

# MAORY: A Multi-conjugate Adaptive Optics Relay for the E-ELT

Emiliano Diolaiti<sup>1</sup>

<sup>1</sup> INAF–Osservatorio Astronomico di Bologna, Italy

Team members:

Andrea Baruffolo<sup>1</sup>, Michele Bellazzini<sup>2</sup>, Valdemaro Biliotti<sup>3</sup>, Giovanni Bregoli<sup>2</sup>, Chris Butler<sup>4</sup>, Paolo Cilieggi<sup>2</sup>, Jean-Marc Conan<sup>5</sup>, Giuseppe Cosentino<sup>6</sup>, Sandro D’Odorico<sup>7</sup>, Bernard Delabre<sup>7</sup>, Italo Foppiani<sup>2</sup>, Thierry Fusco<sup>5</sup>, Norbert Hubin<sup>7</sup>, Matteo Lombini<sup>2,6</sup>, Enrico Marchetti<sup>7</sup>, Serge Meimon<sup>5</sup>, Cyril Petit<sup>5</sup>, Clélia Robert<sup>5</sup>, Pierfrancesco Rossetti<sup>8</sup>, Laura Schreiber<sup>6</sup>, Raffaele Tomelleri<sup>8</sup>

<sup>1</sup> INAF–OAPd, <sup>2</sup> INAF–OABo, <sup>3</sup> INAF–OAA, <sup>4</sup> INAF–IASFBo, <sup>5</sup> ONERA, <sup>6</sup> Univ. Bologna, <sup>7</sup> ESO, <sup>8</sup> Tomelleri s.r.l.

MAORY provides atmospheric turbulence compensation for the E-ELT over a 2-arc-minute field of view in the near-infrared. Correction performance and sky coverage are achieved by three deformable mirrors, driven by a wavefront sensing system based on laser and natural guide stars.

## Science drivers

MAORY is an MCAO module designed for the E-ELT devoted to the compensation of the effects of the atmospheric turbulence in the wavelength range 0.8–2.4  $\mu\text{m}$  over a field of view of up to 2 arcminutes diameter. Among the candidate science instruments fed by MAORY, the high angular resolution camera MICADO requires a correction of high quality and uniformity over a medium-sized field of approximately 1 arcminute. High accuracy photometry and astrometry are key science drivers of MICADO: the achievement of these goals relies on a stable adaptive optics correction and on suitable calibration methods. MICADO also requires a gravity invariant output port. MAORY is also requested to provide a second output port designed to feed another instrument located on the side of the module on the Nasmyth platform. Candidate science instruments that might be served by MAORY are either a single field near-infrared spectrograph, such as SIMPLE, for which the on-axis point spread function energy concentration delivered by the adaptive optics module is a key science requirement, or a multi-object spectrograph, requiring a good level of PSF energy concentration over the full field corrected by MAORY. Other instrument concepts, such as a wide-field imaging camera with reduced angular resolution, might be considered. Sky coverage, defined as the

fraction of sky where adaptive optics provides a useful correction, is a key requirement, common to all science instruments. The sky coverage of MAORY has also to be high at the Galactic pole, where the star density is low.

## Instrument design concept

The expected location of MAORY is the E-ELT Nasmyth platform, on one of the bent foci (see Figure 1). From the optical design point of view, it is a finite conjugate relay formed by two pairs of aspheric off-axis mirrors (see Figure 2). Three flat mirrors fold the relay to fit the reserved area on the Nasmyth platform; two of these flat mirrors are deformable and compensate for the atmospheric turbulence. The optical relay produces an image of the telescope focal plane with unit magnification. A dichroic reflects the science channel light (wavelengths longer than 0.6  $\mu\text{m}$ ) and transmits the laser guide star light (0.589  $\mu\text{m}$ ), that is focused by a refractive objective. The module feeds two focal stations: the gravity invariant port underneath the optical bench, providing mechanical derotation for a light instrument such as MICADO, and the lateral port on one side of the bench to feed an instrument standing on the Nasmyth platform, detached from the module. Using optical coatings similar to those foreseen for the telescope, the thermal background of MAORY is expected to have little impact on MICADO even at ambient temperatures. The post-focal relay has an expected optical throughput larger than 82 % at all wavelengths longer than 0.8  $\mu\text{m}$  and larger than 91 % at all wavelengths longer than 2.0  $\mu\text{m}$ .

MAORY is based on the MCAO concept, first introduced by Beckers (1989). Three levels of wavefront correction are implemented: the telescope adaptive mirror M4, optically conjugated to a few hundred metres above the telescope pupil; and two post-focal deformable mirrors, conjugated at 4 km and 12.7 km from the telescope pupil, in order to correct the high altitude turbulence effectively (see Figure 2). The correction of the tip-tilt, due to the atmosphere and the telescope windshake, is mainly performed by the telescope mirror M5.

