PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Joint MICADO-MAORY SCAO mode: specifications, prototyping, simulations and preliminary design

Clénet, Yann, Buey, Tristan, Rousset, Gérard, Gendron, Eric, Esposito, Simone, et al.

Yann Clénet, Tristan Buey, Gérard Rousset, Eric Gendron, Simone Esposito, Zoltan Hubert, Lorenzo Busoni, Mathieu Cohen, Armando Riccardi, Frédéric Chapron, Marco Bonaglia, Arnaud Sevin, Pierre Baudoz, Philippe Feautrier, Gérard Zins, Damien Gratadour, Fabrice Vidal, Fanny Chemla, Florian Ferreira, Nicolas Doucet, Sébastien Durand, Alexis Carlotti, Clément Perrot, Laura Schreiber, Matteo Lombini, Paolo Ciliegi, Emiliano Diolaiti, Josef Schubert, Richard Davies, "Joint MICADO-MAORY SCAO mode: specifications, prototyping, simulations and preliminary design," Proc. SPIE 9909, Adaptive Optics Systems V, 99090A (26 July 2016); doi: 10.1117/12.2231192

SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2016, Edinburgh, United Kingdom

Joint MICADO-MAORY SCAO mode: specifications, prototyping, simulations & preliminary design

Yann Clénet[a], Tristan Buey[a], Gérard Rousset[a], Eric Gendron[a], Simone Esposito[b], Zoltan Hubert[a], Lorenzo Busoni[b], Mathieu Cohen[c], Armando Riccardi[b], Frédéric Chapron[a], Marco Bonaglia[b], Arnaud Sevin[a], Pierre Baudoz[a], Philippe Feautrier[d], Gérard Zins[d], Damien Gratadour[a], Fabrice Vidal[a], Fanny Chemla[c], Florian Ferreira[a], Nicolas Doucet[a], Sébastien Durand[a], Alexis Carlotti[d], Clément Perrot[a], Laura Schreiber[e], Matteo Lombini[e], Paolo Ciliegi[e], Emiliano Diolaiti[e], Josef Schubert[f], and Richard Davies[f]

[a]LESIA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, Univ. Paris Diderot, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France
[b]Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125-Firenze, Italy
[c]GEPI, Observatoire de Paris, PSL Research University, CNRS, Univ. Paris Diderot, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France
[d]IPAG, Univ. Grenoble Alpes, 38000 Grenoble, France
[e]Osservatorio Astrofisico di Bologna, Via Ranzani 1, 40127-Bologna, Italy
[f]Max Planck Institute for extraterrestrial Physics, 85748 Garching, Germany

ABSTRACT

MICADO is the E-ELT first-light imager, working at the diffraction limit in the near-infrared. Multi-conjugate adaptive optics (MCAO) will be the primary AO mode of MICADO, driving the design of the instrument. It will be provided by MAORY, the E-ELT first-light AO module. MICADO will also come with a SCAO capability, jointly developed by MICADO and MAORY. SCAO will be the first AO mode to be tested at the telescope, in a phased approach of AO integration at the E-ELT.

We present in the following the MICADO-MAORY SCAO specifications, the current SCAO prototyping activities at LESIA for E-ELT scale pyramid wavefront sensor (WFS) and real-time computer (RTC), our activities on end-to-end AO simulations and the current preliminary design of SCAO subsystems. We finish by presenting the implementation and current design studies for the high-contrast imaging mode of MICADO, which will make use of the SCAO correction offered to the instrument.

Keywords: E-ELT, MICADO-MAORY, SCAO, specifications, design, simulation, prototyping, high contrast imaging

1. INTRODUCTION

1.1 MICADO

MICADO (Multi-AO Imaging Camera for Deep Observations) is the European Extremely Large Telescope (E-ELT) first-light imager, working at the telescope diffraction limit in the near-infrared.[1] This ten-year project has now officially started, with a kick-off meeting on October 6, 2015.

The consortium is lead by R. Davies, from the Max Planck Institute for Extraterrestrial Physics (MPE), and comprises, in addition to MPE, the Max Planck Institute for Astronomy (MPIA), the University Observatory Munich (USM), the Institute for Astrophysics of Göttingen, the Netherlands Research School for Astronomy (NOVA), the Institut National des Sciences de l'Univers (INSU, acting on behalf of LESIA, GEPI and IPAG), the A* Austrian partnership and the Instituto Nazionale di Astrofisica (INAF).

Further author information: send correspondence to Y. Clénet, e-mail: yann.clenet "at" obspm.fr

Adaptive Optics Systems V, edited by Enrico Marchetti, Laird M. Close, Jean-Pierre Véran, Proc. of SPIE Vol. 9909, 99090A
 · doi: 10.1117/12.2231192

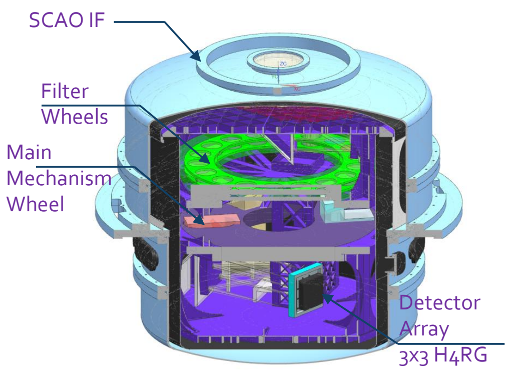

Figure 1. Concept of the MICADO cryostat, figuring its main mechanisms: the entrance focal plane wheel, the two filter wheels, the main mechanism wheel allowing to switch from an observing mode to another as well as the final focal plane array. The interface between the MICADO cryostat and the SCAO system is on top of the cryostat.

