead of the 1 post focal (1PDM) configuration (Ratio 2/1).

WFE 190nm SR [0%-100%]	**P10**	**P25**	**P50**	**P75**	**P90**	**Median**
SRK (2200 nm) @50% 1PDM	39.1	37.2	20.0	2.3	0.8	35.2
SRK (2200 nm) @50% 2PDM	44.4	39.5	27.5	16.5	4.7	37.9
Ratio 2/1	1.14	1.06	1.38	7.17	5.87	1.08
SRH (1650 nm) @50% 1PDM	18.8	17.3	5.7	0.1	0	15.7
SRH (1650 nm) @50% 2PDM	23.6	19.2	10.1	4.1	0.4	17.8
Ratio 2/1	1.26	1.11	1.77	41	N/A	1.13
SRJ (1250 nm) @50% 1PDM	5.5	4.7	0.7	0	0	3.9
SRJ (1250 nm) @50% 2PDM	8.1	5.6	1.8	0.3	0	4.9
Ratio 2/1	1.47	1.19	2.57	N/A	N/A	1.26

Table1 : SR value in J,H and K band using 5 stereo-scidar profiles (P10,P25.P50.P75 and P90) and the technical specification median profiles (last column).

From the value reported in Table 1 it is evident that the 2PDM configuration is more robust to the variation of the profiles, ensuring constant better performance to the worsening of the atmospheric conditions. The gain in SR values (energy concentration at he peak of the PSF) is higher for short wavelengths.

Finally in Figure 30 we report the K band performance with 1 or 2 post focal DM and with 15 stereo-scidar clustered profile obtained with the Octopus code at ESO (RD37). Once again it is evident that the 2PDM configuration is largely more robust than the 1PDM to variation of the profiles as visible in the spread of the blue (1PDM) and red (2PDM) curves in Figure 30.

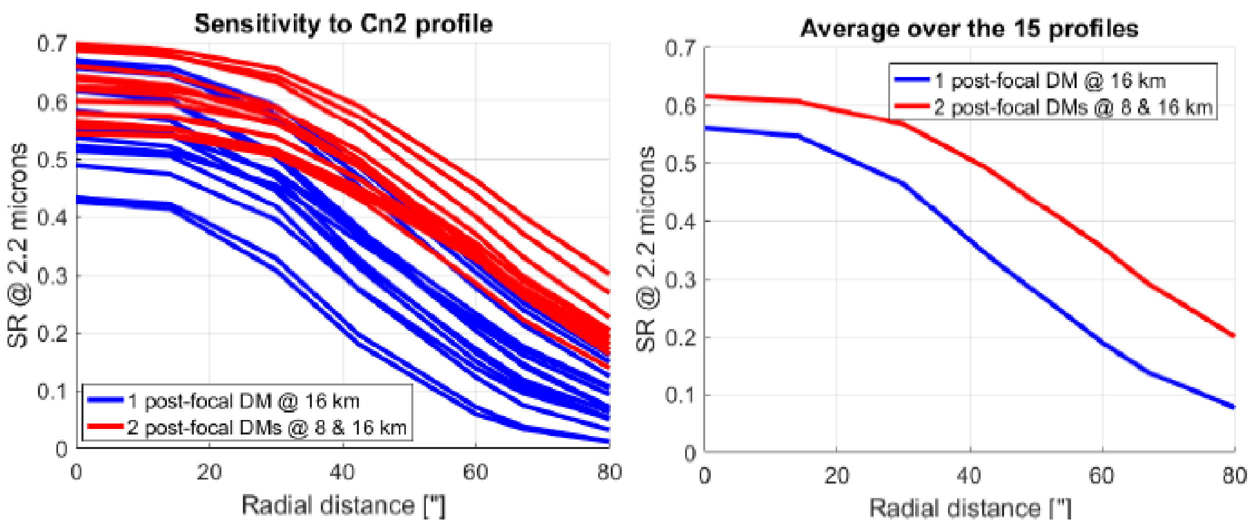

Figure 30: K band performance with 1 or 2 post focal DM and 15 clustered stereo-scidar

A more detailed description of the performances with different atmospheric profiles is available in RD36

9 CONCLUSION

As outlined in Section 5, the baseline design was completely changed in February 2020 after a trade off study in order to satisfy the ESO request for a gravity invariant port also for the second instrument. Although this request was not contractually binding for us, we have considered it reasonable and scientifically well motivated. Therefore, in order to deliver the best possible instrument, we decided to accept this request although this implied considerable work from the Consortium to deliver the PDR documentation in a reasonable time. Moreover, extra work is foreseen during Phase C and D due to a more complex manufacturing and characterization of the optical components and a more complicated assembly process.

The MAORY project is now approaching the PDR with a well consolidated design compliant with all the requirements. We will present only two requests for change. The first one was to increase the total mass limit from 25t to 30t while the second one to is to use a SONY detector for the LGS WFS camera in order to exploit the opportunity offered by the market to use a detector with a larger number of pixels (to reduce the truncation effect) and with a global shutter instead of a rolling shutter.

Finally, the MAORY design has been developed with two deformable mirrors. However, according to the technical specification, the MAORY baseline provides for the presence of only one DM while the second one is replaced by a rigid mirror. As shown in Section 8, a system with a single DM is capable of delivering an SR above the requirement while the presence of the second DM is fundamental to push the system toward maximal performance and higher robustness to varying atmospheric and observing conditions. Fixing the quality of the final image (in terms of mag limits, signal to noise ecc) the gain in performance with the second post focal DM can be converted in open time shutter during the night: in median atmospheric condition it is possible to save about 20% and 10% of the observing time respectively in the I and H band. Such time gain can even increase for more moderate SR.

We are perfectly aware of the economic difficulty related to the overall cost of the whole instrument and of the additional cost of the upgrade path for the second DM. However, since the final goal of the MAORY Consortium is to deliver the best possible instrument (as we have done for the second gravity invariant port) we are ready to collaborate with ESO to find a solution that allows delivering MAORY with two post focal DMs from its first light. The commissioning of the second DM directly at the Telescope, years after the MAORY first light, would be an extremely complex, risky and expensive operation with a very low chance of being realized.

***** End of document *****