Preparing for the phase B of the E-ELT MCAO module project

Emiliano Diolaiti*[a], Carmelo Arcidiacono[a], Giovanni Bregoli[a], Reginald Christopher Butler[b], Matteo Lombini[a], Laura Schreiber[a], Andrea Baruffolo[c], Alastair Basden[d], Michele Bellazzini[a], Enrico Cascone[e], Paolo Ciliegi[a], Fausto Cortecchia[e], Giuseppe Cosentino[f], Vincenzo De Caprio[e], Adriano De Rosa[b], Nigel Dipper[d], Simone Esposito[g], Italo Foppiani[a], Enrico Giro[c], Gianluca Morgante[b], Richard Myers[d], Fabien Patru[g], Roberto Ragazzoni[c], Armando Riccardi[g], Marco Riva[h], Filippo Maria Zerbi[i], Mark Casali[j], Bernard Delabre[j], Norbert Hubin[j], Florian Kerber[j], Miska Le Louarn[j], Enrico Marchetti[j], Suzanne Ramsay[j], Stefan Stroebele[j], Elise Vernet[j]

[a]INAF – Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy;
[b]INAF – Istituto di Astrofisica Spaziale e Fisica Cosmica, via Gobetti 101, 40129 Bologna, Italy;
[c]INAF – Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, 35122 Padova, Italy;
[d]Durham University, Centre for Advanced Instrumentation, Department of Physics, South Road, Durham, DH1 3LE, United Kingdom;
[e]INAF – Osservatorio Astronomico di Capodimonte, Salita Moiariello 16, 80131 Napoli, Italy;
[f]Università di Bologna – Dipartimento di Fisica e Astronomia, via Ranzani 1, 40127 Bologna, Italy;
[g]INAF – Osservatorio Astrofisico di Arcetri, largo E. Fermi 5, 50125 Firenze, Italy;
[h]INAF – Osservatorio Astronomico di Brera (Merate), via E. Bianchi 46, 23807 Merate, Italy;
[i]INAF – Istituto Nazionale di Astrofisica, Viale del Parco Mellini 84, 00036 Roma, Italy;
[j]European Southern Observatory, K.-Schwarzschild-Str. 2, 85748 Garching bei Muenchen, Germany

ABSTRACT

The Multi-Conjugate Adaptive Optics module for the European Extremely Large Telescope has been designed to achieve uniform compensation of the atmospheric turbulence effects on a wide field of view in the near infrared. The design realized in the Phase A of the project is undergoing major revision in order to define a robust baseline in view of the next phases of the project. An overview of the on-going activities is presented.

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

1. INTRODUCTION

The MAORY[1][2] Multi-Conjugate Adaptive Optics (MCAO) module is part of the first light instrumentation[3] of the European Extremely Large Telescope[4][5] (E-ELT). The conceptual design of the module has been developed during the phase A of the MAORY project in the framework of the preliminary studies of the E-ELT instrumentation sponsored by the European Southern Observatory (ESO).

The Phase A design has been optimized to achieve uniform compensation of the atmospheric turbulence effects on a wide field of view in the near infrared.

Wavefront sensing is based on 6 Laser Guide Stars (LGS) and 3 Natural Guide Stars (NGS). The former, projected from the telescope side in a constellation of 2 arcmin angular diameter, are used for high-order wavefront sensing; the latter are necessary for low-order wavefront sensing to measure the modes which cannot be accurately sensed by the LGSs. The NGSs can be positioned over a 2.6 arcmin Field of View (FoV).

*emiliano.diolaiti@oabo.inaf.it; phone +39 051 2095708; fax +39 051 2095700; www.oabo.inaf.it

Adaptive Optics Systems IV, edited by Enrico Marchetti, Laird M. Close,
Jean-Pierre Véran, Proc. of SPIE Vol. 9148, 91480Y · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2056550

Wavefront correction is performed by means of the telescope's mirrors M4 (adaptive, optically conjugated to the low-altitude atmospheric turbulence) and M5 (tip-tilt mirror) and by two additional post-focal Deformable Mirrors (DMs) included in the MCAO module post-focal relay, which are optically conjugated to 12.7 km and 4 km.