1.1.1 The MICADO observing modes

MICADO is being designed to provide four observing modes: imaging, astrometric imaging, spectroscopy and high contrast imaging.

MICADO will provide images in the near-infrared, between 0.8 and 2.4 μm. More than 30 broad-band and narrow-band filters will be available to cover the numerous science cases that such an E-ELT first-light instrument has to address. The default pixel size will be 4 mas, associated with a field of view of $\approx 50'' \times 50''$, allowing the instrument to work at the diffraction limit of the telescope in the H and K bands. A zoom mode, with a 1.5 mas pixel size over a field of view of $\approx 19'' \times 20''$, will be available to work at the telescope diffraction limit over the whole MICADO's bandpass as well as to increase the instrument astrometric precision (Fig. 2). Hence, MICADO will have a sensitivity similar to JWST with a six times better spatial resolution.

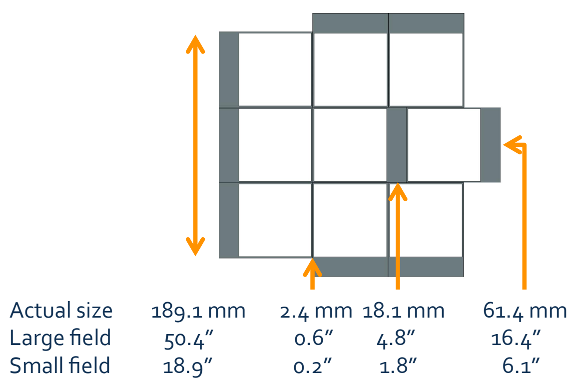

Figure 2. MICADO focal plane arrangement. MICADO focal plane will be made of 3×3 HAWAII 4RG detectors. Grey zones in the figure correspond to gaps due to detector housings. Sizes of the MICADO total field of view, of an individual detector as well as of the small and large gaps between the sensitive parts of the detector are given in actual size, as well as for the large and small pixel scales.

MICADO aims at bringing astrometry into mainstream. The instrument will be designed for that purpose: in a gravity-invariant configuration, it will make use of only fixed mirrors and specific calibration procedures will be developed. The goal is hence to reach 50 microarcsecond precision across the full MICADO field of view, which translates into 10 microarcseconds per year after 3-4 years of observation, i.e. 5 km/s at 100 kpc distance. Based on a study done using GeMS/GSAOI[2] data, Fritz et al.[3] estimate that absolute proper motion measurement errors with MICADO could be reduced down to 1 km/s at a distance of 100 kpc for 5 year observation baseline.

MICADO will also come with spectroscopic capabilities. Using two $3''$-long slits, gratings and order-sorting filters to separate the bandpass, this mode will reach a spectral resolution of $\approx$8000 for the 16 mas-long slit and $\approx$2500 for the 50 mas-long slit. It should be noted that the aforementioned spectral resolution are given for an object filling the slit. In the case of the 16 mas long-slit, an unresolved source will lead to a spectral resolution between 11000 in the J-band and 18000 in the K-band. Hence, the thin slit is rather devoted to point sources while the large one for compact resolved targets. Spectra will simultaneously cover either I/z/J bands or H/K bands.

The last observing mode of MICADO will be high contrast imaging, provided thanks to either the association of focal plane coronagraphs with Lyot stops, all included in the MICADO cryostat, or sparse aperture masking or vAPP masks (see Sect. 6). It will follow the angular differential imaging scheme by having MICADO's derotator working in pupil tracking mode.

1.1.2 Adaptive optics and MICADO

Multi-conjugate adaptive optics (MCAO) will be the primary AO capability for MICADO, for which MICADO will be optimized. This MCAO capability will be provided to MICADO by the MAORY module (see Sect. 1.2).

MICADO will also work in SCAO mode, with the scientific motivation to benefit from the best Strehl ratio for single, compact bright-enough objects (e.g. exoplanets, solar system science, bright AGNs, etc). This mode will be provided thanks to a dedicated natural guide star (NGS) wavefront sensor, associated real-time computer functionalities and dedicated calibration tools.

This SCAO capability will be as well provided to MICADO by the MAORY module. It will be available in MICADO stand-alone, i.e. MICADO not coupled to MAORY, if it comes out to be necessary in case of a delay of the MAORY development.

MICADO and MAORY agreed to have SCAO firstly tested at the telescope, in a phased approach of the integration of AO at the telescope.

1.2 MAORY

MAORY (Multi-conjugate Adaptive Optics RelAy) is the E-ELT first light multi-conjugate adaptive optics module.[4] It will enable near-infrared instruments attached to the E-ELT, in particular MICADO, to benefit from laser guide star adaptive optics assisted observing. This ten-year project has now officially started, with with a kick-off meeting in February 2016.

