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► **To cite this version:**

Yann Clenet, Tristan Buey, Eric Gendron, Sonia Karkar, Fabrice Vidal, et al.. MICADO SCAO: to be or not to be... in MAIT. Adaptive Optics for Extremely Large Telescopes 7th Edition, 2023, 10.13009/AO4ELT7-2023-099 . hal-04402874

**HAL Id: hal-04402874**

**<https://hal.science/hal-04402874>**

Submitted on 18 Jan 2024

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## MICADO SCAO: to be or not to be... in MAIT

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### ABSTRACT

MICADO is the ELT first light instrument, an imager working at the diffraction limit of the telescope thanks to two adaptive optics (AO) modes: a single conjugate one (SCAO), available at the instrument first light and developed by the MICADO consortium, and a multi conjugate one (MCAO), developed by the MORFEO consortium. The MICADO project started the final design review process two years ago, in Feb. 2021, and has

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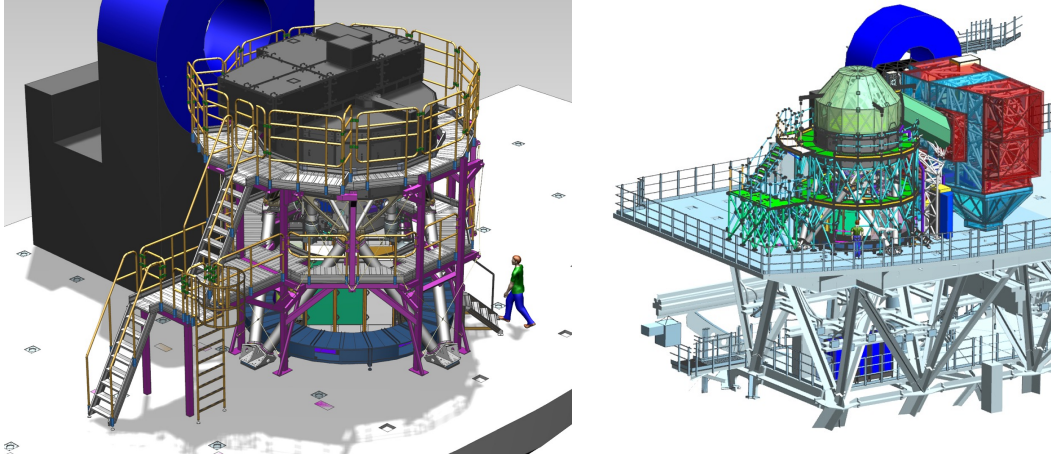


Figure 1. Left: MICADO at the telescope in its standalone configuration, i.e. with the SCAO module alone and a dedicated optical relay. Right: MICADO at the telescope, coupled with MORFEO

been through four successive review sessions since then, covering the different MICADO subsystems, including the SCAO module.

This final design review process should come to an end this year in 2023, allowing to enter officially into the manufacturing, assembly, integration and tests phase. Though, despite the decision of a delta FDR for few MICADO parts, the FDR board and ESO acknowledged after the FDR4 that "the review of the final design can be considered complete for the majority of the MICADO sub-systems" (including the SCAO module) and agreed that MICADO can start manufacturing.

Manufacturing, integration and related tests have actually already started for several SCAO subsystems, in particular to validate the design of several parts by prototyping at "full scale". This strategy allows to optimize the project resources and to save time on the planning. It concerns its K-mirror (allowing to compensate for the pupil derotation), its "WFS core" (i.e. the pyramid optical component, the WFS camera and the pupil imaging lenses that compensate for the axial pupil movements), its field selector, its modulation system, its real-time computer, its instrument control software, but also more basically its various motors.

This contribution presents the MAIT activities of those various components, starting from the critical ones, followed by the core ones and then all the other. This contribution finishes by presenting the next steps of the SCAO MAIT plan.

