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THE MULTI CONJUGATE ADAPTIVE OPTICS RELAY FOR MICADO

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Abstract. MAORY (Multi-Conjugate Adaptive Optics RelaY) is the adaptive optics module that will restore the full angular resolution of a 39m telescope at the focal plane of the ELT's camera MICADO and of another instrument in a more distant future. MAORY is designed to be delivered in first light and must provide a multi-conjugate correction (MCAO) of atmospheric turbulence effects over the entire MICADO field of view (up to 50 ") with excellent uniformity. For that purpose it will use up to 8 laser guide stars (LGS) and 3 natural guide stars (NGS). MAORY will be able to operate in MCAO mode over more than 50% of the accessible sky from the ELT site instead of a few percents with a conventional Single Conjugated Adaptive Optics (SCAO). Two observational techniques will particularly take advantage of MAORY : astrometry and deep photometry in primary science cases such as small bodies and planets of the Solar System, young stellar populations, black holes and galaxies, and the evolution of the young Universe.

Keywords: European Large Telescope, Multi-Conjugate Adaptive Optics, MAORY, MICADO, science cases.

1 Adaptative Optics at the dawn of the extremely large telescope era

At present there is a zoo of AO concepts, which spans different sub-spaces in the Strehl ratio/sky coverage/Field-of-View (FoV): SCAO, LGSAO, GLAO, LTAO, MCAO, MOAO, and ExAO (Davies & Kasper 2012).The Strehl ratio S is a useful figure of merit to characterise the performance of an adaptive optics system which is defined as the ratio of the central intensity of the actual Point Spread Function (PSF) to the central intensity of an ideal diffraction-limited PSF. Equivalently S determines the relative flux in two components of the PSF: the diffraction-limited core and the seeing halo. The sky coverage is the fraction of the sky over which a suitable AO correction can be achieved. The Single Conjugated AO (SCAO) provides wavefront correction at an angular distance no larger than 30 to 40 arcsec from a bright (e.g., $R < 16$) natural guide star with a fast decrease of the Strehl ratio. This leads to a very limited sky coverage of approximately 1%. Laser Guide Star AO (LGSAO) somewhat relaxes this hard constraint by shooting a laser beam at the sodium layer, $\approx$ 90 km high in the Earth atmosphere, creating an artificial guide star by resonant excitation. The sky coverage increases to nearly 30% but at the expense of the Strehl ratio (30% instead of 60% with SCAO). Indeed the correction suffers from the fact that the light is coming from a single LGS that is not point like and not at infinity. The artificial light thus does not probe the entire cylindrical volume of turbulence in the telescope line of sight (cone effect). In addition a NGS is still needed for tip-tilt (TT) compensation. Laser tomography AO (LTAO) mitigates, or entirely solves, the cone effect limitation with several LGSs to probe the cylindrical volume of turbulence. However the so-called tomographic information extracted from the different Wave Front Sensor (WFS) measurements is not fully exploited because the correction of the wavefront is only achieved with one Deformable Mirror (DM). Performances close to SCAO are achieved also over a very limited field of view (anisoplanatic limitation) but around the sky direction of interest that is not tied to a NGS. Sky coverage is similar to LGSAO. With the Multiple Conjugated AO (MCAO) concept (Rigaut & Neichel 2018), the idea is to operate several DMs that are optically focused to different levels of the whole turbulent volume. A DM optically conjugated to some layer will be able to exactly compensate for phase aberrations occurring in this layer. This requires multiple guide stars (NGS or LGS) and a real-time tomographic processor. As a result MCAO reaches a good

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compromise between the Strehl ratio (up to 40%), the field of view over which the uniformity of the PSF is achieved (up to several arcmin) and the sky coverage (50% and more). Note that probing NGS wavefronts is still mandatory to disentangle between sodium altitude fluctuations and atmospheric focus changes in addition to TT compensation. MCAO has been demonstrated for correction in the NIR on 8-m telescopes on NGS only (Multiconjugate Adaptive Optics Demonstrator at the VLT) and LGS (Gemini MCAO System) with excellent performances (Fig. 1). MCAO is particularly adapted for extremely large telescopes because most WFSs become more sensitive. Besides the overlap of the beams coming from the stars of a given asterism becomes larger for larger apertures, making the tomography easier and more stable. Out of the three extremely large telescope projects, two have MCAO as part of their first generation instruments: NFIRAOS at TMT (Herriot & 19 co-authors 2014) and MAORY at ELT (Ciliegi et al. 2018).

