Mem. S.A.It. Vol. 83, 1151

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E-ELT Multi-Conjugate Adaptive Optics module: image quality performance

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Abstract. The Multi-conjugate Adaptive Optics RelaY (MAORY) for the European Extremely Large Telescope (E-ELT) provides a corrected field of view of up to 2 arcmin diameter over the wavelength range 0.8-2.4 micron. It is expected to achieve a correction of high quality and uniformity with high sky coverage: with a seeing of 0.8 arcsec in the visible, the expected Strehl Ratio averaged over a 1 arcmin field is approximately 50% at 2.16 micron wavelength over 50% of the sky at the Galactic Pole. This paper describes the module design and expected image quality performance. The results presented here are based on the MAORY phase-A study that was completed in late 2009. At the moment of this writing the Consortium and the management plan for the next phases of the instrument construction are in preparation.

Key words. Telescopes – Instrumentation: adaptive optics

1. Introduction

The future 40 meter class European Extremely Large Telescope (E-ELT, Gilmozzi et al. 2008) requires adaptive optics to fully achieve its scientific goals. MAORY (Diolaiti et al. 2010) is a crucial adaptive optics facility as it will feed MICADO (Davies et al. 2010), the E-ELT high angular resolution imager. MAORY is based on Multi-Conjugate Adaptive Optics (MCAO), a technique that has been demonstrated to work on sky by MAD (Marchetti et al. 2010) on VLT and by GeMS (Rigaut et al. 2010) on Gemini.

MAORY provides a corrected Field of View (FoV) of 120 arcsec diameter on the

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wavelength range 0.8-2.4 micron. Wavefront correction is carried out by the telescope's adaptive mirror M4, optically conjugated to the ground layer and complemented by the tip-tilt mirror M5, and by two Deformable Mirrors (DM) integrated in MAORY and conjugated to high altitude turbulent layers. Wavefront sensing is performed by a suite of six Laser Guide Star WaveFront Sensors (LGS WFS) and three Natural Guide Star WaveFront Sensors (NGS WFS) for the measurement of the modes which cannot be properly sensed by the LGS WFS. The MCAO system architecture is based on a robust approach, which ensures reliable peak performance as well as high sky coverage.

In this paper we report a very short description of the MAORY system design and a more detailed description of the scientific performance. The results presented here are based on the MAORY phase-A study that was completed in late 2009. At the moment of this writing the Consortium and the management plan for the next phases of the instrument construction are in preparation.

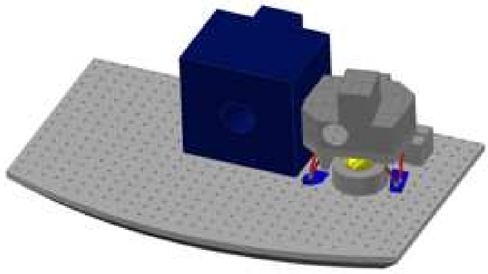


Fig. 1. MAORY on E-ELT Nasmyth platform; MICADO is on the gravity invariant port underneath the optical bench.

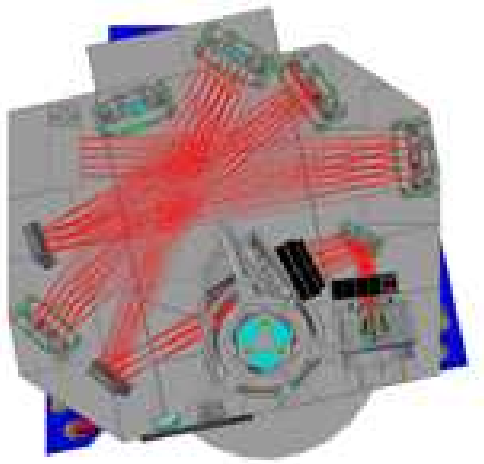


Fig. 2. Top view of the MAORY optical bench without enclosure.

2. System design

This section includes a very short description of the MCAO module. A detailed description of the MAORY system design is beyond the scope of this paper. The interested reader may refer to a more detailed description available in Diolaiti et al., (2011); Diolaiti et al. (2010); Foppiani et al. (2010).