**Keywords:** ELT, MICADO, SCAO, final design, prototyping, MAIT

## 1. AN INTRODUCTION TO MICADO

The MICADO imager is the ELT first light instrument [3]. Working in the near-IR ( $0.8\text{-}2.4\ \mu\text{m}$ ) at the ELT diffraction limit, it will offer four observing modes:

- Standard imaging: with  $1.5$  &  $4$  mas pixel scales, the corresponding FoV will be  $19$  &  $51$  arcseconds<sup>2</sup>. More than 30 broad-band & narrow-band filters will be available.
- Astrometric imaging: it drives MICADO design, with a gravity invariant implementation, a fixed mirror optical design, state-of-the-art ADC and dedicated astrometric calibration and data pipeline.
- High contrast imaging [1, 4]: it will use the central detector and will be enabled via a classical configuration of focal plane coronagraphs and Lyot stops, as well as pupil plane vAPP coronagraphs and sparse aperture masking. Pupil tracking will be available for angular differential imaging.
- Slit spectroscopy: it will provide coverage of a wide wavelength range simultaneously (J:  $1.15\text{-}1.35\ \mu\text{m}$ , HK:  $1.52\text{-}2.45\ \mu\text{m}$  or IzJ:  $0.85\text{-}1.56\ \mu\text{m}$ ) at a resolution of 20000 on faint compact or unresolved sources. Three slits will be available:  $3''\times 16$  mas (IzJ),  $15''\times 20$  mas (J & HK),  $3''\times 48$  mas (IzJ & HK).

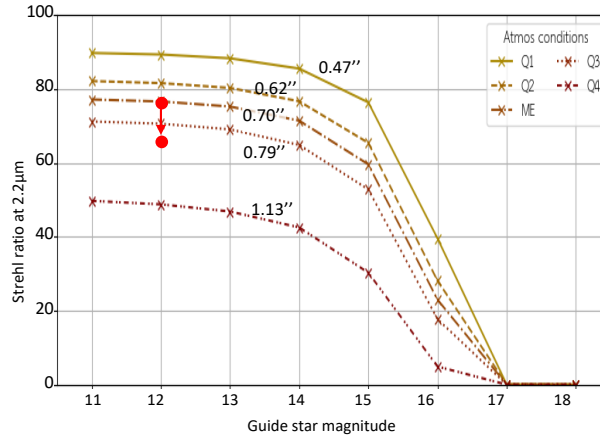


Figure 2. "SCAO loop only" performance (i.e. including fitting, bandwidth, noise propagation, aliasing, atmospheric differential pistons error terms) with respect to the guide star R magnitude, at various seeing values, together with performance including instrumental error terms (red dot under the red arrow) under the specification conditions.

MICADO will know two successive phases:

- the standalone phase (Fig. 1 left), during which it will benefit only from a SCAO correction, developed within the consortium. A passive optical relay is developed by the consortium to feed the instrument. MICADO will be installed on the Nasmyth platform A of the ELT.
- a so-called "M&M" phase (Fig. 1 right), after the arrival of MORFEO at the telescope, few years after the ELT and MICADO first light. The instrument will then benefit from both the SCAO and a MCAO correction, the latter being developed by MORFEO together with an active optical relay [2]. In this phase, MICADO and MORFEO will be on the ELT Nasmyth platform B, requiring to move MICADO (including SCAO) from platform A to B. The SCAO module is not modified when MORFEO is installed: the space envelop, the interlock system, and the software configuration are accounting for MORFEO from the MICADO first light.

MICADO current planning is the following:

- 11/2018: PDR
- 04/2021 - end of 2023: FDR sessions
- 12/2027: PAE
- end of 2028: commissioning
- mid 2029: operations

Early 2023, we have passed the 4<sup>th</sup> FDR session. The FDR board report stated after this session that: "the review of the final design can be considered complete for the majority of the MICADO sub-systems, with no showstoppers over the design but a few actions, most of them being considered normal work and a few being critical ones". The FDR board and ESO agreed then that MICADO MICADO can start procurement and manufacturing for these sub-systems. Hence, despite the FDR is not officially passed, MICADO, and in particular the SCAO module, is starting the MAIT process. It was advertised in [live YouTube event](#) on May 12th, 2023.