MAORY has to provide two exit ports. A gravity invariant port which is devoted to MICADO[6], the E-ELT high angular resolution camera, covering a 53×53 arcsec^2 FoV and working on the wavelength range from about 0.8 to 2.4 μm, and an auxiliary port for an instrument which has yet to be defined.

According to simulations, the Phase A design can achieve a Strehl Ratio of about 0.5 at λ = 2.16 μm, averaged over the MICADO FoV, over about 50% of the sky at the Galactic Pole.

An in-depth revision of the design is in progress concerning hardware components and design options. This paper contains an overview of the on-going activities aiming at the definition of a robust baseline design in view of the next project phases.

2. DEFORMABLE MIRROR STUDY

The post-focal DMs are crucial hardware components for the MCAO module. Properties such as the DM diameter and actuator density have a major impact on the module design. The Phase A design of MAORY was based on the use of piezo-electric actuator DMs[7]. Recently a study has been started on the possibility to adopt voice-coil motor actuators DMs[8], which have been proven to work well as adaptive secondary mirrors on 8 meter class telescopes and which are also the baseline for the E-ELT M4 adaptive mirror.

According to the Phase A design, the actuator spacing of the post-focal DMs inside the MCAO module has to be 1 m, as projected onto the atmospheric layer. Considering the conjugation range of the two post-focal DMs and the full technical FoV of the MCAO module (2.6 arcmin for NGS search), the required number of actuators across the DM diameter is about 48 and 42 respectively for the DMs conjugated to 12.7 km and 4 km.

The MCAO system analysis performed in Phase A by a Fourier modeling code showed that a relaxation of the projected spacing up to 1.5 m for instance produces negligible performance degradation. This result has been confirmed by recent end-to-end simulations.

The VLT adaptive secondary mirror has a 1120 mm diameter and a 29 mm actuator spacing. Assuming these values also for the DMs inside MAORY, the corresponding projected spacing onto the atmospheric layers would be 1.25 m and 1.08 m respectively for the DMs conjugated to 12.7 km and 4 km. These values of projected spacing are fully consistent with the requirement mentioned above.

An optical design for voice-coil DMs is shown in Figure 1. This example is part of on-going extensive design work[9]. The MCAO module is placed in the folded telescope focus after the M6 mirror. In order to create images of the atmospheric layers matching the size of the DMs, a long focal length collimator (M7) is required. The M7 mirror in the design shown is actually a quasi-collimator, in the sense that the beams are slightly diverging so that the diameter of the meta-pupils on the two DMs are almost the same, allowing the use of DMs of identical size. The distance between the collimator and the first DM is rather large (about 15 m) and has to be folded by a flat mirror (M8 in the figure) in order to fit the available space on the Nasmyth platform where the module is located. In the design shown in the figure, the first DM (M9) is flat, while the second (M10) is an off-axis concave ellipsoid: this reduces the number of optical surfaces in the design. Following M10, a three mirror system (M11: concave, M12: convex, M13: concave) creates the exit port focal plane for MICADO in gravity invariant configuration. The dichroic beam-splitter after M11 is used to transmit the LGS light and reflect the science and NGS light.

On the basis of the analysis performed so far, voice-coil actuator DMs similar to the VLT adaptive secondary mirror ensure the achievement of the required MCAO performance and are fully compatible with the MCAO module design.

