Programme: **E-ELT**

Project: **ELT MCAO Construction – MAORY**

MAORY for dummies

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Owner :	Carmelo Arcidiacono		
Approved by PI:	Paolo Ciliegi		
Released by PM:			
	Name	Signature	Date

Authors

Name	Affiliation
Michele Bellazzini	INAF OABO
Emiliano Diolaiti	INAF OABO
Giuliana Fiorentino	INAF OABO
Laura Schreiber	INAF OABO
Paolo Ciliegi	INAF OABO
Carmelo Arcidiacono	INAF OAPD

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Contents

1. Introduction

1.1 Purpose

This document is for internal use of the MAORY Science Team (ST hereafter).

It is intended to provide a brief and handily summary of the characteristics of MAORY (and of the instruments fed by MAORY, when relevant) based on the official documentation available at the epoch of the document release. Some simplifications may be applied to give the clearest and simplest view for the final scientific user, leaving aside unnecessary technical complications.

Note: throughout this document the size of Fields of View (FoV) may be provided as diameters (D) or radii (R).

1.2 Definitions, Acronyms and Abbreviations

AO	Adaptive Optics
FoV	Field of View
FP	Focal Plane
LGS	Laser Guide Star
MAORY	Multi conjugate Adaptive Optics RelaY
MCAO	Multi Conjugate Adaptive Optics
MICADO	Multi-AO Imaging Camera for Deep Observations
NGS	Natural Guide Star
PSF	Point Spread Function
SCAO	Single Conjugate Adaptive Optics
ST	Science Team
TBC	To Be Confirmed
TBD	To Be Defined
WFS	WaveFront Sensor

2. Related Documents

2.1 Applicable Documents

The following applicable documents form a part of the present document to the extent specified herein.

AD1 Common Requirements for E-ELT Instruments
Number ESO-254547 Version 2

AD2 Relevant Atmospheric Parameters for E-ELT AO Analysis and Simulations
Number ESO-258292 Version 2

AD3 MAORY Technical Specifications
Number ESO-254311 Version 1

AD4 MICADO System Overview
Number ELT-TRE-MCD-56300-0064, version 1.0, 25.09.2018

AD5 ADC, Filter & Pupil wheel Design and Analysis
Number ELT-TRE-MCD-56305-0009, version, 1.0, 17.09.2018

2.2 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 Top Level Requirements for ELT-CAM
Number ESO-193104 Version 2

3. MAORY: a basic description

MAORY is a post-focal adaptive optics module. It supports the MICADO near-infrared camera by offering two adaptive optics modes: Multi-Conjugate Adaptive Optics (MCAO) and Single-Conjugate Adaptive Optics (SCAO).

In the MCAO mode, wavefront sensing is performed by a system based on up to six Laser Guide Stars (LGS) for high-order wavefront sensing and three Natural Guide Stars (NGS) for low-order wavefront sensing. The six LGS are produced by excitation of the atmospheric sodium layer (at an altitude of ~90 km) with six laser beacons (with $\lambda = 589.2$ nm) propagated from E-ELT.

Wavefront compensation is achieved by up to two deformable mirrors in MAORY, which work together with the telescope adaptive and tip-tilt mirrors M4 and M5 respectively. In the SCAO mode, wavefront distortions are measured by a single NGS wavefront sensor and compensated by the telescope M4 and M5 mirrors, while the deformable mirrors inside MAORY are kept at their reference shape.

MAORY also offers provision for a second port for a future instrument, as yet undefined.

MAORY is supposed to operate at ambient temperature. The operating temperature range is 0°C-15°C (AD1).

Note that MAORY in MCAO mode is required to provide an unvignetted corrected field of diameter D=75" (R=37.5") for MICADO and an unvignetted field of D=150" (R=75") for the second instrument. The NGS WFS sub-system for the second instrument is not a deliverable by the MAORY consortium: its design might therefore be optimised once the second instrument is defined.

4. Light path and focal plane - MCAO mode

Within the MAORY module, the light coming from E-ELT encounters a dichroic element that

- reflects the light with $\lambda > 600$ nm to the MAORY exit focal plane;
- transmits the light with $\lambda < 600$ nm, thus reaching the LGS wavefront sensors.

Figure 1 gives a schematic overview of the MAORY exit focal plane. Hence, in the present baseline, the AO correction will be performed over the whole D = 160" FoV (outer blue circle, Figure 1), although the performance is expected to decrease at the edge of the field.