## 2. THE MICADO SCAO: MAIN SPECIFICATIONS AND FEATURES

The MICADO SCAO system is a pyramid-based AO system, sensing the light in the visible from 600 to 960 nm (fed with 100% of the light in this bandpass). The pyramid pupils are imaged on the CCD220 detector of the ESO ALICE camera in 96×96 pixels (leading to a subaperture size of 0.40 m). The total number of WFS

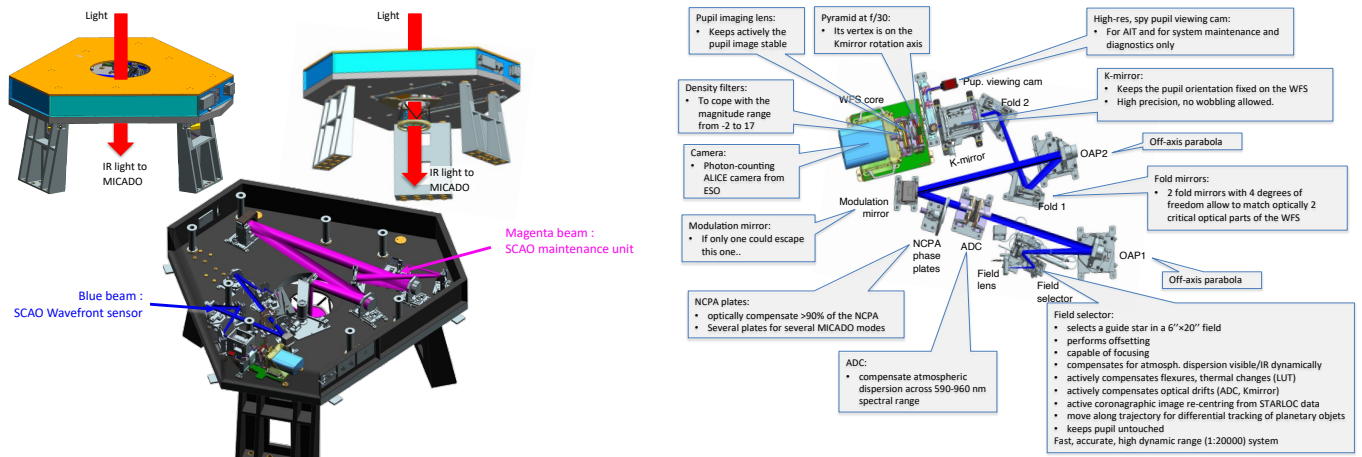


Figure 3. Left: top and bottom views of the SCAO module in its on-sky configuration and top view of the SCAO module with its baffles removed, showing the wavefront sensor and the calibration unit paths. Right: the wavefront sensor components and their functions.

measurements is then made of about 26000 elements. The pupil will be stabilized in position and clocking. The SCAO system will make use of the ELT M4 and M5 mirrors and the number of controlled modes will be from 2 to 4000. The loop will be running at up to 500 Hz.

The SCAO system will be able to use a natural guide star with a R magnitude ranging from -1.5 (Betelgeuse) to 16.5. It will also be able to close the loop on extended objects, up to 1 arcsec in diameter (e.g. Solar system satellites) and will support differential tracking up to 100 arcsec/hour. The guide star will be selectable in a 6"×20" patrol field.

In terms of AO performance, the MICADO SCAO specification is 60% of Strehl ratio at 2.2  $\mu\text{m}$ , at 30° from zenith with a  $m_R=12$  reference star, under medium seeing (0.702"), excluding vibrations and windshake. Fig. 2 shows the curves of pure AO performance (from end-to-end simulations made with our COMPASS platform) together with the estimated final performance (i.e. including instrumental error budget terms) with respect to these specifications.

Finally, for regular tuning of NCPA and aging diagnostics, the SCAO module will include a dedicated calibration/maintenance unit with sources and a low order adapted ALPAO DMX37 mirror.

The main sub-systems of the SCAO module are: a pyramid-based wavefront sensor, a calibration unit, a dichroic plate assembly, a support structure, a real-time computer, a control software. The left figure of Fig. 3 shows different views of the SCAO module and these different sub-systems while the right figure shows the different components of the SCAO wavefront sensor together with their different functions.

### 3. THE SCAO MAIT: THE CRITICAL COMPONENTS FIRST

Our development plan had identified two critical components: the field selector, ensuring several essential functions (see Fig. 3 right), and the K-mirror, in charge of the pupil stabilisation in rotation. We decided to start prototyping at the final scale those two elements at the early stage of the project, even before PDR. We give below details of these prototypes.

#### 3.1 The SCAO field selector

The field selector is made of 2 plane mirrors, supported by a movable mechanical structure. The mechanical structure will move and rotate the mirrors together in such a way that the beam will be displaced all across the patrol field, in a 2D fashion. The field selector also has the capability of introducing some amount of defocus between input and output beams.