The measurement of the high-order wavefront distortions is performed by means of six sodium laser guide stars, arranged on a circle of 2 arcminutes diameter. This angular separation was found to be a good compromise between errors related to the LGS cone effect, pushing towards larger launching angles, and isoplanatic effects. The LGS are assumed to be projected from the telescope edge: this choice translates into a slightly higher measurement error than central projection, due to the larger perspective spot elongation, however it can eliminate the so-called fratricide effect among different guide stars, related to the Rayleigh and Mie scattering in the atmosphere. The guide stars feed six Shack–Hartmann wavefront sensors (WFS). The LGS constellation is kept fixed with respect to the telescope pupil, so that it rotates with the elevation axis as seen from the Nasmyth platform. This choice minimises the requirements on the derotation, either optomechanical or software, of the LGS WFS probes and of the LGS footprints on the post-focal deformable mirrors.

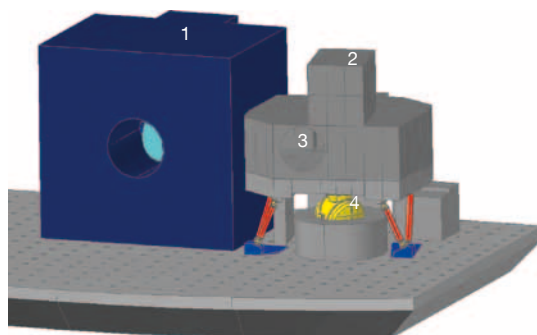


Figure 1. MAORY on the E-ELT Nasmyth platform; MICADO is on the gravity invariant port underneath the optical bench.

- 1 Pre-focal station
- 2 MAORY
- 3 Lateral port
- 4 MICADO

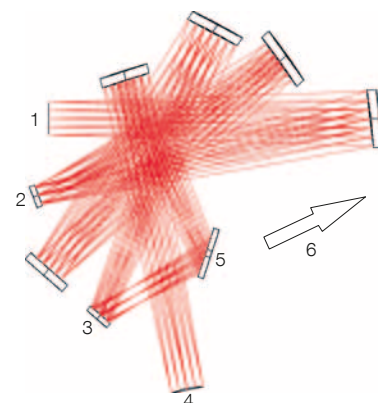
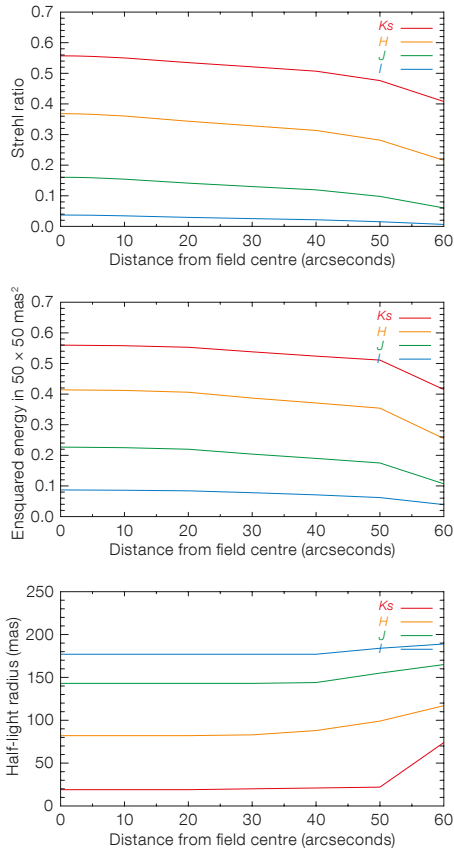


Figure 2. The post-focal relay optical layout of MAORY; the two post-focal deformable mirrors are shown (2 and 3).

- 1 E-ELT focus
- 2 DM 4 km
- 3 DM 12.7 km
- 4 MAORY output focus (lateral port)
- 5 Dichroic
- 6 LGS channel



**Figure 3.** MCAO correction performance vs. radial distance from centre of field of view. Different colours correspond to different wavelengths. Upper: Strehl ratio. Middle: PSF energy enclosed in a  $50 \times 50$  mas aperture. Lower: Radius of circular aperture enclosing 50% of the PSF energy (half-light radius). All simulations for median seeing.

