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THE MULTI-CONJUGATE ADAPTIVE OPTICS MODULE FOR THE E-ELT

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Abstract. The Multi conjugate Adaptive Optics RelaY (MAORY) for the European Extremely Large Telescope is designed to compensate the effects of the atmospheric turbulence over a 2 arcmin field of view in the wavelength range 0.8-2.4 micron. The wavefront correction is performed by three deformable mirrors driven by a wavefront sensing system based on laser and natural guide stars. Accurate relative photometry and astrometry and infrared spectroscopy are the key science applications of the adaptive optics module with its client instruments.

Keywords: Extremely Large Telescopes, E-ELT, multi-conjugate adaptive optics, laser guide stars, sky coverage

1 Introduction

MAORY (acronym for Multi-conjugate Adaptive Optics RelaY) is a post-focal adaptive optics module for the European Extremely Large Telescope (E-ELT) (Gilmozzi and Spyromilio 2008). A Phase-A study of this module was carried out by a consortium formed by Istituto Nazionale di Astrofisica (INAF) and Office National d'Etudes et de Recherches Aerospatiales (ONERA) in the framework of the E-ELT instrumentation studies (Ramsay et al. 2010) sponsored by the European Organisation for Astronomical Research in the Southern Hemisphere.

The E-ELT high angular resolution camera MICADO (Davies et al. 2010) is a candidate client instrument of MAORY. It requires an image correction of high quality and uniformity across a 53×53 arcsec^2 field of view in the wavelength range 0.8-2.4 μm. Accurate relative photometry and astrometry are key science drivers of MICADO which requires reliable and stable adaptive optics correction with calibrations limited to low order distortion compensation. Infrared spectroscopy is also a potential application of MAORY: a possible client instrument is SIMPLE, a single field high resolution spectrograph (Origlia et al. 2010). During the Phase-A study other instrumental concepts were considered, exploiting the energy concentration of the point spread function provided by MAORY: a wide field imaging camera with reduced angular resolution with respect to MICADO and a multi-object infrared spectrograph. Having in mind these concepts, a target science field of view of 120 arcsec diameter was considered for the module design and performance optimization. High sky coverage is a request common to all science instruments.

MAORY is based on Multi-Conjugate Adaptive Optics (MCAO), a concept proposed by Beckers (1989) and proven on sky by MAD, the MCAO demonstrator for the Very Large Telescope (Marchetti et al. 2008). The atmospheric turbulence is corrected by three deformable mirrors conjugated at different ranges: in this way the

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module design provides a performance of high quality and uniformity over the science field. The deformable mirrors are driven in closed loop by a wavefront sensing system based on Laser Guide Stars (LGS) and Natural Guide Stars (NGS). These general design choices are similar to those adopted in other MCAO systems as GeMS for the Gemini telescope (Ellerbroek et al. 2003) and NFIRAOS for the Thirty Meter Telescope (Herriot et al. 2010).

2 Design overview

The foreseen location of MAORY is a bent focus on the E-ELT Nasmyth platform (Figure 1). From the optical design point of view the MCAO module is a unit magnification finite conjugate relay based on off-axis aspheric mirrors. The splitting of the science and LGS beams in the optical relay is accomplished by means of a dichroic, that transmits the LGS light (wavelength 0.589 μm) and reflects the science channel light (wavelength longer than 0.6 μm). The LGS beam transmitted by the dichroic is focused by a refractive objective. Assuming high performance optical coatings, based on multi-layer protected silver, the thermal background of MAORY is expected to have an acceptable impact on the currently foreseen science instruments: for this reason as a baseline MAORY is not cooled. This choice might have to be re-assessed in the future, depending on refined or new science instrument requirements. The post-focal relay feeds two output focal stations: a gravity invariant port underneath the optical bench, providing mechanical derotation for a light instrument as MICADO, and a lateral port on a side of the bench to feed an instrument standing on the Nasmyth platform, detached from the module.