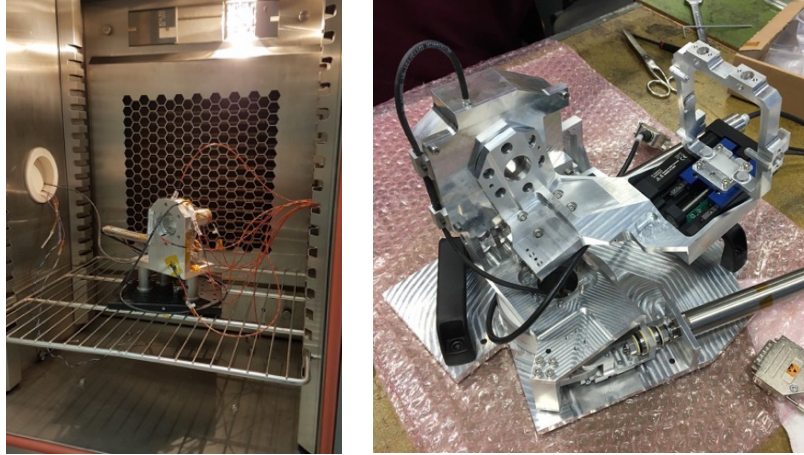


Figure 4. The SCAO field selector. Left: Prototype axis under testing in thermal chamber. Right: Final mechanics assembled and verified (not yet blackened).

Its complex positioning system needed multiple iteration in order to reduce mechanical imperfections such as hysteresis, drift, and positioning precision. Besides its mechanics, PLC tuning for controlling its speed, differential tracking and closed loop is a complex task. Hence we started a prototyping phase in 2016, following a protoflight strategy: the prototype has been manufactured at scale and the design has been adapted according to the test results so that the final prototype is the version of the field selector to be integrated in the SCAO module.

During this prototyping phase, we demonstrated an positioning accuracy better than 1 mas on a single axis as well as the fulfillment of the speed specification, on a single axis too. Thermal requirements have also been validated with the according tests in thermal chamber.

Today, the final mechanics of the field selector has been manufactured, mounted, adapted (according to final adjustments) and verified. The optics has also been procured. We have started the fine tuning of the 3-axis servo system, mainly consisting in correctly parametrizing the driving of the stages. Full testing and calibration will soon follow.

### 3.2 The SCAO K-mirror

The K-mirror consists of a prism with 2 reflecting surfaces at  $120^\circ$  and a flat mirror. There are two separate alignments to be made for the K-mirror alignment:

- The internal alignment, consisting in correctly positioning the 3 reflecting surfaces with respect to the mechanical axis of rotation (so that any image anywhere rotates around a fixed centre located on the axis of rotation).
- The external alignment, consisting in adjusting the relative positioning between the mechanical axis of rotation and the external world (field and pupil).

The internal alignment of the K-mirror is performed on a separate dedicated bench, developed at the end of 2017. The principle of this bench is to look through the K-mirror simultaneously with two fixed cameras using beam splitters: one camera looking at a source at infinity (where the pupil is), the other one looking at a source  $\sim 30$  mm from the K-mirror entrance (field). The degrees of freedom of the K-mirror's mirrors have been optimised so that two of them primarily affect the pupil, while the other two affect mostly the field. A special computer-assisted alignment procedure allows rapid convergence to the solution, which consists on the one hand in finding the perfect internal alignment and on the other hand in a precise optical determination of the position of the mechanical axis of rotation by placing the sources directly on it. The procedure can be iterated as many times as required, resulting in a very high level of accuracy. Our final tests show that the residual epicycloidal motion, typical of slightly misaligned K-mirrors, is eliminated to such an extent that it has become smaller than the size of the diffraction pattern in the visible for both the field and the pupil.