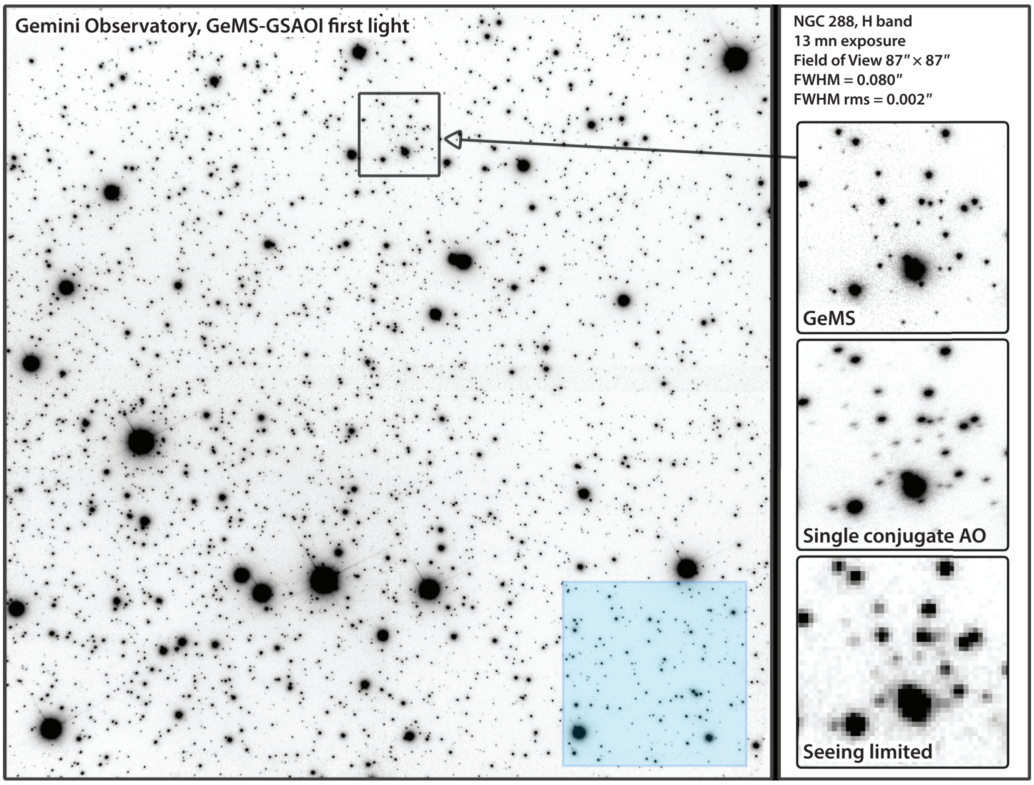

Fig. 1. Figure illustrating the gain in FoV brought by MCAO with NGC 288 observed by GeMS in the H band. Figure extracted from Rigaut & Neichel (2018).

2 MAORY: the project and its French contribution

MAORY is the Multi-Conjugate Adaptive Optics RelaY for the ELT; PI, Paolo Ciliegi, INAF-Bologna. The agreement for the MAORY instrument was signed on December 10th 2015 between ESO and a consortium of European institutes composed of the Istituto Nazionale di Astrofisica (Italy) and the INstitut des Sciences de l'Univers of Centre National de la Recherche Scientifique (France). The MAORY kick-off meeting was held in Bologna, Italy on February 2, 2016. MAORY will support the MICADO near-infrared camera by offering two adaptive optics modes: MCAO and SCAO. Currently the former mode of MAORY is developed in collaboration with 3 Italian institutes (OAS Bologna, OA Padova, OA Arcetri Firenze) and one french IPAG (co-I P. Feautrier), the latter being responsible for the wavefront sensors of the LGSs (Schreiber et al. 2018). The SCAO mode (Clénet & 39 co-authors (2018), and Clénet et al. 2019, these proceedings) is being developed under the responsibility of MICADO by INSU (LESIA, GEPI, Observatoire de Besançon, DT INSU, IPAG) in collaboration with OA Arcetri, first as a stand-alone module that will serve directly MICADO then, integrated within the main MAORY system upon completion and commissioning (2027). The Preliminary Design Review

(PDR) of MAORY is planned for mid 2020 and the Final Design Review (FDR) less than two years latter. A scientific team has been gathered within the MAORY project with 15 members including 3 from IPAG. The leader of the team is Carmelo Arcidiacono researcher at Instituto Nazionale di Astrofisica (INAF), Padova.

