Preliminary design of the MAORY Calibration Unit

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Abstract. MAORY (Multi-conjugate Adaptive Optics RelaY) is one of the first light instruments for the ESO Extremely Large Telescope (ELT). It will be firstly used by MICADO (Multi-AO Imaging Camera for Deep Observations), a near-infrared high-angular resolution imager, to compensate aberrations and provide high-Strehl images within a (53” × 53”) Field of View (FoV). The complexity of MAORY requires calibration functionalities for both the AIV (Assembly-Integration-Verification) and the operational phase. The function of the Calibration Unit (CU) is keeping the high efficiency of the adaptive correction provided by MAORY during the operational phase, through proper calibration sources, acting as both Natural Guide Stars (NGS) and Laser Guide Stars (LGS) sources. An overview of the system, the status of the current design and the main challenges to face in the future are presented in this work.

1. Introduction
MAORY (Multi-conjugate Adaptive Optics RelaY) is a post-focal adaptive optics module for the ESO Extremely Large Telescope (ELT), based on Multi-Conjugate Adaptive Optics. It is designed to enable high-angular resolution observations in the near infrared by correcting in real-time the wavefront distortions due to atmospheric turbulence over a large Field-of-View (FoV) [1].
It shall support MICADO (Multi-AO Imaging Camera for Deep Observations) [2] by offering two correction modes: Multi-Conjugate Adaptive Optics (MCAO) and Single-Conjugate Adaptive Optics (SCAO).
The optical relay, supported by a structure mounted on the telescope Nasmyth platform in a gravity invariant configuration, re-images the telescope focal plane for the science instruments and offers a provision for a second port for a future instrument, as well.
The Laser Guide Star Wavefront Sensor (LGS WFS) is composed of eight Shack-Hartmann (SH) sensors, each one sampling a LGS located at 45” far from the MICADO FoV centre.
The Natural Guide Star Wavefront Sensor (NGS WFS - LOR) covers a 160” FoV with three probes, each one consisting of a Low-Order (LO) channel, with a SH sensor working in H-band at AO speed, and a Reference channel (R), with a SH sensor working in R- and I- bands at slow speed.
The real-time computer collects the signals from all wavefront sensing channels and computes the commands for the post-focal DM and for the telescope adaptive mirrors, in order to perform the MCAO correction. The baseline wavefront reconstruction approach is Pseudo-Open Loop Control.
MAORY is required to deliver a Strehl Ratio (SR) of 0.3 (goal 0.5) at K-band over a 1’ FoV with 50% sky coverage.
The complexity of MAORY requires calibration functionalities for both the AIV (Assembly-Integration-Verification) and the Operational phase. For this purpose, two different sub-systems are foreseen: the Test Unit (TU) for the AIV phase and the Calibration Unit (CU) for the Operational phase.

The CU has primarily to provide proper calibration light sources to keep the high efficiency of the adaptive correction provided by MAORY, and is conceptually composed by a series of modules:
- a Sources Masks Unit (SMU), equipped with both NGS light sources and movable LGS light sources, mounted on two separate masks
- a Focusing Optical System (FOS), to properly focus the light sources
- a Light Sources Unit (LSU), which hosts the physical light sources
- a Source Selector Unit (SSU), to select the sources and set their brightness.

2. Overview of MAORY calibrations

Calibrations are fundamental to remove the instrumental signature from the scientific data [3]. Inside MAORY, calibrations can be divided into functionality checks and AO loop parameters calibrations.

Functionality checks consist in:
- WFSs characterization (linearity, dynamic range, flatness, etc.)
- pupil check (motion, illumination uniformity, sampling, etc.)
- optical system check (overall transmission, alignment, stability, etc.).

AO loop parameters calibrations consist in:
- non-nommon-path aberrations (NCPA) calibrations (static, quasi-static, dynamic)
- interaction matrixes (IM) construction (both for each active element and combined).

In addition, a set of periodical checks are needed, basically for predictive and preventive maintenance purposes, to be performed at a lower rate.

The Calibration Unit is a specific hardware necessary to do the calibrations specified in the MAORY Calibration Plan, that cannot be performed on-sky or whose execution on-sky would be too demanding in terms of night observation time.

The CU is fundamentally asked to provide:
- a grid of several NGS sources, diffraction-limited (DL) in H-band
- some LGS sources at 589 nm, distributed on specific asterisms, conjugated on different Laser Focal Planes (LFPs).

3. Calibration Unit current design

The CU design is intended as an iterative trade-off process, started from the analysis of the calibration use cases and of the defined requirements [4]. A first overall architecture has been chosen (trying to maximize the flexibility), conceptually divided into modules, to develop in parallel. In particular, the current solution forsakes the concept of the sources physically positioned on focal planes, no longer viable, in favor of a unique sources module plus an optical relay, including a folding mirror to inject the light into the MAORY optical path.