To solve the LGS tip-tilt indetermination problem, three natural guide stars are required (Ellerbroek & Rigaut, 2001): as a baseline two of them are used to measure tip-tilt only, while the third, positioned on the brightest star found on the search field, is used to measure tip-tilt and focus in order to provide a reference for the rapidly varying focus term in the LGS signals due to the sodium layer instability. The three NGS are searched over a wide field of 2.6-arcminute diameter; they are observed in the near infrared ( $H$ -band, 1.5–1.8  $\mu\text{m}$ ), to take advantage of the spot-shrinking resulting from the high-order correction driven by the LGS WFS, thus allowing the use of faint NGS that translates into a high sky coverage. In each of the three NGS probes, light of wavelength 0.6–0.9  $\mu\text{m}$  is split from the infrared light used for tip-tilt and focus measurement. This light feeds a reference WFS, operating at frequencies in the range 0.1–1 Hz and used to monitor the LGS non-common

**Table 1.** Expected performance and corresponding sky coverage at the Galactic pole. The performance is expressed in terms of Strehl ratio averaged over the MICADO field of view ( $53 \times 53$  arcsecond) for median seeing.

Minimum field-averaged Strehl ratio (field $53 \times 53$ arcsecond)				Sky coverage
$Ks$	$H$	$J$	$I$	
0.53	0.34	0.14	0.03	39%
0.51	0.32	0.13	0.02	50%
0.41	0.22	0.06	< 0.01	80%

path aberrations related to the sodium layer profile variability (Pfrommer et al., 2009). During normal operations, the reference WFS has a pupil sampling of approximately  $10 \times 10$  subapertures. An engineering mode with up to  $84 \times 84$  subapertures is foreseen as well. This mode would allow a high-order MCAO correction based on three NGS, in a configuration similar to MAD (Marchetti et al., 2007), to be performed.

### Performance

The MCAO performance was evaluated by an analytic code, allowing the power spectral density of the residual turbulence to be estimated. All the error sources that could not be directly included in the code were accounted for in the global error budget, which amounts to a wavefront error of  $\sim 300$  nm root-mean squared (rms). PSFs were computed over a grid of directions in the field and for different wavelengths ( $Ks$ : 2.16  $\mu\text{m}$ ,  $H$ : 1.65  $\mu\text{m}$ ,  $J$ : 1.215  $\mu\text{m}$ ,  $I$ : 0.9  $\mu\text{m}$ ). The performance is shown in Figure 3 for median seeing conditions (FWHM = 0.8 arcseconds at 0.5  $\mu\text{m}$  wavelength,  $\tau_0 = 2.5$  ms,  $\theta_0 = 2.08$  arcseconds,  $L_0 = 25$  m). The top panel shows the Strehl ratio, i.e. the ratio of the central value of the MCAO PSF to the central value of the ideal PSF. The middle panel shows the PSF enclosed energy in a square aperture of  $50 \times 50$  mas. The enclosed energy in the rectangular slit of SIMPLE ( $28 \times 54$  mas) is only slightly lower than this: in  $Ks$ -band it decreases from 0.56 to 0.50, in  $I$ -band from 0.09 to 0.08. The lower panel shows the half light radius of the PSF. The sky coverage, estimated by means of Monte Carlo simulations of random asterisms with star densities derived from the TRILEGAL code (Girardi et al., 2005), is shown in Table 1 for the Galactic pole. The first line in this table refers to the nominal performance: in this case the limited NGS brightness translates into an image jitter within 2 mas rms. To draw a few conclusions on the estimated performance: MAORY provides the science instruments with a field of 2 arcminutes diameter (up to 2.6 arcminutes, considering the whole field available for NGS search), corrected with good quality (average Strehl ratio  $\sim 0.5$  in  $Ks$ -band

over 2 arcminutes under median seeing) and with an exceptional correction uniformity (rms variation of Strehl ratio lower than 0.05 over the full field). A notable feature is the high sky coverage that is obtained by a robust closed loop correction over the whole NGS search field.

On the basis of a study on simulated images, accounting for PSF shape, field variation and seeing dependency, it was shown that the relative photometric accuracy (0.03 mag rms) and the relative astrometric accuracy (0.05–0.1 mas) required by MICADO are both achievable. A more detailed analysis of these errors, including atmospheric effects, will be pursued further in the future, using PSFs obtained by end-to-end simulations.

Additional information on the performance and PSF datasets may be found on the project web page<sup>1</sup>.

### References

- Beckers, J. 1989, SPIE, 1114, 215
- Ellerbroek, B. & Rigaut, F. 2001, J. Opt. Soc. Am. A, 18, 2539
- Girardi, L. et al. 2005, A&A, 463, 895
- Marchetti, E. et al. 2007, The Messenger, 129, 8
- Pfrommer, T. et al. 2009, Geophysical Research Letters, 36, L15831

### Links

<sup>1</sup> <http://www.bo.astro.it/~maory>