The innermost red square illustrates the MICADO FoV. Note that only ~70% to ~90% of this field will be covered by the 9 detectors constituting the detector array of MICADO, the actual fraction depending on a trade-off between field coverage and read-out time. A circular gap of about 5"-10" (TBD) is required between the circle enclosing the MICADO FoV (red circle, Figure 1) and the inner edge of the NGS *patrol field* (inner blue circle), to avoid vignetting of the MICADO FoV.

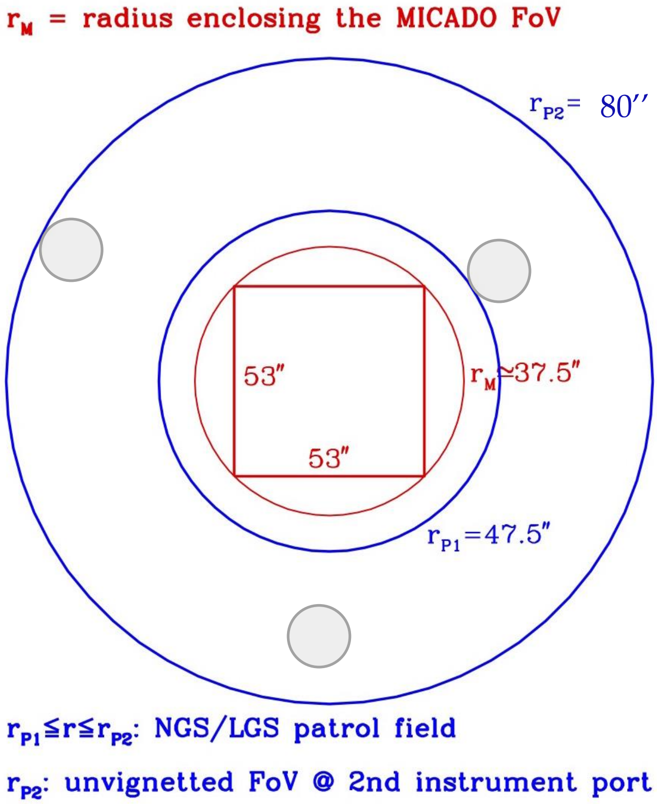

Figure 1. Schematic view of the MAORY exit focal plane. The red square is the MICADO FoV. The three grey circles are the pick-off mirrors for the three NGS, which can be deployed on the NGS patrol field.

The NGS patrol field may be approximately depicted as the annulus enclosed between the two blue circles in Figure 1. A more detailed scheme is presented in Figure 2.

In MCAO mode three probes (small movable pick-off mirrors) will pick the light from three suitable NGS lying within the NGS patrol field. The asterism providing the most uniform AO correction over the MICADO FoV would have the three NGS located at the vertices of a nearly-equilateral triangle.

Each probe patrols one of three 120° sectors S1-S2-S3 (in azimuth in the MAORY exit focal plane, FP-azimuth hereafter) in which the whole patrol field is divided (it should be noticed that the division of the patrol field into three sectors is an approximation only – the details depending on the mechanical design of the probe positioning system). Each probe can intrude into the sectors patrolled by the other two probes by a certain amount TBD; in Figure 2, 20° of intrusion (overlap) are assumed only for display purposes, although the guideline for the instrument design is to have as much overlapping as possible, within technical constraints. Hence, in principle, the three NGS can be located all in the same sector of the patrol field but they should have a mutual distance in FP-azimuth of a few tens of degrees. In principle MAORY can work with less than three NGS, with lower performances.