3.1. Architecture

A number of physical sources, fibre-terminated broadband light sources for NGS, and 589 nm Solid State laser sources for LGS, are part of the Light Source Unit (LSU), located into the Electronics Cabinet, placed directly onto the Nasmyth platform. The Source Selector Unit (SSU) is also located into the Electronics Cabinet: it receives the light from LSU, adjusts the flux and selects the proper output fibre, through linear stages. A set of fibres connects the SSU to the SMU, where customized fibre splitters provide a proper splitting, in order to have the
correct number of fibres to feed each source on the two masks with the required flux range. Such an architecture, shown in Fig.1, is simple and flexible, although some issues may arise, especially from the length of the fibers between Cabinet and SMU and from the fiber splitters: prototyping activities on these components will allow to properly evaluate the amount of losses.

Figure 1. CU Architecture. Light sources are generated into the LSU; the SSU selects output lines and sets fluxes; fibres carry the light up to the SMU, where all the sources on the masks are fed via fibre splitters; the light from the masks reaches the FOS, that properly focuses it.

3.2. Sources module
The CU shall provide:
- a grid of several NGS sources uniformly distributed within the NGS WFS technical FoV (160" diameter), bright enough to cover the range 12-22 mags, DL in H-band,
- three asterisms, each including 8 LGS extended sources at 589 nm wavelength, on LFPs conjugated with defined altitudes (150 km, 104 km, 90 km),
while meeting the mechanical constraints (e.g. fitting into the assigned volume and respecting the mass budget).

The solution is conceptually shown in Fig.2. Light sources are positioned on two separated masks (for NGS and LGS sources respectively), so that this configuration is less demanding in terms of axial size and all the sources can be imaged together without vignetting. However, the insertion of a dichroic Beam Combiner (BC) in the CU optical path is required, with the typical drawbacks of such an optical device (alignment issues, additional aberrations, etc.). The size of the masks depends on the FOS design and is constrained by the (large) amount of sources and their physical separation.
3.3. Optical module

An accurate optical system (FOS) is required to ensure that the light sources from CU mimic the light coming from the telescope, matching the requirements listed in the Calibration Plan. The main optical constraints this system shall respect, besides the requirements briefly described in Section 3.2, are listed below:

- optical beams shall match ELT f-numbers (from 17.75 at infinity to 20.98 at 80 km);
- light sources shall focus on focal planes matching ELT curvature radii;
- NGS light sources shall be DL on the TFP (35 um in H-band);
- LGS light sources shall be extended on the LFPs (3”);
- the optical system shall form an exit pupil located on the telescope entrance pupil.

Two possible solutions are being developed: a refractive one and a reflective one.

The first one, shown in Fig.3, is based on lenses: a first lens (LENS1) fixes the f-number and acts as Pupil Stop, and a second lens (LENS2), very close to the Telescope Focal Plane (TFP), fixes the pupil position and acts as Field Lens. This model matches most of the requirements...
(except the axial size), but is still to be strongly improved (by turning LENS1 from paraxial to real, adding Beam Combiner and Folding Mirror) and optimized, first of all to fix the chromatism over the wide spectral range expected (R-, H-, K- bands).

The second one, shown in Fig.4, is based on three off-axis mirrors and a corrective surface placed on the pupil. It presents a good quality on the NGS part, but needs to be optimized for the LGS part, at the current stage.

Both solutions offer pros and cons: the reflective one is a stand-alone solution, heavier but more compact, and limits chromatic issues, while the refractive one might share a part of the optical design (the large and expensive Field Lens) with the Test Unit, with a prospective technical and economic saving, but needs to be carefully optimized in order to limit the chromatism and to maximize the optical quality, which quickly degrades increasing the distance between the Field Lens and the Telescope Focal Plane. Moreover, being positioned very close to the TFP, the Field Lens of the refractive solution needs to be moved, to switch from CU-On to CU-Off position, putting severe opto-mechanical constraints (e.g. positioning precision).

3.4. Electronics Cabinet

The Electronics Cabinet, shown in Fig.5 left, hosts all the Power, Electronics and Control devices, plus the LSU and SSU. A CAD design of the Cabinet has been realized, to better understand the necessary volume, as well as racks types and disposition. This will definitely simplify the choice of the different devices and their arrangement.

4. Next steps

Both optical solutions will be brought to the Preliminary Design Review (PDR): the choice of the baseline design will be the result of a careful trade-off study. The mechanical design will rapidly proceed as soon as the baseline optical design is consolidated. The functional analysis of the whole CU subsystem has been performed, in order to have a better understand of the whole system, and to identify possible issues from the RAMS (Reliability-Availability-Maintainability-Safety) point of view. Other key activities, planned within both the Preliminary and Critical Design phase, are the design of the test apparatus for the future CU AIV phase, as well as prototyping and test activities for all the transmission chain (physical sources, fibre splitters, fibres).
Figure 5. On the left: CU Electronics Cabinet. On the right: a (custom) Selector of SSU.

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