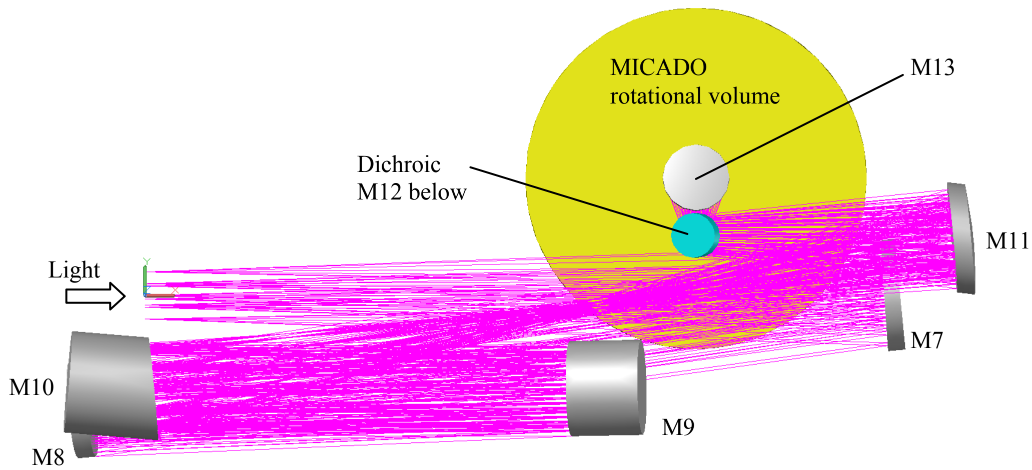

Figure 1. Example of MCAO module optical design including voice-coil actuator deformable mirrors. Some optical elements look superimposed in this top view because they are on different planes to minimize the size of the design.

3. BEAM-SPLITTER STUDY

In a typical adaptive optics system it is necessary to split the light collected by the science instrument from the light used by the Wavefront Sensors (WFS) to measure the wavefront distortions. This requirement also applies to MAORY.

In the design shown in Figure 1 or in the Phase A baseline design, the LGS light is split from the science and NGS light according to wavelength. A dichroic beam-splitter in an intermediate pupil plane transmits the light of wavelength $\lambda < 0.6$ μm to the LGS WFS and reflects the light of wavelength $\lambda > 0.6$ μm to the exit port focus. At this location further splitting occurs according to the position of the sources in the FoV: the central part of the FoV is transmitted to the client instrument (MICADO), while three NGS outside the science FoV are selected by the NGS WFS probes, avoiding any vignetting of the science FoV (section 6).

The size of the dichroic beam-splitter in the designs for voice-coil actuator DMs ranges from about 0.6 m to 1.1 m, depending on the optical design. The choice to reflect the infrared light has been adopted to overcome the problem of the very limited availability of infrared transmitting materials up to this size: a simple optical glass would be acceptable to transmit the LGS light through the dichroic beam-splitter.

The approach described so far is feasible. However there are some reasons to investigate an alternative solution. For instance, the optimization of the spectral performance of such a dichroic could be difficult and its reflectivity at near infrared wavelengths is likely to be worse than a normal reflecting mirror. The possible alternative solution is splitting the light in an intermediate focal plane by a perforated dichroic beam-splitter (Figure 2).

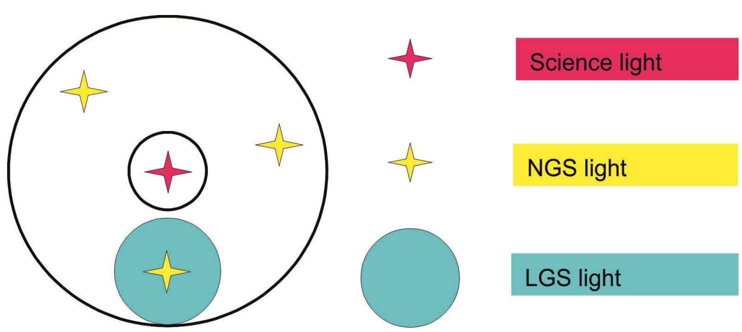

Figure 2. Scheme for light splitting in focal plane by a perforated dichroic beam-splitter. The in-focus science beam passes unaffected through the central hole. The in-focus NGS beams are transmitted by the annular part of the dichroic. The out-of-focus LGS beams are reflected by the annular part of the dichroic.

The in-focus science light is transmitted through a central hole (Figure 2). The NGS light, also in focus on the perforated dichroic, is transmitted through the annular region. The LGS light, which is out-of-focus, is reflected. As the NGS light maximum wavelength is $\lambda \approx 1.8$ μm, the spectral performance optimization of this device is easier than the dichroic in the pupil plane, which has to work up to a wavelength $\lambda \approx 2.4$ μm. More details on the optical design of the perforated dichroic beam-splitter are provided in Lombini et al.[9].