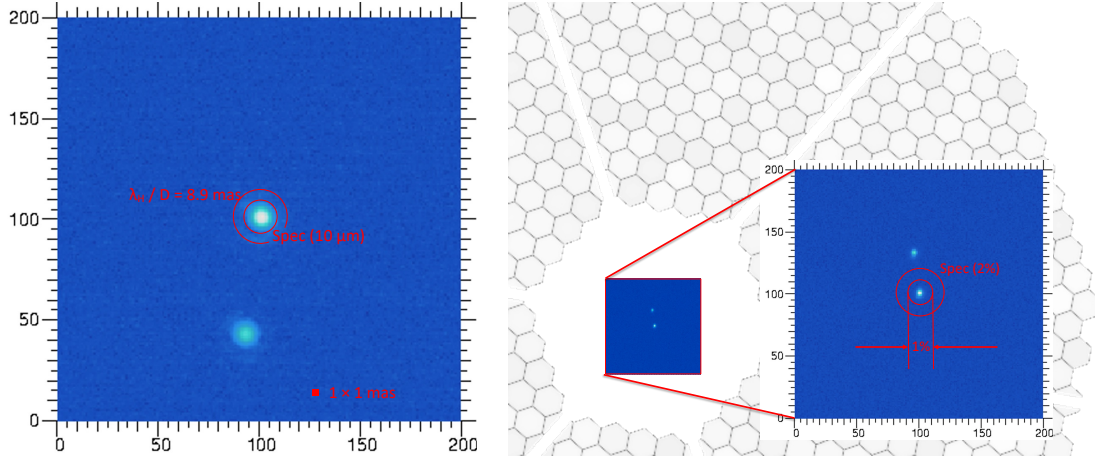


Figure 5. K-mirror test images. Left: Image taken by the field camera. Right: Image taken by the pupil camera. See text for details.

Figure 5 shows on the left an image taken by the field camera on our bench. The source consists of two diffraction-limited spots: this duplicity is required by our specific alignment procedure. The brightest spot is the main one, located on the mechanical axis of rotation. The large red circle indicates the size of the diffraction in the infrared, and the inner circle the specification. A full rotation of the K-mirror results in a movement of the bright spot that does not exceed  $\pm 5 \mu\text{m}$ , i.e. well within the specification. Figure 5 shows on the right the same type of image for the pupil camera. In this case the specification for the spot movement is expressed as a percentage of the pupil diameter. The two red circles show the specification ( $\pm 1\%$ , i.e. 2% in diameter), while our tests demonstrate that the movement of the spot remains well within a range of less than 0.5% in diameter for a full revolution of the K-mirror.

#### 4. THE SCAO MAIT: THE CORE COMPONENTS IN SECOND

Our development plan includes the procurement of the core elements of the SCAO module, those that allow to run an AO loop, and in practice to validate the AO control functions. They are the RTC and the so-called wavefront sensor core.

##### 4.1 The RTC

The SCAO hard real-time core (H-RTC) is based on the COSMIC platform [5]. Following today's ESO IT standards, it will be made of a DELL PowerEdge R7525 server with  $2 \times 24$ -core CPUs (AMD EPYC 74F3 3.2GHz, 196 GB) and of three NVIDIA A100 GPU (80 GB memory). 7kW are expected at max as peak power. The real-time pipeline is already implemented and running with the following features: GPU Direct acquisition of RTMS flux (tested against compass simulation & ESO WFS simulator, image calibration & pixels extraction, modal reconstruction including modal gains compensation, temporal filtering and disturbances injection

The SCAO soft real-time cluster (S-RTC) is based on the ESO RTC Toolkit (RTC Tk). The latter provides a definition for the hardware structure, software libraries and tools to develop ELT-scale RTC around a common architecture:

- S-RTC Gateway: interface with ICS + RTC supervision
- H-RTC Gateway : interface with the H-RTC
- Storage node: telemetry recorder
- Compute node: S-RTC related computations