The consortium is lead by E. Diolaiti, from the Bologna Astronomical Observatory and comprises, in addition to the latter, the Arcetri Astrophysical Observatory, IASF of Bologna, the Padova Astronomical Observatory, the Brera Astronomical Observatory, the Capodimonte Astronomical Observatory and IPAG (represented by INSU).

In addition to MICADO, MAORY will be able to provide MCAO correction to a second instrument through a dedicated port.

The MAORY MCAO correction will be obtained by using the six E-ELT laser guide stars and three natural guide stars, each of these nine guide stars having in MAORY its dedicated WFS. The NGS WFSs will have two channels: one in the infrared for fast, low order sensing and one in the visible for slow reference sensing. The field of view covered by these NGS WFSs is a ring with an outer diameter of $2.6'$ and an inner diameter avoiding to vignette MICADO.

The MAORY MCAO correction will be also obtained by implementing in the AO module post-focal deformable mirrors, one as a baseline, two as a goal.

The MAORY performance requirement in the $50''$ MICADO field of view is to reach a Strehl ratio of 30% at K with a 50% sky coverage, with a goal of a Strehl ratio of 50% at K, still with a 50% sky coverage.

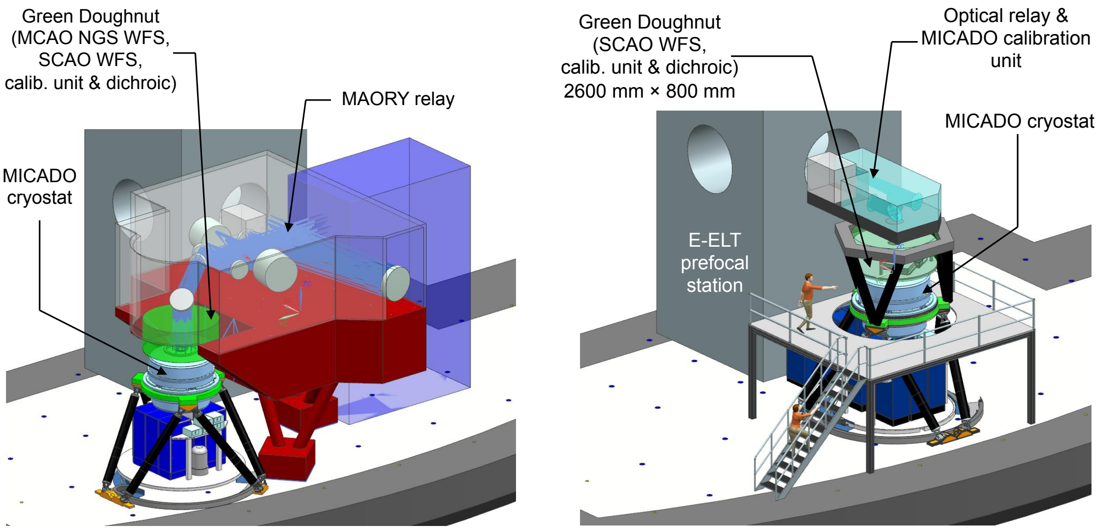

Figure 3. Left: Baseline implementation of MICADO+MAORY at the E-ELT. Right: Possible implementation of MICADO stand alone at the E-ELT.

1.3 MICADO-MAORY SCAO

SCAO will be physically implemented in the so-called Green Doughnut. This volume is at the interface between MICADO cryostat and the MAORY or stand-alone optical relay required to transport the light to MICADO (Fig. 3). This cylinder of 800 mm high and 2.6 m in diameter will host the SCAO subsystems, i.e. SCAO WFS, calibration unit and dichroic, as well as the three MCAO NGS WFSs.

SCAO will be a joint development by MICADO and MAORY.

MICADO has the management responsibility of this development as well as the system engineering responsibility, with system engineering tasks (specifications, simulations, AIT plan, etc) being jointly carried out. MICADO is also in charge of the SCAO RTC and SCAO calibration unit.

MAORY has a major role in the design and technical implementation by being responsible of the Green Doughnut and the SCAO WFS.

2. SCAO SPECIFICATIONS

We list in the following the general specifications or functionalities that SCAO shall comply with:

- SCAO shall be able to be operated in the MAORY baseline and in the stand-alone paths, and designed accordingly
- SCAO shall be available for the different MICADO observing modes
- SCAO shall supports non-sidereal tracking
- SCAO shall supports MICADO secondary guiding using position of sources on the MICADO detector
- SCAO shall be operated on-axis. This main reasons for this specification are 1) that SCAO main driver is high contrast imaging, 2) that it leads to a simpler and more robust design (since a limited field of view has to be transmitted to the WFS and the displacement requirement for the WFS in that configuration is limited). The scientific target will be observable in this configuration by taking advantage of the rather large MICADO field of view. As a consequence, spectroscopy with SCAO will only be possible on-axis, which is acceptable given the anisoplanatism affecting off-axis targets.