The foreseen location of MAORY is the E-ELT Nasmyth platform, on one of the bent foci (Figure 1). From the optical design point of view it is a finite conjugate relay formed by two pairs of aspheric off-axis mirrors. Three flat mirrors fold the relay to fit the reserved area on the Nasmyth platform; two out of these flat mirrors are deformable and compensate the atmospheric turbulence.

The module feeds two focal stations: the gravity invariant port underneath the optical bench, providing mechanical derotation for a light instrument 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, as the infrared spectrograph SIMPLE. A detailed top view of the opto-mechanical layout of MAORY without enclosure is shown in Figure 2. Wavefront correction is obtained by means of the E-ELT adaptive mirrors M4/M5 and of two post-focal deformable mirrors conjugated at 4km and 12.7km from the telescope pupil. Wavefront sensing is performed by 6 Sodium laser guide stars and by 3 natural guide stars, used to measure atmospheric and windshake tilt and to provide a reference for the focus and for the low-order aberrations induced by the Sodium layer.

3. Performance

In this section we report a summary of the performance of the MAORY system in terms of image quality and sky coverage. The point source image quality of the MAORY module is defined including the nominal performance of the telescope optics and all the known error sources affecting the MCAO module, without considering the instrument that will be coupled with MAORY. Two parameters have been used to estimate the image quality: the Strehl Ratio (SR) defined as the ratio between the central value of a given PSF and the central value of the diffraction limited PSF and the Enclosed Energy (EE), defined as the fraction of the PSF energy enclosed in a given box.

3.1. Image quality

The MCAO image quality performance was evaluated by an analytic code, based on a Fourier method, allowing fast simulations of an ELT by computing the MCAO corrected power spectral density of the atmospheric turbulence phase, from which it is possible to deduce residual variance, long exposure PSFs and associated performance metrics. The Fourier code assumes implicitly infinite pupils except in the PSF calculation part, it assumes plane waves and does not incorporate LGS specific issues. These limitations were mitigated using a specific estimation of performance loss in the field induced by unseen regions associated to the combination of conic (spherical waves) and cylindrical beams (plane waves). The Fourier code with unseen region correction term was validated on downscaled cases by means of an end to end code, taking into account LGS specific issues like cone effect (Petit et al. 2010). Although for future phases a global end to end simulation code will be mandatory, for the past study the Fourier code with unseen region correction, validated on downscaled cases, proved to be a very efficient tool for the optimization of the MCAO system performance. PSFs were computed using the previously mentioned tool over a grid of directions in the FoV for different wavelengths (Ks: 2.16 μm, H: 1.65 μm, J: 1.215 μm, I: 0.9 μm). Error sources that could not be directly included in the Fourier code were accounted for in the PSF calculation with an error budget approach. Performance statistics were derived from these PSFs for a reference median seeing atmospheric condition (seeing FWHM = 0.8 arcsec at 0.5 μm wavelength and at zenith pointing) and for a good seeing condition (seeing FWHM = 0.6 arcsec).

3.1.1. Strehl ratio

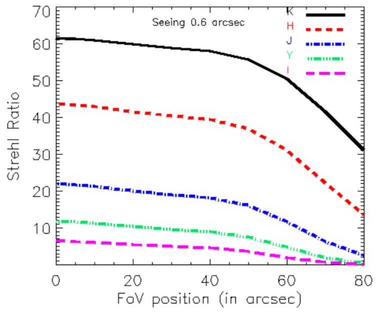
Figure 3 shows the Strehl ratio plots vs. the radial distance from the FoV center. The performance is remarkably uniform out to a radial distance of approximately 60 arcsec corresponding to the optimization FoV. The degree of correction is still relevant also in the outer part of the technical FoV (radial distance up to 80 arcsec) especially at longer wavelengths, where the NGS are looked for: this constitutes a solid basis for the sky coverage.

3.1.2. Enclosed energy

In this section we characterise the PSF in terms of its half-light radius, r50, and the enclosed energy (EE) within a given box. In order to provide useful information for different type of instruments that could be coupled with MAORY (imager or spectrograph) we calculate the EE using two different boxes : 75×75 mas^2 and 54×27 mas^2. The former value might be an interesting performance metric for a multi-object spectrograph while the latter value is similar to the on-axis slit of the E-ELT spectrograph SIMPLE (Origlia et al. 2010). Figures 4 shows the PSF half-light ratio and the PSF EE in a box of 75×75 mas^2 and 54×27 mas^2 for two different seeing condition.