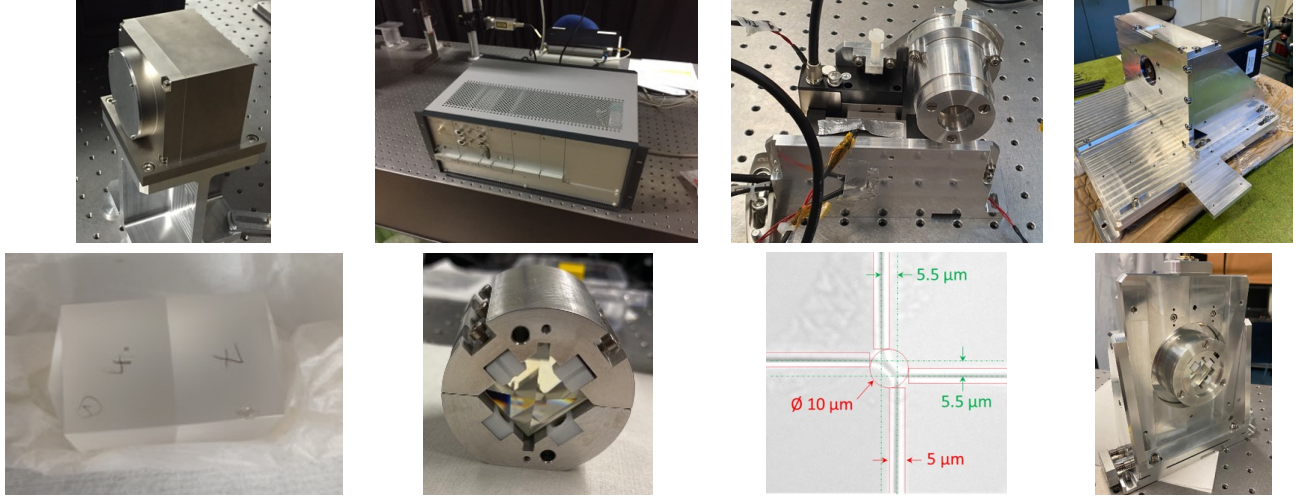


Figure 6. Top, from left to right: the CEDRAT modulation head, the CEDRAT modulation electronics rack, the PIL mechanics & motors under thermal testing, the mechanics of WFS core under verification. Bottom from left to right: the double pyramid optical component, the double pyramid component in its housing, the pyramid vertex as seen with a microscope, the pyramid mount mechanics.

We have started the integration activity of the RTC Tk on a single node S-RTC to test the RTC Tk functionalities. We have achieved a first full loopback between H-RTC and S-RTC: the H-RTC publishes telemetry data, the S-RTC consumes it and computes background, the computed background is sent to H-RTC, which applies it. These tests have been recently pursued in a multi-node configuration and at 500 Hz.

## 4.2 The WFS core

The WFS core is made of the WFS camera, the pyramid optical component (with its support), the pupil imaging lens (PIL, to control laterally the pupil) and the modulation system.

The final double pyramid has been procured from the company WZW and its support already manufactured. The optics and the mechanics of the PIL has been delivered. Waiting for the delivery of the ESO ALICE camera we have procured an OCAM2 camera from the company First Light Instrument. The overall mechanics of the the WFS core is manufactured. The modulation system has been delivered by CEDRAT but still need final adjustment of the electronics rack.

## 4.3 Towards the $\beta$ flat configuration

In a first step towards testing the MICADO SCAO loop at full scale, we have integrated on our R&D AO bench Sésame the MICADO SCAO double pyramid and run the AO loop with the MICADO SCAO H-RTC. Correction has been made using our high order AIT deformable mirror procured from ALPAO and made of 3200 actuators. Under this configuration we have been able to close the loop and then demonstrate, to our knowledge, the first ELT scale AO loop running at full speed i.e. 500 Hz (Fig. 7).

But this configuration on the Sésame bench is rather far from the final configuration: the source is monochromatic (laser) and the pupil a bit smaller than the final one. We are then planning to soon work using the so-called  $\beta$  flat configuration, which will be much closer to the final MICADO SCAO configuration, though still restricted to the SCAO core elements. A description of this  $\beta$  flat configuration is made in Fig. 8. All components of the  $\beta$  flat configuration have been today procured except the Beckhoff terminals (with a delivery time longer than 20 weeks) and the PI motors (with a delivery time longer than 40 weeks), but we plan to start working in a degraded mode until their respective delivery. And we are still finalizing the source module mechanics. Then, we should start working with this configuration early 2024. AO tests in this configuration are planned for about one year.