We list now the main technical specifications for SCAO:

- the expected on-axis Strehl ratio in the K-band is 60% for V $<$ 12 guide star, at a zenith angle smaller than 30° and under median seeing conditions
- the maximum WFS bandpass will 0.45 - 0.9 μm. The MCAO laser guide star dichroic being located upstream the SCAO system, the exact lower cut-off wavelength will be discussed with MAORY, depending if a notch filter at 589 nm is possible for this dichroic or if a strict cut is done by the dichroic below 589 nm. The exact upper cut-off wavelength will be discussed with MICADO and its science team, depending if a share of the photons between 0.8 and ≈0.9 μm is possible or not.
- the AO patrol field radius will be from 2" to 3"
- the maximum size of the guiding source will be 1" in diameter
- SCAO shall not vignette the MCAO NGS WFS patrol field of view
- SCAO shall not vignette the MICADO field of view

3. SCAO PROTOTYPING

At LESIA, we are making prototyping of various SCAO subsystems to master in advance issues we will face at the E-ELT. Prototyping concerns pyramid WFS, RTC with the goal of a global SCAO prototype.

3.1 Pyramid WFS prototyping: PYRCADO

We are currently working on a pyramid WFS prototype, PYRCADO, with the aim of addressing ELT-scale issues in wavefront sensing:

- high number of phase measurements,
- impact of atmospheric dispersion,
- pupil stabilization to be included in the sensor,
- hexagonal shape of the pupil with probable side effects,
- primary mirror segmentation,
- large spiders

PYRCADO is implemented on our AO test bench Sésame at LESIA and includes the following components (Fig. 4):

- a spatial light modulator (SLM) to emulate both turbulence and high-order compensation
- additional phase screens
- a 31-actuator bimorph deformable mirror to precompensate the turbulence before the pyramid WFS
- a PI tip-tilt mirror for the modulation
- a zoom for selectable F-number on the pyramid (F/50, F/150)
- a 10 Gb Ethernet 1k^2 pixel CCD

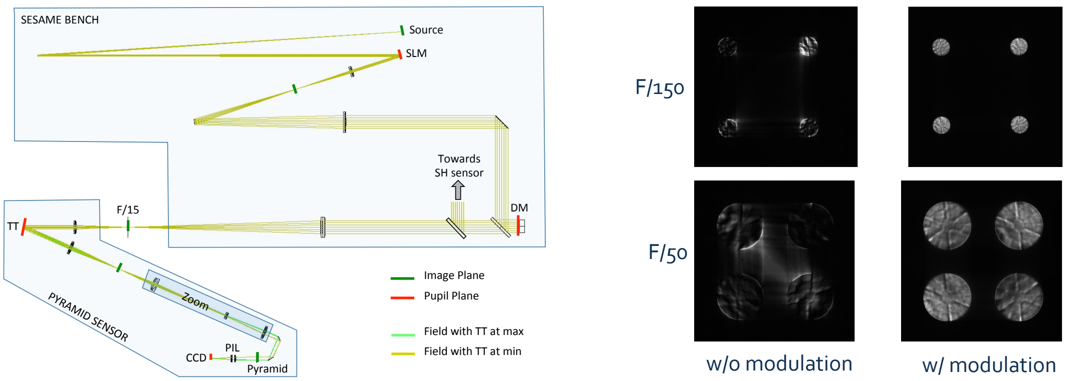

Figure 4. Left: Implementation of our pyramid prototype on our Sésame AO test bench. Right: Examples of pyramid pupil images both with and without modulation and for the two beam F-numbers, F/150 and F/50.

This set-up has been designed to provide us with an E-ELT like configuration, both in terms of pyramid pupil diameter, roughly equal to 100 pixels, and in terms of data transfer, with the 10 Gb Ethernet camera (Fig. 4).

We are finishing the fine calibration of the modulation, in terms of frequency, amplitude in X and Y, offset in X and Y and phase difference between X and Y.

We contemplate in the near future to implement in PYRCADO a K-mirror prototype since the issue of pupil derotation is crucial for wavefront sensing at the E-ELT scale. Derotation by software or by hardware, with a K-mirror, are the two possible solutions. While we think that a pure software solution could be risky (accuracy of the solution in low flux case, load of the RTC with a control matrix to be updated on the fly every few seconds or few tens of seconds), we propose to evaluate the K-mirror solution by building such a prototype following the tight requirements for such a device at the E-ELT scale.

We also plan to implement a polychromatic pyramid WFS, to get closer to the final SCAO system set-up. A double pyramid has been already proposed as a solution.[5] Alternative are under studies.

In the end, we plan to integrate the final version of this pyramid prototype inside our SCAO prototype (see Sect. 3.3).

3.2 RTC prototype

Our SCAO RTC prototyping is achieved in the framework of the Green Flash project.[6] This H2020 project, lead by D. Gratadour at LESIA and gathering LESIA, University of Durham and two SME (Microgate in Italy, PLDA in France) aims at prototyping an E-ELT MCAO-scale RTC, testing the various possible architectures and hardware.