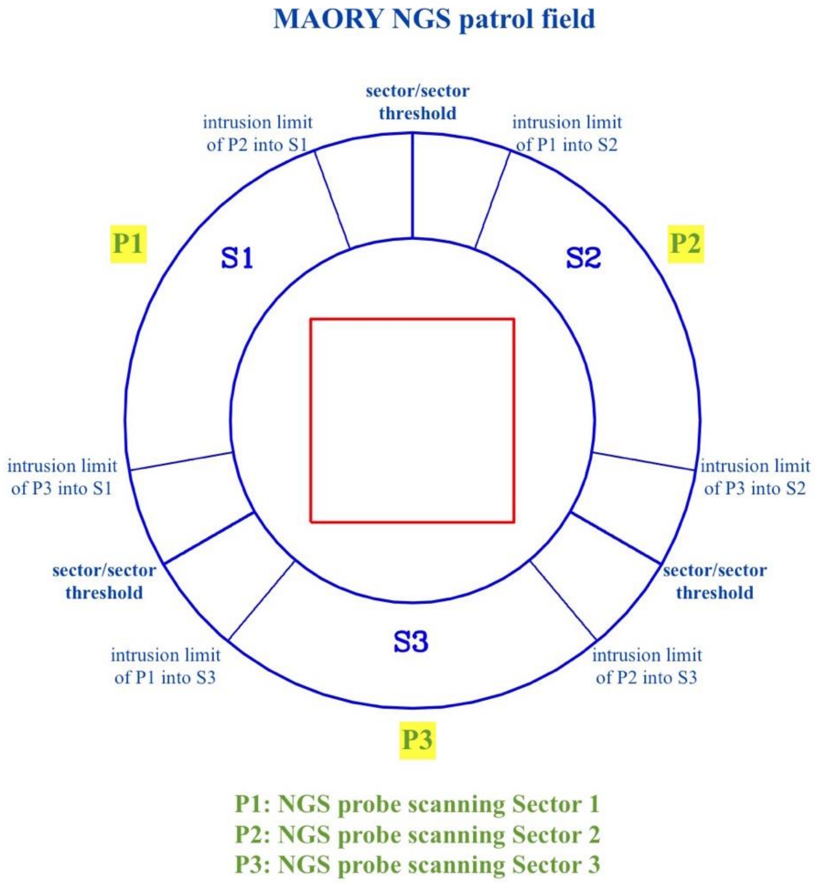

Figure 2. Schematic view of the MAORY NGS patrol field and its sectors. The overlap between sectors is indicative only. The red square is the MICADO FoV. The width of the Patrol Field annulus is not to scale.

The light picked up by the NGS probes will be split by a dichroic into two beams (one approximately spanning the R and I bands and the other spanning approximately the H band) that will be redirected to two independent set of wavefront sensors (three optical NGS WFS and three infrared NGS WFS, respectively), that will take care of different components of the low order aberrations.

The approximate faint magnitude limit for a star to be eligible as a NGS is H ~ 18.0-19.0 mag (TBC); the bright magnitude limit should be H~6.0.

5. SCAO mode

The SCAO mode (AD4) is expected to provide a better AO correction than MCAO in a small FoV (D ≈ 10'', R ≈ 5'') surrounding a bright star (V ≤ 12 to obtain an on-axis Strehl Ratio 60%-70% at λ = 2.2 μm) that will serve as a single NGS. It can correct using NGS as faint as V ~ 16 mag.

When SCAO is used, the dichroic moves from its park position into the optical path. The opti-cal/IR dichroic cut-off is set to 0.965 μm in order to allow sufficient light to reach the SCAO WFS without compromising too much the short wavelength science (>0.965 μm).

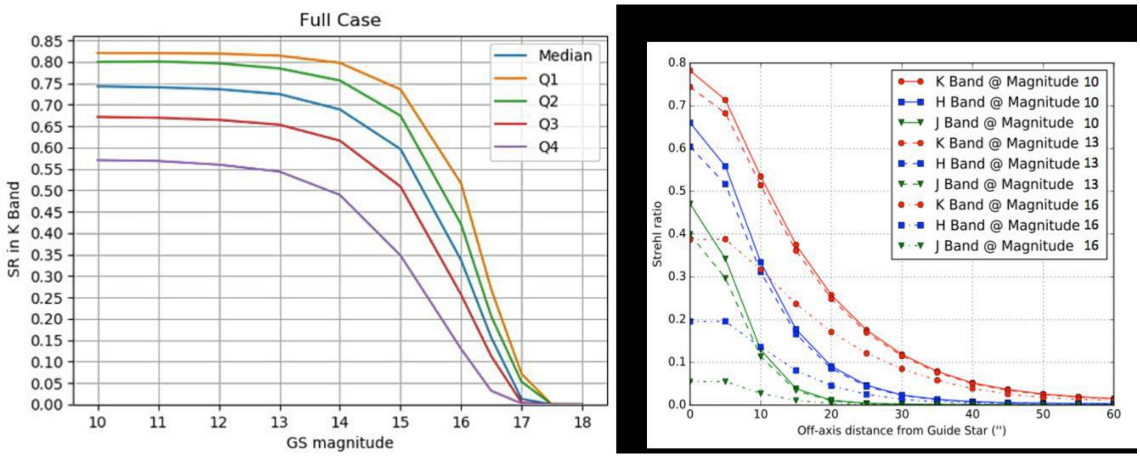

Figure 3 [FROM AD4, Fig.15] Left – simulations of the expected SCAO performance, including NCPA, windshake, island effect, and turbulence for four quartiles atmospheric conditions Q1-Q4 (defined by different seeing, wind speed, and CN2 profile, as provided by ESO; they have been converted to 30° zenith distance to enable comparison to the SCAO performance requirements). The panel shows Strehl ratio as a function of V-band magnitude in K-band; the equivalent Q2 performance for H and J band can be seen in the right panel. Right – off-axis performance for Q2 with various guide star magnitudes. The anisoplanatism sets the off-axis guide star distance at which SCAO performance matches that expected for MCAO (30% Strehl in K-band with a goal 50% in optimal conditions).