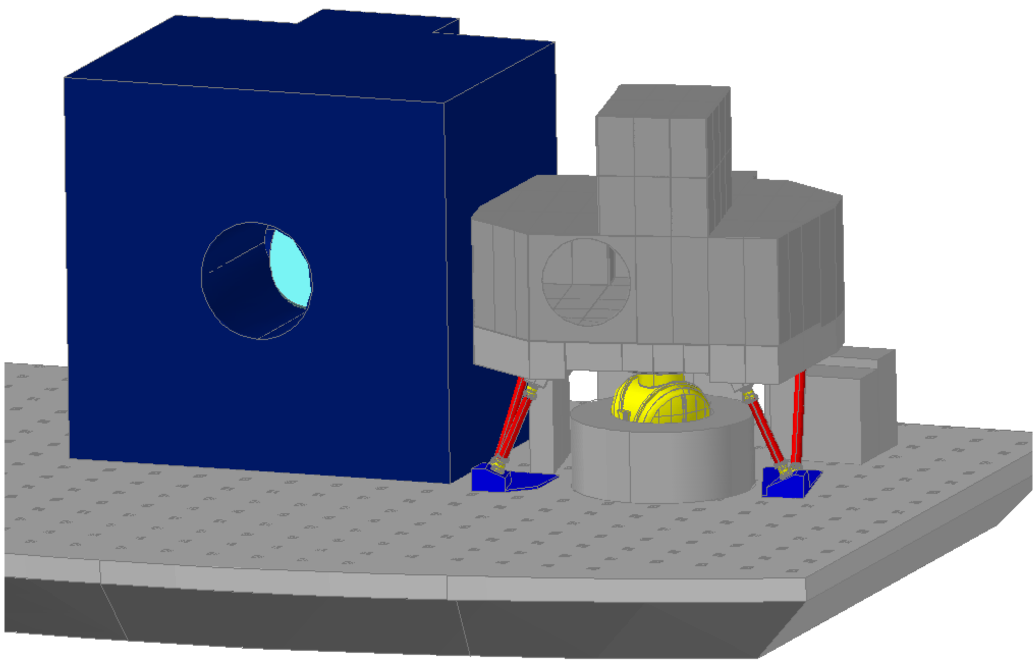

Fig. 1. Layout of MAORY on the E-ELT Nasmyth platform. The telescope pre-focal station is on the left part of the picture; MAORY is on the right. MICADO is shown underneath the optical bench of MAORY.

MAORY features three levels of wavefront correction: the telescope adaptive mirror M4, optically conjugated to few hundred meters above the telescope pupil and complemented by the telescope field stabilization mirror M5, and two post-focal deformable mirrors, conjugated to 4 km and 12.7 km from the telescope entrance pupil and located in the optical relay of MAORY. High-order wavefront sensing is performed by means of six sodium LGSs, arranged on a circle of 120 arcsec angular diameter. The LGSs are assumed to be projected from the telescope edge: this choice translates into a slightly higher slope measurement error than central projection, due to the larger perspective spot elongation, however it allows to get rid of the so-called fratricide effect among different guide stars, related to Rayleigh scattering of the laser light in the atmosphere. Six Shack-Hartmann wavefront sensors of order 84×84 subapertures are used to sense the LGS wavefronts by means of advanced spot position measurement algorithms in order to mitigate the impact of the spot elongation effect. The LGS wavefront sensor measurements are complemented by three NGSs, searched over a technical field of up to 160 arcsec diameter. The light of wavelength 1.5-1.8 μm is used for fast tip-tilt and focus measurement, providing the necessary information to solve the LGS tip-tilt indetermination problem and to retrieve the LGS focus which is affected by the sodium altitude instability. The high order correction achieved at these wavelengths by means of the LGS wavefront sensor ensures a spot shrinking which allows to exploit faint NGSs, translating into a high sky coverage. The light of wavelength 0.6-0.9 μm of the NGSs feeds a so-called Reference wavefront sensor of order $\sim$10$\times$10 subapertures, operated at temporal frequencies in the range 0.1-1 Hz, used to monitor the LGS non common path aberrations related to the sodium layer profile variability. A high order engineering mode of the Reference wavefront sensor is foreseen as well, allowing a NGS-based MCAO correction to be performed. The baseline strategy for the MCAO correction loop is pseudo open loop control (Gilles 2005), representing a good compromise in terms of performance and computational complexity between an optimal approach as linear quadratic gaussian control and a plain least squares approach.

3 Performance

The estimated performance of the MCAO module is shown in Figure 2 as a function of the angular distance from the field center at four wavelengths (K_s: 2.16 μm, H: 1.65 μm, J: 1.215 μm, I: 0.9 μm) for two atmospheric turbulence conditions (median seeing: 0.8 arcsec; good seeing: 0.6 arcsec).