At LESIA, we made progress on the following points:

- concerning the real-time box activities, we implemented a multi-GPU version of the real-time pipeline, which includes pixel calibration, centroiding and MVM. As a result, in a MAORY-scale case (i.e. about 15000 commands and about 10000 slopes), we achieve 500 Hz using two GPU per WFS, this result being scalable to 1 kHz with four GPU per WFS. Using our end-to-end AO simulation platform COMPASS (see Sect. 4), we have also validated the pyramid pipeline computation (including pixel misregistration handling, centroiding, MVM). The validation of the Shack Hartmann pipeline computation is on-going

- concerning the soft real-time box activities, we can now perform the interaction matrix inversion in about 2 seconds in SCAO case. We have also developed smart interconnection based on FPGA boards in order to optimize the access to the GPU memory

- we have also connected our RTC to COMPASS, with a 10 GbE UDP connection, to set up a test bed for RTC checker.

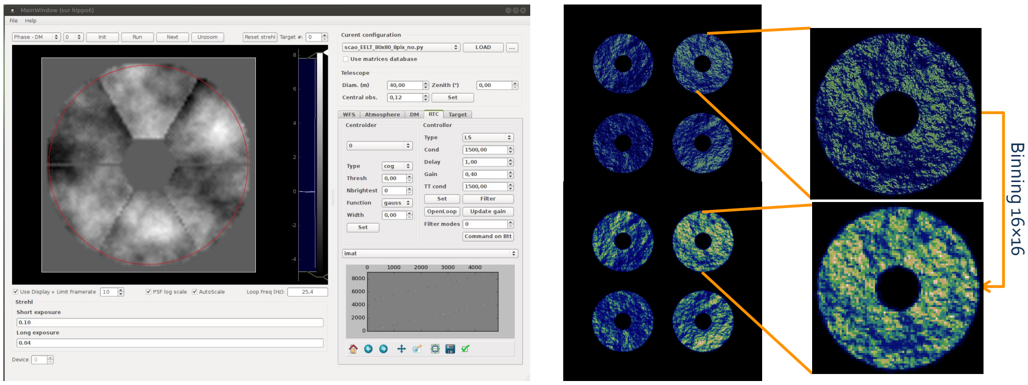

Figure 5. Left: COMPASS GUI as it appears for a E-ELT simulation using the E-ELT segmented pupil. Right: Illustration of E-ELT scale pyramid pupils in our high resolution pyramid model. Top: high resolution pupil maps (4096×4096 array). Bottom: binned pupil images (256×256 array). Left: full array, figuring the four pyramid pupils. Right: Zoom on the upper right pyramid pupil.

The progress made by the others partners of Green Flash are the following:

- at Durham University, a study of Xeon Phi and/or FPGA for the real-time box is on-going
- PLDA is making a GPU direct development to allow direct access to the GPU memory through PCIe bus from FPGA
- Microgate is currently designing two custom FPGA boards, one for communication and one for computation

The next milestones of the Green Flash development is to make a first release of the SCAO RTC prototype next July and to have it fully ready by next October. Then, a first release of the MCAO RTC prototype is scheduled for October 2017, with a fully ready prototype in October 2018.

3.3 Towards SCAO prototyping and AIT

Our plan is to integrate the aforementioned prototypes (WFS, RTC) together with a high order (4k actuators) deformable mirror we plan to buy in order to build a SCAO system prototype.

Our first goal is to perform an AO closed loop in lab at the E-ELT scale to be faced and to find solutions for the issues we will have to cope at the E-ELT, such as measurement issues (pupil registration, diffraction outside pupils, polychromatism, etc), data transfer between the camera and the RTC or between the RTC and the deformable mirror, real-time calibration of the loop (update of CM, pupil tracking, etc), etc.

A second goal is to prepare the SCAO AIT during which we will have to cope with similar issues to those aforementioned but with the final SCAO subsystems.

A joint AIT plan between MAORY and MICADO, able to accomodate both baseline and stand alone developments, is currently under study.

4. END-TO-END AO SIMULATIONS

At LESIA, we are performing our end-to-end AO simulations with the GPU-based COMPASS platform.[6,7] In the recent years, we have worked to major upgrades of the platform.

Originally conceived as a Yorick plugin bound to the NVIDIA CUDA toolkit, we modified the platform to make it now a Python plugin bound to CUDA. It required to recoded all the high level software involved in the initialization of the simulation as well as to code a new API between the Python layer and the C++ layer.

We have implemented E-ELT specific functionalities, such as the E-ELT segmented pupil or the E-ELT M4 influence functions, using a package delivered by ESO (Fig. 5).

Table 1. GPU occupancy and simulation execution speed when parallelizing the modulation computation of different numbers of GPUs.

		1 GPU	2 GPU	4 GPU	8 GPU
16 modulation points, modulation amplitude = 3 λ/D	GPU occupancy	99	99/70	99/50×3	99/30×7
	Simulation rate (iteration/s)	4.4	7.5	10.13	9.32
32 modulation points, modulation amplitude = 5 λ/D	GPU occupancy	99	99/80	99/70×3	99/40×7
	Simulation rate (iteration/s)	2.35	4.3	6.76	7.58
64 modulation points, modulation amplitude = 10 λ/D	GPU occupancy	99	99/99	99/80×3	99/60×7
	Simulation rate (iteration/s)	1.22	2.31	4.05	5.5

We have also implemented a new, high resolution, pyramid model in addition to a YAO-like, low resolution pyramid model (Fig. 5). This model accounts as in reality for the diffractive effects between neighboring pupils. It makes use of a large resolution support for the initial phase screen (before binning and gradient computation) to sufficiently sample the turbulence and to allow for large modulation amplitudes to bootstrap the correction. Our model also allows a modulation amplitude with an amplitude non equal to an integer number of pixel.