6. MICADO: basic concepts

From the AD4:

- MICADO in imaging will have two options for the plate/pixel scale:
  - 1.5 mas/px and FoV D ~ 19'',
  - 4 mas/px and full 50.5'' x 50.5'' FoV.
- It will be equipped with a large set of broad (I, z, Y, J, H, K) and narrow band filters. It will have a coronographic mode.
- It will allow long-slit spectroscopy with spectral resolution R ~ 4000 - 8000. A restriction on the usage arises because the atmospheric dispersion compensation is done only at the cold pupil rather than before the focal plane mask, and means that the slit should be oriented along the parallactic angle.
- The current best guess 5σ limiting magnitude are K=29.5, H=30.4, J=29.7 ABmag (K~27.6, H~29, J~28.8 Vegamag), in t_{exp}=5.0 h, for point sources, assuming a pixel angular size of 4 mas.

7. Reference numbers

It may be useful to have a quantitative idea of the characteristic size of the diffraction-limited PSF at the relevant wavelengths, for a telescope with an aperture D = 39 m. We use the equation

$$\theta_{diff}\ [\text{mas}] = 206.3\ \lambda\ [\mu\text{m}]\ /\ D\ [\text{m}]$$

where λ is the wavelength. Table 1 shows the diffraction limited PSF FWHM at some relevant wavelengths and the corresponding FHWM of the atmospheric seeing for median seeing conditions according to AD1.

λ [µm]	Diffraction limit FWHM θ_{diff} [mas]	(best seeing) Seeing FWHM [arcsec]	(median seeing) Seeing FWHM [arcsec]	(sub-optimal) Seeing FWHM [arcsec]
0.88	4.7	0.39	0.57	0.65
1.22	6.5	0.36	0.54	0.60
1.63	8.6	0.34	0.51	0.57
2.20	11.6	0.32	0.48	0.54

Table 1. Full-width at half maximum of the diffraction-limited PSF and of the seeing at zenith for some relevant wavelengths.

A useful figure of merit to characterise the performance of an adaptive optics system is the Strehl Ratio, which is defined as the ratio of the central intensity of the actual PSF to the central intensity of an ideal diffraction-limited PSF.

The adaptive optics PSF may be approximately depicted as being made of two main components:

- Diffraction-limited core
- Seeing halo

The angular width of the two components follows Table 1. The relative flux in the two components is (approximately) determined by the Strehl Ratio (S): the diffraction limited core (~inside the first black ring or a bit larger: R=1.1 λ /D in I, R= 2.3 λ /D in Ks) contains a fraction S of the energy, while the seeing halo contains a fraction (1-S) of the energy. This approximation holds only when $FWHM_{DL} << FWHM_{seeing}$, also depending on the considered wavelength. The condition is always fulfilled in the cases shown in Table 1 with the Strehl ratios listed in Table 2.

Table 2 shows the expected Strehl Ratio for the MCAO mode of MAORY taken from the Technical Specifications AD3. The values in the table have to be considered as approximate values to be confirmed.

By February 2019, expected performance almost meet the Goal Specification (provided three Natural Guide Star brighter than H-18 are provided, just ~10% less than the listed value).

λ [μm]	Best seeing conditions 30° from zenith D = 20" FoV		Median conditions close to zenith D = 1' FoV		Sub-optimal conditions 30° from zenith D = 2' FoV	
	Reqs.	Goal	Reqs.	Goal	Reqs.	Goal
0.88	0.01	0.04	-	0.01	-	-
1.22	0.10	0.19	0.02	0.10	-	0.02
1.63	0.28	0.39	0.11	0.28	0.03	0.11
2.20	0.50	0.60	0.30	0.50	0.15	0.30

Table 2. Expected Strehl Ratio for some representative wavelengths in MCAO mode. All values are TBC.

More detailed table will be provided with MCAO PSF second release and at the confirmation of the baseline expected by June 2019.

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