3.2. Sky coverage

To solve the LGS tip-tilt indetermination problem (Ellerbroek and Rigaut 2001) and to provide a reference for the rapidly variable focus term in the LGS signals due to the sodium layer instability, three Natural Guide Stars (NGS) are required. These stars are searched on a wide technical field of 160 arcsec diameter.



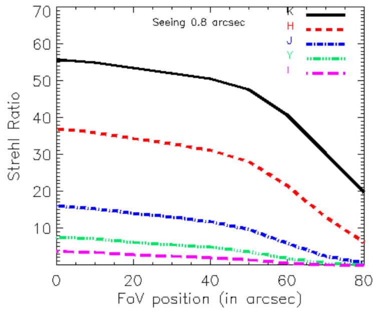


Fig. 3. Strehl ratio vs. distance from FoV center for two different seeing conditions (left: FWHM 0.6 arcsec; right: FWHM 0.8 arcsec).

The observing strategy is based on a central field reserved for the scientific instrument, where the 3 probes of the NGS WFS cannot access, and an outer part used to search the reference sources for the NGS WFS. The NGS probes introduce a shadowing of the field: the obscured areas are less than 20 arcsec in width. A wide field scientific instrument not affected by this kind of shadowing may have access to the whole 160 arcsec technical FoV. Of course the performance at the edge of this extended field is worse than the nominal one, that is optimized over the 120 arcsec FoV.

The sky coverage was estimated at the North Galactic Pole by means of Monte Carlo simulations of random asterisms with star densities derived from the TRILEGAL code (Girardi et al. 2005). Random trials were extracted, distributing the extracted stars uniformly over the NGS search field; all the possible three star asterisms were considered, associating a figure of merit to each asterism. This figure of merit included the anisoplanatic errors due to the asterism geometry and uneven brightness distribution of the NGSs, the measurement noise and the temporal error. Windshake, a major contributor to image jitter, was included in the calculation of the temporal error, assuming a Kalman filter which is more efficient than a pure integrator as it takes into account the windshake statistical properties. The asterism with the best figure of merit, i.e. with the lowest associated wavefront error, was chosen for that particular trial. The process was repeated 1000 times in order to have statistically significant results. Stars as faint as magnitude H = 21 were considered. 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 of MAORY is usually expressed in terms of the fraction of sky at the North Galactic Pole where a minimum Strehl Ratio, averaged over the MICADO FoV, can be achieved. The nominal performance shown in Figure 3 (right panel) corresponds to average SR 0.50 at $\lambda = 2.16\,\mu$m over the MICADO FoV. This performance is achieved on ~50% of the sky at the North Galactic Pole. The percentage increases up to 80% if a moderate degradation of the average performance down to SR ~0.40 at $\lambda = 2.16\ \mu$m is accepted. These estimates are based on the assumption that all three NGS WFS measure instantaneous tip-tilt, but only one of them measures focus. As previously discussed, all three NGS WFS may have to measure focus: the sky coverage degradation in this case would be acceptable.

4. Conclusion

On the basis of the Phase-A study, the following preliminary conclusions about the