We have implemented multi-GPU parallelisazion of the modulation, distributing the modulation point computations on several GPUs. Using Kepler GPUs with 12 Go RAM for an E-ELT SCAO simulation with a 80×80 pyramid and a piezo-stack deformable mirror (4096×4096 pupil maps), going from one GPU to 8 GPUs allows us to gain a factor almost 5 in the simulation execution speed (Table 1). We have also optimized the simulation scripting by implementing a data base saving critical data of the simulation (interaction matrix, command matrix, turbulence-related arrays, etc), preventing us from unnecessary reinitialisations. In a data mining fashion, we have also set up a data server allowing to explore the simulation results vs. the simulation parameters.

It is to be noted that our SCAO colleagues in Arcetri are using their home-made Passata code for the end-to-end AO simulations.[8]

5. PRELIMINARY DESIGN

We present below the design work that has been done on two SCAO subsystems: the Green Doughnut and the SCAO calibration unit.

5.1 The Green Doughnut

The Green Doughnut is the volume at the interface between MICADO and MAORY in which will be installed the different natural guide star WFS, the one for SCAO as well as the three ones for MCAO. The Green Doughnut system analysis is starting between our teams in LESIA, for MICADO, and in Arcetri, for MAORY.

We present in Fig. 6 a preliminary design proposed by MAORY. To minimize the interface between the SCAO WFS and the MCAO NGS WFS, it is based on a slice architecture in which each WFS has its owned reserved slice, the MCAO NGS WFS being separated by 120°. SCAO resides in the upper part of the Green Doughnut while the MCAO NGS WFS are located at the lower part of it in order to limit the NGS pick-off size (and therefore maximize the MAORY sky coverage). MCAO and SCAO WFS are mounted on linear stages to patrol the field of view as already successfully implemented for FLAO at LBT and designed for ERIS at VLT.[9,10] The WFS and the SCAO dichroic are designed deployable. In this concept, the implementation of the SCAO calibration unit in the Green Doughnut is still under study. In the next future, we plan to iterate on this design for a closer match of the SCAO specifications.

5.2 The SCAO calibration unit

Hosted in the Green Doughnut, the SCAO calibration unit aims at calibrating the SCAO functions. We also plan to use it to perform close loop functionality tests at the telescope directly with MICADO without using the telescope M4/M5 mirrors. This SCAO calibration unit will inherit from the bench we plan to develop for the SCAO AIT. The SCAO calibration unit is composed of:

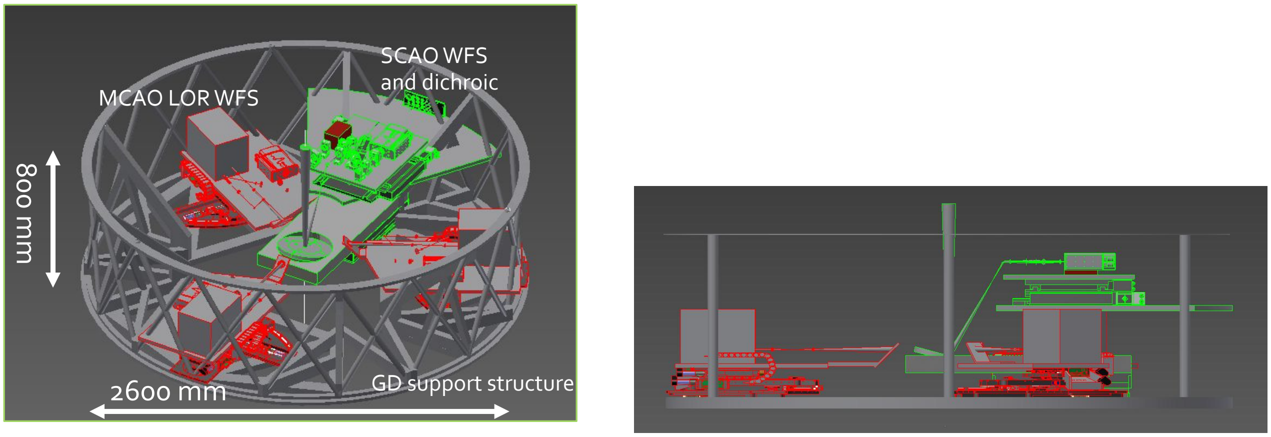

Figure 6. Preliminary design of the Green Doughnut.

- infrared and visible calibration sources to perform interaction matrix, to check the image quality and the focus on the MICADO focal plane, to calibrate the non-common path aberrations, to control the close-loop functionality, for falt-fielding the WFS camera
- a low order deformable mirror to calibrate the non-common path aberrations and control the close-loop functionality
- pupil masks
- a turbulence simulator for the control of the close-loop functionality (TBC)

We show in Fig. 7 the current design of the SCAO calibration unit. It follows a two-level architecture. In the bottom part, one finds the low order deformable mirror, pupil masks, alignment tools, as well the artificial sources. The volume of this part is mainly driven by the low order deformable mirror pupil size of 1 inch. In the upper part, one finds the optical relay allowing to copy the intermediate focal point to the MICADO entrance focal plane. In the next future, we plan to iterate on this design to make it fit inside the architecture of the Green Doughnut.