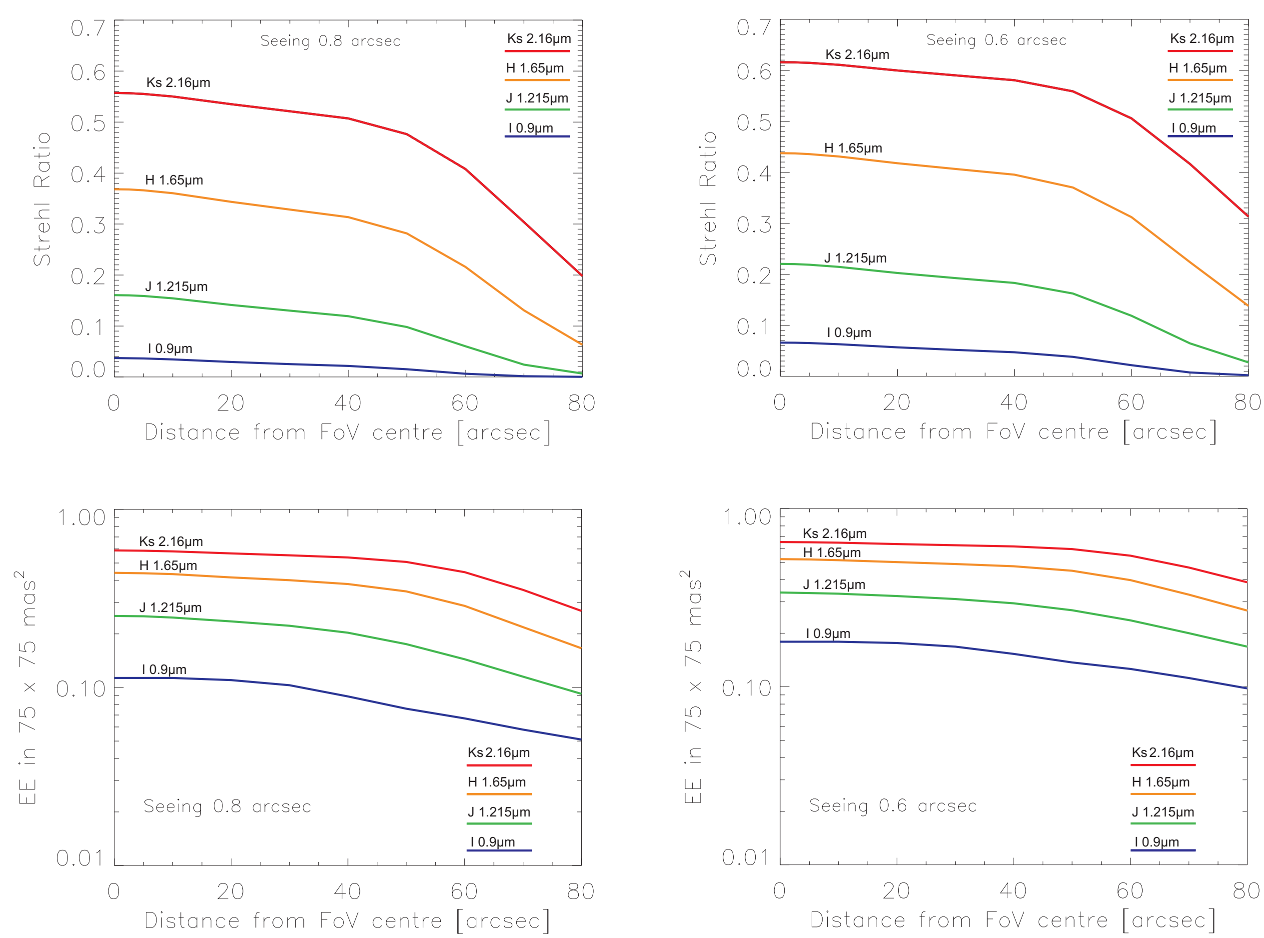

Fig. 2. MCAO module correction performance. Above: Strehl Ratio. Below: point spread function Ensquared Energy in 75$\times$75 mas^2. Left: seeing FWHM 0.8 arcsec. Right: seeing FWHM 0.6 arcsec.

The performance is remarkably uniform out to a radial distance of approximately 60 arcsec corresponding to the optimization field of view. For median seeing conditions the point spread function Ensquared Energy in a 75×75 mas^2 square slit, an interesting performance metric for a spectrograph, is higher than 30% in H band on average over the 120 arcsec field.

On the basis of a study on simulated images, accounting for point spread function shape, field variation and seeing dependency, it was shown that the relative photometric accuracy (0.02-0.03 mag RMS) and the relative astrometric accuracy (0.05-0.1 milli-arcsec) required by MICADO are both achievable. A more detailed analysis of the attainable accuracy, including all atmospheric effects, shall be pursued further in the future. To assist the data analysis a study was started to develop a point spread function model including the field variation.

The sky coverage at the North Galactic Pole for median seeing is shown in Table 1. It was estimated on the basis of Monte Carlo simulations of random asterisms with star densities derived from the TRILEGAL code v1.2 (Girardi et al. 2005). Anisoplanatic effects, measurement noise and temporal error were considered; windshake, a major contributor to image jitter, was included in the calculation of the temporal error, assuming a Kalman filter taking into account the windshake statistical properties. Stars as faint as magnitude H=21 were used: currently available infrared star catalogues do not reach this magnitude limit, but it was assumed that such catalogues will be available by the time the E-ELT will be operating or that it will be possible to make a pre-imaging of the target field. The sky coverage in the table is expressed in terms of the percentage of sky at the North Galactic Pole where a given minimum performance averaged over the MICADO field is achieved. The first line of the table corresponds to the nominal performance shown in Figure 2 for median seeing. The sky coverage shown here relies on a solid basis: the relatively good correction performance achieved in closed loop over the whole NGS search field.

Strehl Ratio				Sky coverage
K_s	H	J	I	
0.53	0.34	0.14	0.03	39%
0.51	0.32	0.13	0.03	50%
0.41	0.22	0.06	0.01	80%

Table 1. Sky coverage at the North Galactic Pole.

More detailed information about MAORY may be found in Diolaiti et al. (2010), Foppiani et al. (2010) and on the project web page `www.bo.astro.it/maory`.

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