The drawback of this approach is that the LGS constellation angular diameter is constrained to be larger than a certain minimum value in order to transmit the science FoV through the central hole in the perforated dichroic. This limitation is less severe for a smaller science FoV. In the case of the MICADO science FoV, the minimum value is about 3.3-3.4 arcmin. The next table shows the impact of this limitation on the MCAO performance, which has been estimated by end-to-end simulations with the Octopus code[10]. The values of Strehl Ratio in the table are normalized to the value at the center of the FoV for a 2 arcmin LGS constellation diameter. The performance at the center of the FoV decreases from relative 1.00 to relative 0.75 increasing the LGS constellation diameter from 2 arcmin to 3.4 arcmin. At the edge of the MAORY technical FoV, the trend is the opposite: the performance with a 3.4 arcmin LGS constellation diameter is remarkably similar to the performance at the center of the FoV and larger than the performance at the edge with a 2 arcmin LGS constellation diameter. The increased performance at the edge of the FoV improves sky coverage. In fact fast tip-tilt and focus sensing in MAORY is performed on NGSs observed in the near infrared, where the spot shrinking due to MCAO allows the use of faint stars: a better MCAO correction on the NGS search field leads to potentially higher sky coverage. On the other hand, the loss of performance on the science FoV has to be carefully analyzed considering the science requirements.

Simulations performed by a different end-to-end simulation code[11] are consistent with this trend, although the detailed results are different because of different reconstruction schemes adopted in the simulations performed by the two codes.

Table 1. Relative MCAO performance for different angular diameters of the LGS constellation.

LGS diameter	**Relative Strehl Ratio $\lambda = 2.16$ μm**	
	FoV center	1.3 arcmin from FoV center
2.0 arcmin	1.00	0.61
3.4 arcmin	0.75	0.72

4. THERMAL BACKGROUND

Thermal background from the MCAO module optics should be kept below a reasonable fraction of the thermal background due to the sky and to the telescope optics, in order to avoid affecting scientific observations.

An option to achieve this goal is to cool the MCAO module following the same approach adopted in the design of NFIRAOS[12], the MCAO system for the Thirty Meter Telescope. This option was also investigated at a general level in the Phase A and is under revision at present.

In order to cool the MCAO module, it would be necessary to enclose it and add optical windows. Due to the need to transmit the LGS beams, the entrance window would be rather large, about 800 mm diameter for the 2 arcmin LGS constellation. Building such a window is a challenging task, considering not only the size but also the requirement of maximizing internal transmission through the substrate. Sky background, telescope emissivity and the assumed emissivity of the optical components inside the MCAO module (mirrors, dichroic beam-splitter if applicable, windows) are crucial input parameters of the on-going study.

An alternative to cooling is the reduction of the number of optical surfaces in the MCAO optical relay, possibly without the dichroic beam-splitter in a pupil plane, which could be a major contributor to the thermal background according to the discussion of section 3. Fewer surfaces also imply smaller wavefront errors from the optics and simpler integration procedures. Optical designs with a total of 6 surfaces only have been developed. The main drawback of these designs is that the exit port optical interface is significantly different from the telescope one: in particular the field curvature could make the MICADO design more complex.

The on-going study takes into account all the aspects mentioned above, in order to find the most favorable trade-off between performance and risks.

5. MCAO SYSTEM MODELING

A numerical end-to-end code for the MCAO system simulations is under development[13]. The code is developed for a dedicated server with two 6-core processors, 256 GB RAM and 4 Graphical Processing Unit (GPU) processors. Massive parallelization has been adopted whenever possible.

Detailed modeling of the LGS spot formation and wavefront sensing is implemented in the end-to-end code. Due to the complex features of the Sodium layer density profile coupled with the finite FoV of the LGS WFS (Figure 3), time-dependent spurious wavefront aberrations could be injected by the LGS WFS into the MCAO loop. These effects will be studied with the end-to-end code under development.