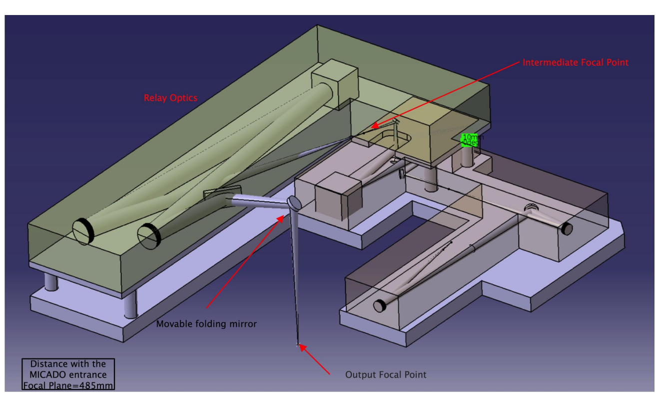

Figure 7. Preliminary design of the calibration unit.

6. HIGH CONTRAST IMAGING

High contrast imaging is one of the specified observing mode of MICADO. It will make use of the SCAO mode correction.

6.1 Implementation

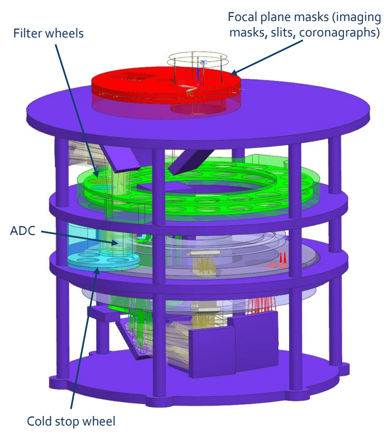

Figure 8. Structure of the MICADO cryostat interior, featuring the different wheels used for coronagraphy: the entrance focal plane wheel at the top, the filter wheels and the cold stop wheel.

High contrast imaging will either consist in focal plane coronagraphy or pupil plane coronagraphy. Focal plane coronagraphy will be obtained thanks to Lyot and/or vector vortex masks placed in a wheel located close to the entrance focal plane of MICADO (where are also located imaging masks and slits for spectroscopy). These masks will be associated to filters available in two filter wheels as well as Lyot stops located in the cold stop wheel close to a pupil plane. One should note that this coronagraphic mode will not benefit from atmospheric dispersion correction since the ADC in the MICADO cryostat is located after the MICADO entrance focal plane, between the filter wheel and the cold stop wheel. This cold stop wheel will also host masks for sparse aperture masking coronagraphy.

Pupil plane coronagraphy may also be available, making use of vector apodized phase plate[11] placed in the MICADO cold stop wheel.

6.2 Design studies

We have started the design studies of the high contrast imaging mode, looking first at the impact of the lack of ADC for the focal plane coronagraphy. We computed the offset in position of the PSF between the two ends of SPHERE/VLT[12] filter full width at half maximum, with respect to the zenith angle. We computed as well as the corresponding images for the broad band filters (Fig. 9). As a conclusion, cononagraphy will be limited to narrow-band filters at J and H wavelengths and to medium-band filters at K wavelengths.

We have also studied the optimization of the Lyot stop size, using a contrast-like criteria, based on contrast divided by the transmission of the planet flux and averaged over the region between 7 and 20 λ/D. Hence we show in Figure 10 the evolution of this criteria for different Lyot mask radius, ranging from 2 λ/D to 6.5 λ/D, with respect to the Lyot stop transmission (directly related to the Lyot stop size). For the 2 and 5 λ/D radius Lyot masks, our contrast-like criteria is found to be optimal at Lyot stop transmission around 60%.

7. CONCLUSION

The next important milestones of the MICADO-MAORY SCAO development are related to both project schedules. Hence, MICADO plans an internal interface and system requirements review in April 2017 and a preliminary design review in October 2018. MAORY plans on its side an internal interface and system requirements review in October 2016 and a preliminary design review in February 2018.