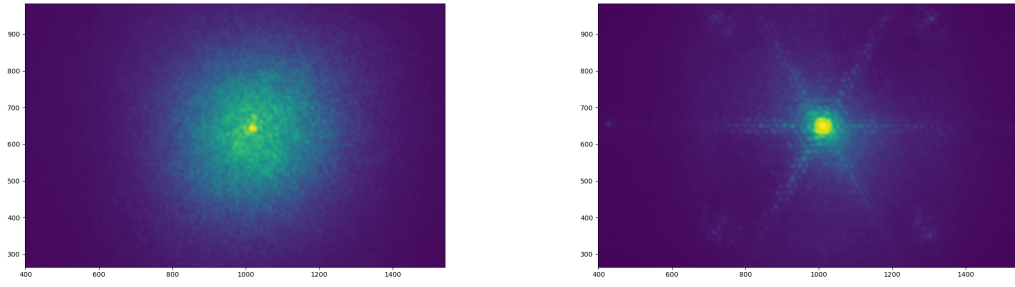


Figure 7. First ELT scale AO loop running at full speed i.e. 500 Hz. Left: PSF without loop opened. Right: PSF with loop closed.

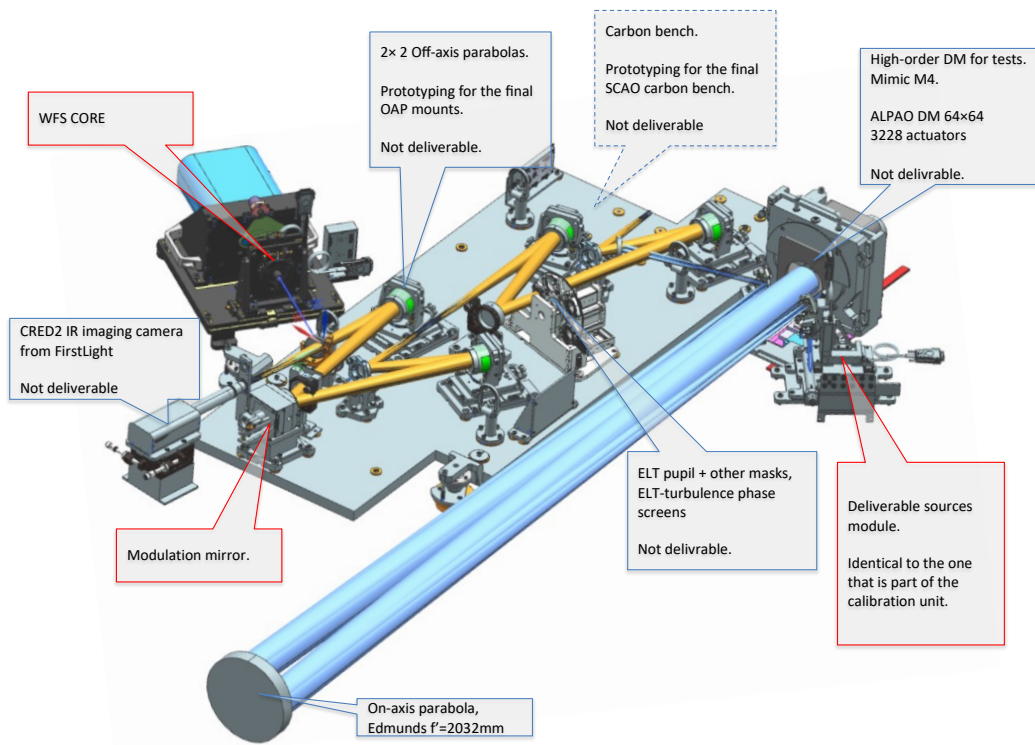


Figure 8. Description of the  $\beta$  flat configuration.

## 5. THE SCAO MAIT: ALL THE OTHER SCAO ELEMENTS

In parallel to the implementation of the  $\beta$  flat configuration, procurement and manufacturing of the SCAO elements other than the critical and core ones have started. A contract has been signed with Bertin Winlight for the procurement of almost all the SCAO optics (expected delivery date: mid 2024). Another contract has been signed with the same company for the delivery of two SCAO dichroic blanks of  $\text{CaF}_2$  (305 mm in diameter), with an expected delivery date in Q3 2025. The final low order DM for calibration and maintenance has been ordered to ALPAO and is to be delivered in November 2023. The DM support is currently manufactured at the Pole Instrumental of Paris Observatory. Mechanical supports of optics are either being manufactured at the Pole