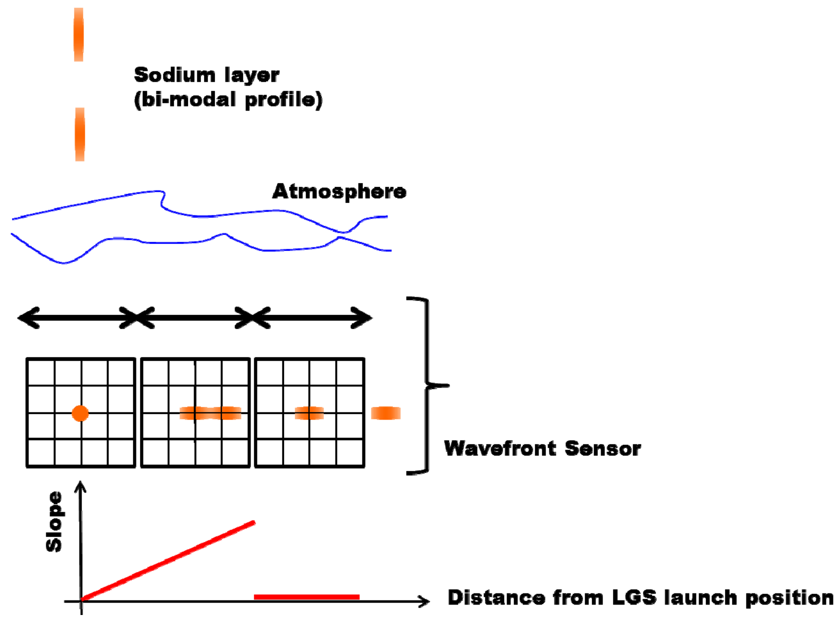

Figure 3. Schematic explanation of the errors arising in the LGS WFS because of the structures in the Sodium layer density profile and limited FoV in the WFS. The bi-modal profile of the Sodium layer does not fit the WFS sub-aperture affected by the largest perspective elongation effect: this translates into a spurious wavefront error.

A simplified modeling tool has also been developed for fast simulation of the effects due to the Sodium layer issues[14]. This tool assumes no atmospheric turbulence. The wavefront aberrations generated by 6 Sodium LGSs are injected into the MCAO loop assuming a simplified reconstruction scheme and are monitored by 3 NGS WFSs (so-called "Reference WFSs", see section 6), which have to provide a kind of reference wavefront to limit the effects of the spurious aberrations. According to preliminary analysis[14], the number of sub-apertures in the NGS Reference WFS does not need to be large (order 6×6 - 8×8 seem acceptable). The LGS WFS FoV on the other hand seems a crucial parameter, although this preliminary result probably depends on the simplified reconstruction scheme, without weighting the LGS slopes according to the measurement noise. This aspect deserves further investigation.

6. NGS WAVEFRONT SENSOR AND SCAO OPTION

As anticipated in the previous section, the NGS WFS is the sub-system which monitors the spurious wavefront aberrations induced by the LGS WFS and by the Sodium layer features. An opto-mechanical drawing of this sub-system is shown in Figure 4.

Three NGS probes are deployable in the technical FoV, searching for 3 NGSs. Inside each probe, light is internally split into two wavelength ranges: 1.5–1.8 μm and 0.6–0.9 μm. The former range is used for fast tip-tilt and focus measurement, taking advantage of the spot shrinking ensured by the high-order MCAO correction, that allows the use of faint NGSs translating into high sky coverage; the NGS image shrinking also allows the windowing of the star image, providing an effective way to reject the infrared background. The latter range feeds a so-called Reference WFS, which is expected to operate at frequencies from 0.1 to 1 Hz and is used to monitor the LGS aberrations mentioned above.

During normal operations the Reference WFS has a relatively low pupil sampling as explained in section 5. An engineering mode with high-order pupil sampling and fast frame rate is also foreseen: this mode allows high-order Single-Conjugate Adaptive Optics (SCAO) or MCAO correction based on one or three NGS respectively.

A permanent SCAO mode inside MAORY has been recently requested to fulfill the scientific requirements of MICADO. The SCAO mode achievable with one Reference WFS probe has the disadvantage that the NGS has to be outside the science FoV, relatively far from the center of the FoV, thus reducing the achievable on-axis performance. For this reason an alternative SCAO scheme is under study, based on the use of a deployable dichroic on top of the NGS WFS shown in Figure 4 reflecting the visible light to an optimized WFS for the SCAO mode.