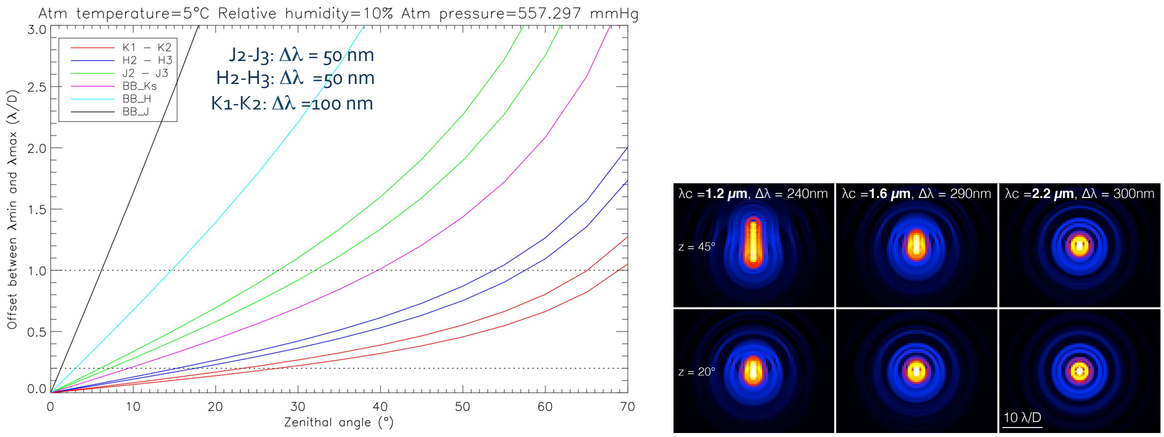

Figure 9. Left: sensitivity to the atmospheric dispersion measured as the offset between the ends of VLT/SPHERE filters with respect to the zenith angle. Right: corresponding images for the broad band filters.

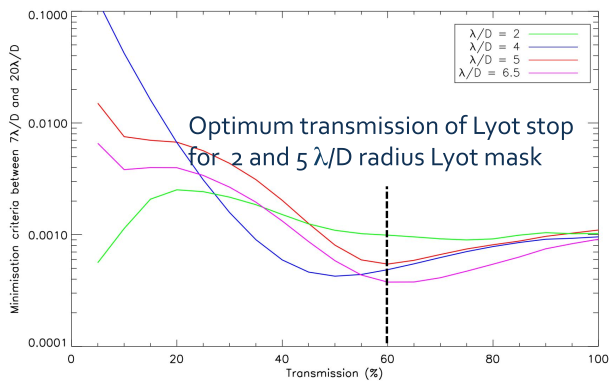

Figure 10. Evolution of a minimization criteria (see text) with respect to the Lyot stop transmission, for different Lyot mask sizes.

REFERENCES

[1] Davies, R., Schubert, J., Hartl, M., et al., "MICADO: first light imager for the E-ELT," in [*Ground-based and Airborne Instrumentation for Astronomy VI*], Evans, C. J., Simard, L., and Takami, H., eds., *Proc. SPIE* **9908** (2016).

[2] Rigaut, F., Neichel, B., Boccas, M., et al., "Gemini multiconjugate adaptive optics system review - I. Design, trade-offs and integration," *MNRAS* **437**, 2361 (2014).

[3] Fritz, T., Kallivayalil, N., Carrasco, R., et al., "Astrometry with MCAO at Gemini and at ELTs," *AO4ELT4 conference proceedings* (2015).

[4] Diolaiti, E., Ciliegi, P., Abicca, R., et al., "MAORY adaptive optics module for E-ELT: instrument design overview," in [*Adaptive Optics V*], Marchetti, E., Close, L. M., and Véran, J.-P., eds., *Proc. SPIE* **9909** (2016).

[5] Diolaiti, E., Tozzi, A., Ragazzoni, R., et al., "Some novel concepts in multipyramid wavefront sensing," in [*Adaptive Optical System Technologies II*], Wizinowich, P. L. and Bonaccini, D., eds., *Proc. SPIE* **4839**, 299 (2020).

[6] Gratadour, D., Dipper, N., Biasi, R., et al., "Green Flash: energy efficient real-time control for AO," in [*Adaptive Optics V*], Marchetti, E., Close, L. M., and Véran, J.-P., eds., *Proc. SPIE* **9909** (2016).

[7] Ferreira, F., Gendron, E., Rousset, G., et al., "Deriving comprehensive error breakdown for wide field adaptive optics systems using end-to-end simulations," in [*Adaptive Optics V*], Marchetti, E., Close, L. M., and Véran, J.-P., eds., *Proc. SPIE* **9909** (2016).

[8] Agapito, G., Puglisi, A., and Esposito, S., "PASSATA: object oriented numerical simulation software for adaptive optics," in [*Adaptive Optics V*], Marchetti, E., Close, L. M., and Véran, J.-P., eds., *Proc. SPIE* **9909** (2016).

[9] Esposito, S., Riccardi, A., Fini, L., et al., "First light AO (FLAO) system for LBT: final integration, acceptance test in Europe, and preliminary on-sky commissioning results," in [*Adaptive Optics Systems II*], Ellerbroek, B., Hart, M., Hubin, N., and Wizinowich, P., eds., *Proc. SPIE* **7736**, 773609 (2010).

[10] Riccardi, A., Antichi, J., Quirós-Pacheco, F., et al., "The NGS Pyramid wavefront sensor for ERIS," in [*Adaptive Optics Systems IV*], Marchetti, E., Close, L. M., and Véran, J.-P., eds., *Proc. SPIE* **9148**, 91483D (2014).

[11] Snik, F., Otten, G., Kenworthy, M., et al., "Coronagraphy with two PSFs," in [*Adaptive Optics V*], Marchetti, E., Close, L. M., and Véran, J.-P., eds., *Proc. SPIE* **9909** (2016).

[12] Beuzit, J.-L., Feldt, M., Dohlen, K., et al., "Sphere: a 'Planet Finder' instrument for the VLT," in [*Ground-based and Airborne Instrumentation for Astronomy II*], McLean, I. S. and Casali, M. M., eds., *Proc. SPIE* **7014**, 701418 (2008).