3 Characteristics and performances of MAORY

MAORY is a post-focal adaptive optics module which functional diagram appears in Fig. 2. In the MCAO mode, wavefront sensing is performed by a system based on six to eight 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 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 present baseline, the AO correction will be performed over the whole $D = 160$" technical FoV that contains MICADO 53×53" FoV. The approximate faint magnitude limit for a star to be eligible as a NGS is $Hlim \sim 18.0 - 19.0$ mag; the bright magnitude limit should be $H \sim 6.0$. Note that the NGS will be analyzed by two independent set of wavefront sensors (three optical NGS WFS and three infrared NGS WFS, respectively). From simulations (Arcidiacono et al. 2018) the expected performances of MAORY are the following. The average Strehl ratio in the K band will be $\approx 35\%$ (22% in H, 6% in J) throughout MICADO wide field of view (51") on 50% of the sky. With excellent seeing conditions the Strehl ratio could reach 50-55% for the same sky coverage. With a NGS asterism closer to the central part, the average Strehl ratio could reach 40-45% throughout MICADO medium field of view of (20") on 50% of the sky. PSF uniformity across the corrected field of view is very important and, from past experiences, variation of the FWHM across the images should be less than 10% over MICADO wide field of View. One should emphasise the fact that astrometry is one of the main science drivers for building the next generation MCAO systems like MAORY for future extremely large telescopes. The goal is to reduce the amount of distortion, provide a large number of uniformly high-quality astrometric reference sources, deliver uniformity of the corrected point spread function (PSF) thus improving the accuracy of the image analysis. Through calibration, observation, and data reduction processes dedicated to astrometry, the MICADO/MAORY system will offer a 10-50 μas precision relative to a reference source anywhere in the field.

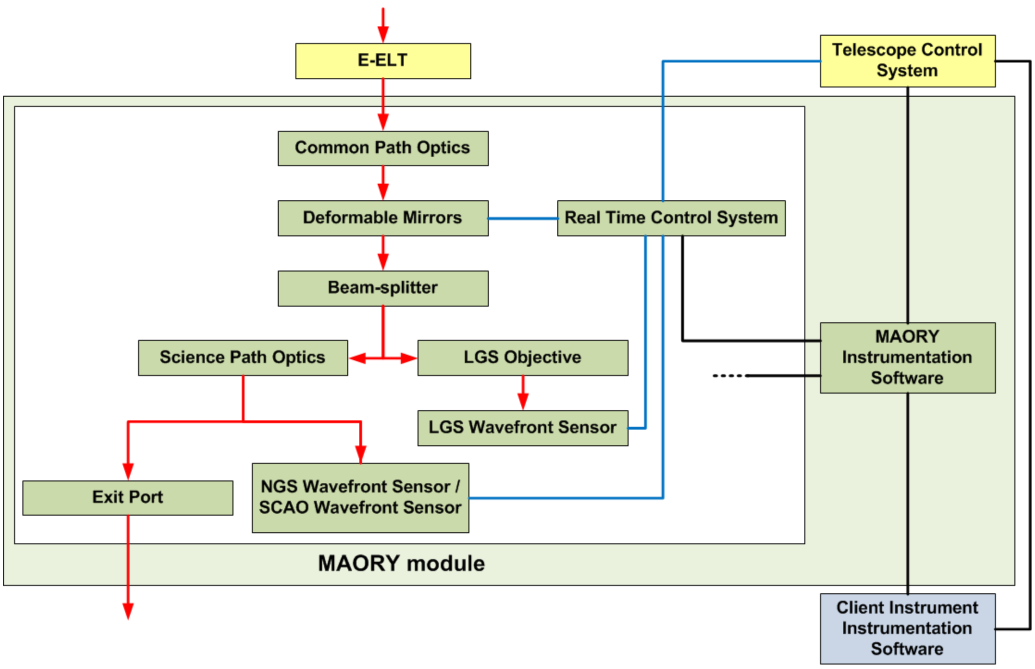

Fig. 2. MAORY functional diagram of the instrument.

4 Contribution of MAORY to MICADO Science

There is an ongoing work by the scientific team of MAORY to define priority cases that will be adressed by MICADO with the added value of MAORY in various themes: cluster of stars in formation, stellar cluster of galactic centers, evolution and dynamics of galaxies, gamma-ray bursts, protoplanetary disks, exoplanets and objects of the System Solar. A white book was published (Fiorentino et al. 2017) from which we summarize the main objectives.

4.1 Solar System

MICADO-MAORY will address two main themes, the formation and evolution of the minor bodies in the Solar System and the study of the composition of Giant planets and their satellites. For the first theme, imaging and spectroscopy will be put to work to determine the size, shape, colors, and chemical composition of the main asteroids, Centaurs, and trans-Neptunian objects. High-resolution astrometry will allow to determine their orbital and internal properties when these objects are in multiple systems. For the second theme, temporal variation of the atmospheres of Giant Planets will be monitored and spectroscopy will be used to measure the abundance of CH_4, N_2, and hydrocarbons in the atmosphere of Titan. In both themes a MCAO mode is required to resolve faint asteroids and KBO (mag. <15 in H band) and to get the maximal spatial resolution for objects with an apparent diameter $>$ 300 to 400 mas.