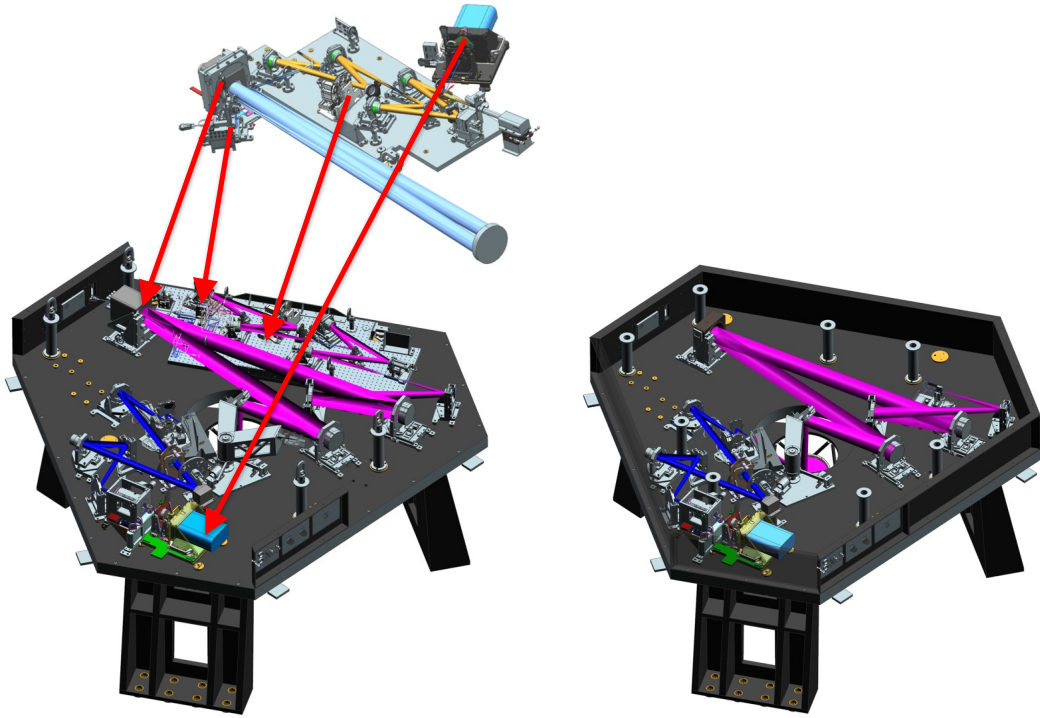


Figure 9. Left: The SCAO module in its final AIT configuration, making use of elements of the  $\beta$  flat configuration. Right: Final on-sky configuration of the MICADO SCAO module, as delivered at the telescope.

Instrumental (SCU parabolas) and at LESIA (K-mirror) or subject to an on-going call for tender (support for WFS parabolas, WFS and SCU folding mirrors, ADC, NCPA phase plates). They all should be available by the end of next year. We also plan to manufacture in 2024 the mechanics of the WFS entrance field lens and pupil steering mirror.

After fine tuning of their design, we plan to place a call for tender in 2024 to manufacture the calibration unit deployment arm, the dichroic support and the SCAO carbon bench.

## 6. THE SCAO MAIT: THE NEXT PHASES

After the  $\beta$  flat configuration, the next phase of the SCAO MAIT plan is the so-called flat configuration where the WFS and the SCU are integrated on separated benches with all their elements. It will allow to test the functionalities of all the components non present in the  $\beta$  flat configuration. The SCAO elements will then be integrated on the final SCAO bench, in its AIT configuration, i.e. with the elements already available in the  $\beta$  flat configuration that allow to simulate the telescope and the atmosphere (Fig. 9). This AIT configuration will allow the validation of the SCAO module specifications and will be used for a partial MICADO SCAO PAE. After this partial PAE, the specific MAIT elements will be removed to get the final on-sky version of the SCAO module.

## ACKNOWLEDGMENTS

This work has benefited from the support of 1) the French Programme d'Investissement d'Avenir through the project F-CELT ANR-21-ESRE-0008, 2) the project WOLF ANR-18-CE31-0018, 3) the CNRS 80 PRIME program, 4) the CNRS INSU TGIR budget, 5) the Action Spécifique Haute Résolution Angulaire (ASHRA) of CNRS/INSU co-funded by CNES, 6), the Observatoire de Paris and 7) the Ile de France region (DIM ACAV/ACAV+ and ORIGINES).

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