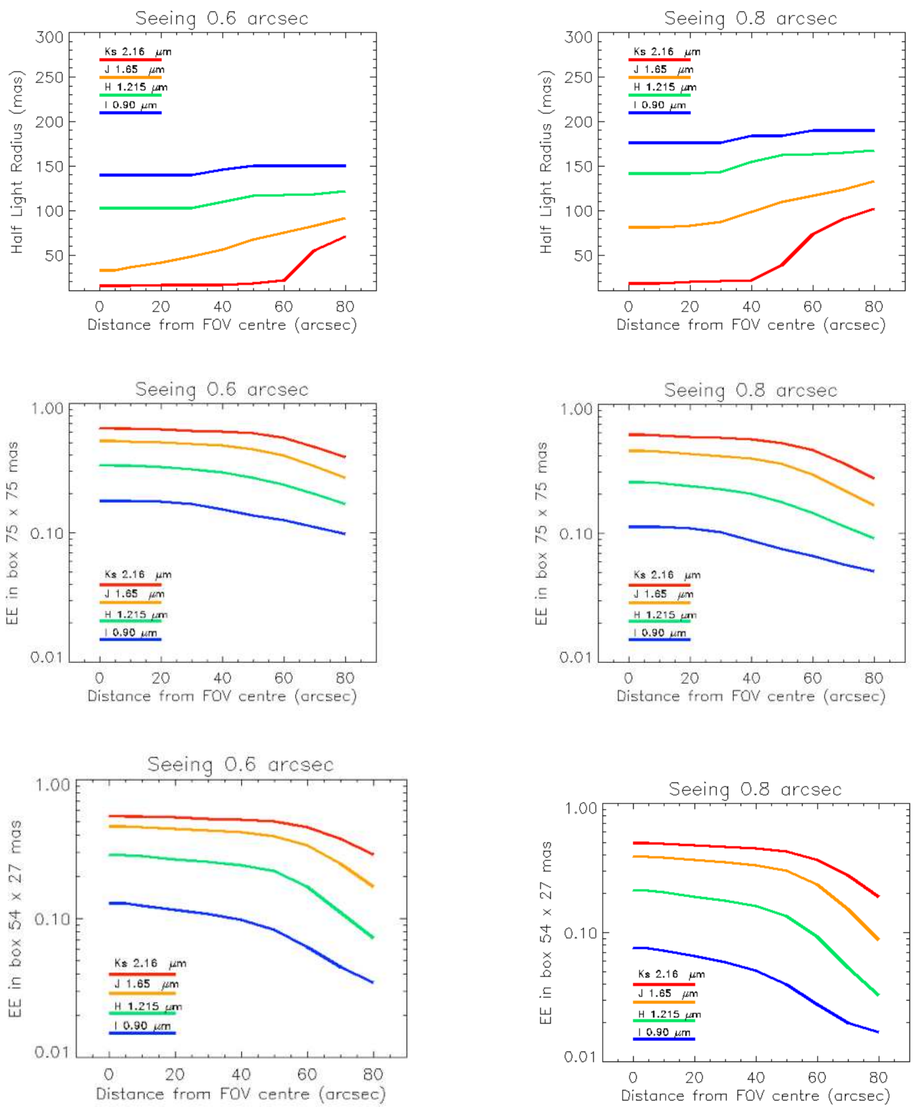


Fig. 4. PSF half-light radius and PSF Enclosed Energy (75×74 mas^2 and 54×27 mas^2) vs. distance from FoV center for two different seeing condition (left: FWHM 0.6 arcsec; right: FWHM 0.8 arcsec).

MAORY estimated performance can be drawn. The MAORY module provides a corrected field of 120 arcsec diameter (up to 160 arcsec considering the whole field available for NGS search) corrected with a good quality (average Strehl ratio ∼ 0.5 in Ks band over 120 arcsec) and with an exceptional correction uniformity (RMS variation of Strehl ratio lower than 0.05 in Ks band over the full FoV). A uniform correction is very important in order to reach an accurate precision both in terms of differential photometry and relative astrometry and to match the scientific requirements of MICADO (see http://www.mpe.mpg.de/ir/micado) the high angular resolution camera fed by MAORY. Moreover, a uniform correction over large fields is a requirement of the majority of the prominent science cases selected by the ELT Science Working Group (see http://www.eso.org/sci/facilities/eelt/science/).

In terms of PSF enclosed energy in a small aperture (as 75×75 mas^2) MAORY provides an excellent gain over the full FoV with respect to the seeing-limited case or to a ground-layer adaptive optics system. Moreover, likewise the SR values, the enclosed energy value remain almost constant up to an off-axis value of about 60 arcsec. Consistent and high uniform gains in term of EE over large FoV are the ideals conditions for MOS or IFU spectrographs.

Finally, the sky coverage is obtained by a robust closed loop approach, that ensures an intrinsically good level of correction of the NGS images.

Acknowledgements. This work was supported by the European Community (Framework Programme 6, ELT Design Study, contract N. 011863; Framework Programme 7, Preparing for the Construction of the European Extremely Large Telescope, contract N. INFRA-2007-2.2.1.28) and by the European Organization for Astronomical Research in the Southern Hemisphere (Agreement No 16669/ESO/INS/07/17243/LCO).

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