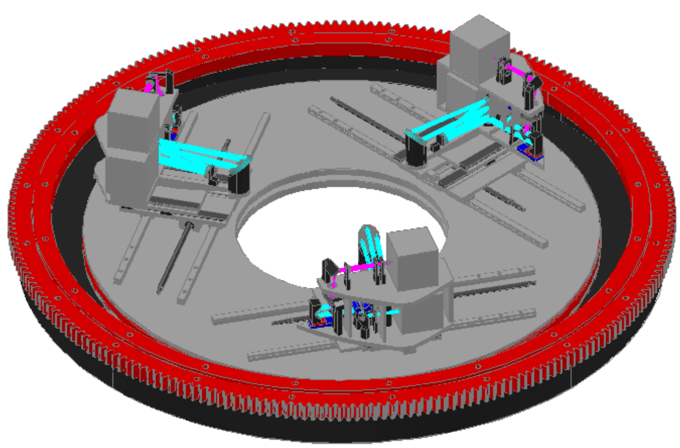

Figure 4. Opto-mechanical layout of the NGS WFS of MAORY. Three NGS probes span a 2.6 arcmin diameter FoV. The central part of the field if transmitted to the science instrument.

Concerning how to feed the light from the telescope focal plane to the SCAO WFS when MAORY is used in SCAO mode, two options are under investigation. The first one is to use the MCAO relay, propagating the light through the post-focal DMs which have to be kept static in their "reference" position. The second option is to create an optical by-pass with the same exit port as the MCAO relay, using two deployable mirrors, skipping the MCAO relay and the DMs. The design of a possible optical by-pass is shown in Figure 5.

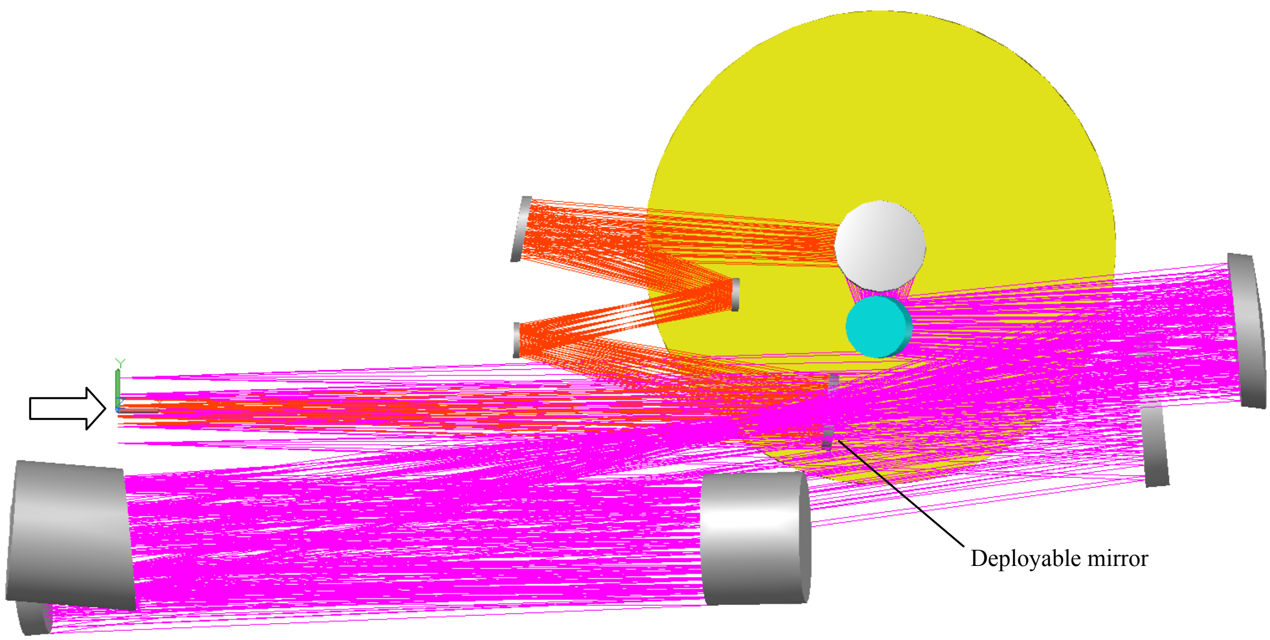

Figure 5. Layout of MCAO post-focal relay (magenta in color version) superimposed with optical by-pass (red in color version) for the SCAO mode of MAORY. The MCAO relay is the same as that shown in Figure 1. The exit port position and optical interface are the same for the two relays.