4.2 Stellar Systems

The formation and evolution of stellar systems notably globular clusters (GCs), young massive clusters, and star-forming regions is an objective of paramount importance for MICADO-MAORY. Indeed MCAO shines for such fields with a high density of stars because it provides the advantage of a large field of view with a more uniform PSF. The result is a sensitivity gain for point sources, a minimization of the confusion of the stellar population, a more complete and stable photometry as well as the possibility to measure the proper motion of many individual stars at once increasing statistics. As a consequence the following objectives become accessible: (i) a better determination of the initial mass function (IMF) accessing the high mass, the low mass, and the substellar part of the stellar IMF, (ii) the IMF study in far away very massive young clusters such as the Arches, Westerlund 1, or NGC3603 in our galaxy as well as young clusters in the SMC/LMC (e.g. 30 Doradus), (iii) spatial properties and internal kinematics of multiple stellar populations in (young) globular clusters (an accuracy of 0.05 mas over at least 1 year corresponds to a few km/s at 10 Kpc), and (iv) accretion and disk fraction of young stellar objects in low-metallicity environments. It is worth noting that NIR MCAO astrometry studies such as the one conducted with MAORY are fully relevant even in the Gaia era as they provide complementary information for very embedded regions (like the Galactic Center) and/or very crowded regions (like GCs) in which Gaia is blind.

4.3 Disks & Exoplanets

MICADO will be the instrument of choice to understand the formation, the physics of Giant Planets, and planetary architectures in general thanks to its high contrast mode mixing SCAO correction, coronography, and angular differential imaging (see P. Baudoz et al. 2019, these proceedings). The MAORY science team is there closely collaborating with the MICADO consortium for this key science case. The use of MAORY in MCAO mode might be an option for the direct imaging or astrometric monitoring of fainter targets/lower mass stars and younger and more embedded objects, for the search and characterization of brown dwarf to planetary mass companions.

4.4 Extragalactic

Extragalactic studies are main scientific drivers for MICADO and most investigations will benefit greatly from the MCAO correction provided by MAORY because of sky coverage issue, the PSF uniformity over large field, and the target magnitude constraint. Compared to seeing-limited observations, the expected signal-to-noise ratio gain provided by MCAO for extended objects will be of the order of 2 to 3. Considering average Strehl ratio provided by MAORY, typical sensitivity obtained in 5hr acquisitions is 29.5mag in Kband, 30.4mag in H band, and 29.7mag in J band. Under the best conditions an additional gain of 0.3 mag can be expected. Such performance is the way to a much more detailed view of the local Universe and a new window on the High redshift Universe.

4.4.1 Local Universe

MICADO-MAORY will address three main themes: co-evolution between Black Holes (BHs) and their host galaxies, galaxy formation, growth, and assembling through composition studies, and finally measuring the local universe with greater precision (Cepheids, TRGB, and Surface brightness fluctuations). Different objectives can be cited for each theme like revealing the intermediate-mass BHs in dwarf galaxies by modelling the kinematic of the gas around the BH with high resolution spectroscopic observations, studying the stellar population in a variety of galaxies, in their nuclear star clusters, and in their massive GCs within $\approx$5-18 Mpc, and constraining formation scenarii of early-type galaxies (e.g. NGC 3379) by identifying individual planetary nebulae and deriving their abundance. A benefit of a high angular resolution combined to confusion reduction is the possibility of detecting and characterizing (distance, stellar content) for the first time nearby galaxies in the Zone of Avoidance.

4.4.2 High redshift Universe

MICADO-MAORY should contribute greatly to the understanding of the star formation history in early galaxies because it will be able alone to resolve galactic structures and kinematics as well as characterizing the young stellar population in the distant Universe (at redshift 2-4). Other possible contributions in studying galactic evolution is probing the assembly of high redshift early-type galaxies and confirming the primordial nature of $z>10$ galaxy candidates. The co-evolution theme between BHs and their host galaxies can be extended to the high redshift universe. Super Massive Black Holes will be probed in several AGN ($d<100$ Mpc) with high resolution observations of stellar kinematics. The accretion processes around the nuclei of AGN will be studied by imaging the warm dust in the near-IR on parsec scales. The mass of the central BH and the properties of its host will be measured for a suitable sample of galaxies (quasars) at different redshift.

5 Conclusions

After a slow start, perhaps due to the disbelief of the community that such a complex technique could be put to work, the interest of the community in MCAO is growing. MAD at ESO, GeMS at Gemini and Clear at the Big Bear Solar Observatory have demonstrated that MCAO works and provides uniform, almost diffraction-limited images over fields of 1 arcmin^2 or more. MCAO is still the subject of active research and development but it is mature enough to be developed for a commissioning at the ELT at the horizon 2027. This is of paramount importance so that the imager MICADO (and, latter, a second instrument) reaches its optimal performance in terms of angular resolution and sensitivity over a large portion of the accessible southern sky. This is also a requirement to be fully competitive against concurrent future telescopes such as the JWST and the TMT.

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