ACKNOWLEDGMENTS

This work has been partly supported by the "Progetto Premiale E-ELT 2012 (PI Monica Tosi)" funded by the Italian Ministero dell'Istruzione, dell'Università e della Ricerca.

REFERENCES

[1] Diolaiti, E., Conan J.-M., Foppiani I., Marchetti E., et al., "Conceptual design and performance of the multiconjugate adaptive optics module for the European Extremely Large Telescope," Proc. SPIE 7736, article id. 77360R, 9 pp. (2010).

[2] Diolaiti, E., "Overview of the E-ELT MCAO module project," Proceedings of the Third AO4ELT Conference. Firenze, Italy, May 26-31, 2013, Eds.: S. Esposito and L. Fini Online at http://ao4elt3.sciencesconf.org/, id.88 (2013).

[3] Ramsay, S. K., Casali, M. M., Gonzalez, J. C. and Hubin, N., "The E-ELT instrument roadmap: a status report," Proc. SPIE 9145, this Symposium.

[4] Gilmozzi, R. and Spyromilio, J., "The 42m European ELT: status," Proc. SPIE 7012, article id. 701219, 10 pp. (2008).

[5] Tamai, R. and Spyromilio, J., "European Extremely Large Telescope: progress report," Proc. SPIE 9145, this Symposium.

[6] Davies, R. I., Ageorges, N., Barl, L., Bedin, L. R., et al., "MICADO: the E-ELT adaptive optics imaging camera," Proc. SPIE 7735, article id. 77352A, 12 pp. (2010).

[7] Sinquin, J.-C., Lurçon, J.-M., Guillemard, C. and Morin, P., "Recent Progress on Correcting Components (useful for ELTs) at CILAS," Proceedings of the 1st AO4ELT conference - Adaptative Optics for Extremely Large Telescopes, held 22-26 June, 2009 in Paris, France. Edited by Y. Clénet, J.-M. Conan, Th. Fusco, and G. Rousset. EDP Sciences, 2010, id.06004 (2010).

[8] Biasi, R., Gallieni, D., Salinari, P., Riccardi, A. and Mantegazza, P, "Contactless thin adaptive mirror technology: past, present, and future," Proc. SPIE 7736, article id. 77362B, 14 pp. (2010).
[9] Lombini, M., Diolaiti, E. and De Rosa, A., "Optical design trade-offs of the multi conjugate adaptive optics relay for the European Extremely Large Telescope," Proc. SPIE 9148, this Symposium.
[10] Le Louarn, M., Clare, R., Béchet, C. and Tallon, M., "Simulations of adaptive optics systems for the E-ELT," Proc. SPIE 8447, article id. 84475D, 7 pp. (2012).
[11] Basden, A. G., Butterley, T., Myers, R. M. and Wilson, R. W., "Durham extremely large telescope adaptive optics simulation platform," Appl. Opt. 46, 1089-1098 (2007).
[12] Herriot, G., Andersen, D. R., Atwood, J., Boyer, C., et al., "NFIRAOS: first facility AO system for the Thirty Meter Telescope," Proc. SPIE 9148, this Symposium.
[13] Arcidiacono, C., Schreiber, L., Bregoli, G., Diolaiti, E., et al., "End to end numerical simulations of the MAORY multiconjugate adaptive optics system," Proc. SPIE 9148, this Symposium.
[14] Schreiber, L., Diolaiti, E., Pfrommer, T., Arcidiacono, C., et al., "Impact of Sodium Layer variations on the performance of the E-ELT MCAO module," Proc. SPIE 9148, this Symposium.