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METIS SCAO – implementing AO for ELT

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ABSTRACT

METIS, the Mid-infrared ELT Imager and Spectrograph is among the first-generation instruments for ESO's 39m Extremely Large Telescope (ELT). It will provide diffraction-limited spectroscopy and imaging, including coronagraphic capabilities, in the thermal/mid-infrared wavelength domain ($3\ \mu\text{m} - 13.3\ \mu\text{m}$). Its Single Conjugate Adaptive Optics (SCAO) system will be used for all observing modes, with High Contrast Imaging imposing the most demanding requirements on its performance.

The final design review of METIS took place in the fall of 2022; the development of the instrument, including its SCAO system, has since entered the Manufacturing, Assembly, Integration and Testing (MAIT) phase. Numerous challenging aspects of an ELT AO system are addressed in the mature designs for the SCAO control system and the SCAO hardware module: the complex interaction with the telescope entities that participate in the AO control, wavefront reconstruction with a fragmented and moving pupil, secondary control tasks to deal with differential image motion, non-common path aberrations and mis-registration. A K-band pyramid wavefront sensor and a GPU-based RTC, tailored to needs of METIS at the ELT, are core components. The implementation

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of the METIS SCAO system includes thorough testing at several levels before the installation at the telescope. These tests require elaborate setups to mimic the conditions at the telescope.

This paper provides an overview of the design of METIS SCAO as it will be implemented, the main results of the extensive analyses performed to support the final design, and the next steps on the path towards commissioning.

Keywords: METIS, SCAO, PWFS, FDR, Simulations, RTC

1. INTRODUCTION

METIS, the Mid-infrared ELT Imager and Spectrograph will provide the Extremely Large Telescope (ELT) with a unique window to the thermal- and mid-infrared [2, 3].

A suite of observing modes will offer

- direct imaging at L, M, and N band
- High Contrast Imaging (HCI) at L, M, and N band, deploying different coronagraphic techniques [1]
- longslit spectroscopy at L, M and N band
- high resolution ($R \sim 10^5$) Integral Field Unit (IFU) spectroscopy at L/M band, including a mode with extended instantaneous wavelength coverage
- combined IFU and HCI spectroscopy.

Thermal self emission is the by far dominating noise contribution in the wavelength range in which METIS operates. To limit its impact it is essential for the instrument to be realized within a stable cryogenic environment (cf. Figure 1).



Figure 1. METIS will be located on one of the Nasmyth platforms of the ELT. At a height of 6m above the platform the light coming from the telescope enters the METIS cryostat, which hosts the entire optical path of the instrument down to the science detectors. It provides a very stable cryogenic environment, suppressing the thermal background emission. The SCAO wavefront sensor also resides within the cryostat. Rendering: ESO

Each observing mode of METIS is designed to make use of the diffraction limit of the ELT's 39m aperture. The METIS SCAO System is the real-time wavefront control system enabling diffraction limited observations. High contrast imaging imposes challenging requirements on METIS SCAO. In order to reach the (post processed) contrast level pursued (cf. Table 1), the performance of the SCAO system must not only be met in terms of the Strehl ratio. Other parameters, such as the residual pointing jitter and the petal piston error also need to be constrained.

Table 1. Selected top level requirements for METIS SCAO

	Requirement	Goal	λ
Strehl Ratio	> 93 %	> 95 %	10 μm
	> 60 %	> 80 %	3.7 μm
Contrast	< $3 \cdot 10^{-5}$ at $5\lambda/D$	< 10^{-6} at $2\lambda/D$	3.7 μm

Several distributed entities are involved: in the instrument domain, the SCAO System consists of the *SCAO Module* and the *AO Control System (AOCS)*. Further entities that are essential for SCAO are located in the telescope domain. Figure 2 shows a simplified block diagram for METIS SCAO.

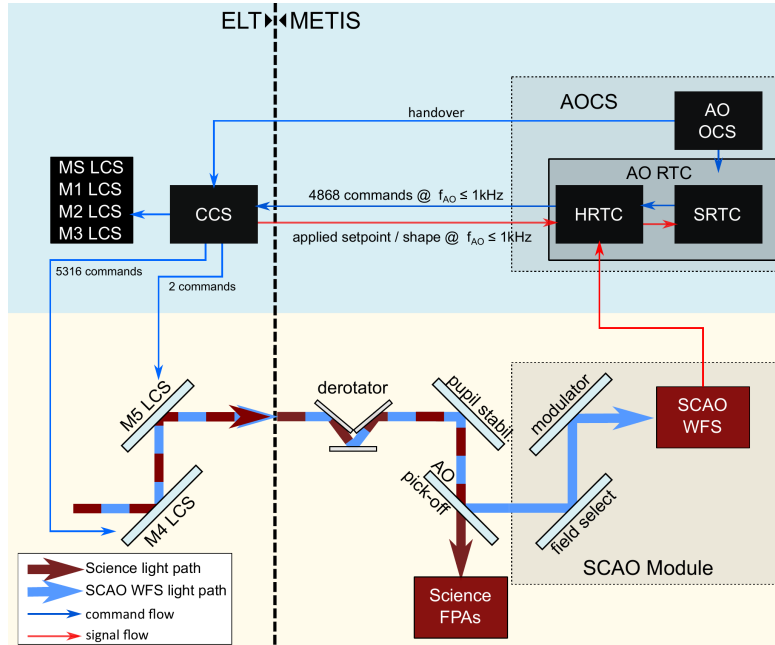


Figure 2. Simplified block diagram of the METIS SCAO system: The AO Control System (AOCS) and the SCAO Module (shaded boxes) are the entities of the SCAO system that belong to the instrument domain. The key entities for the real-time correction of the incoming light of the 'ELT' domain are located on the left side of the figure. In a closed wavefront control loop, the blue, NIR light is used to measure the instantaneous residual wavefront error by the wavefront sensor (SCAO WFS). The measurement signal is analyzed by the Real-Time Computer (AO RTC), and a computed correction is sent to the Central Control System (CCS) to be applied with the adaptive mirrors M4 and M5 of the ELT.

The *SCAO Module* is located inside the cryostat. A cold dichroic pick-off mirror immediately in front of the SCAO Module is used to separate the NIR part of the light, which is used for wavefront sensing. The SCAO Module provides a Pyramid Wavefront Sensor (PWFS) as well as opto-mechanical actuators for field selection and modulation of the natural guide star in the accessible field of view.

The *AO Control System (AOCS)* hosts the main wavefront control loop as well as a number of secondary control loops. A key entity of the AOCS is the RTC [9]. Its Hard Real-Time Core (HRTC) is used for the time critical aspects of the wavefront control loop: wavefront sensor signal processing, wavefront reconstruction and the determination of correction commands that are applied with the adaptive M4 and M5 mirrors of the ELT via the Central Control System (CCS).

2. WAVEFRONT CONTROL STRATEGY

This section outlines some key aspects of the wavefront control strategy for METIS. A more detailed description is provided elsewhere [5, 6].

A common approach to a wavefront control loop is the combination of a wavefront spatial reconstruction algorithm and a temporal controller that provides the optimal corrections to be applied with the adaptive components of the loop. It is always necessary to establish and maintain a relationship between the PWFS signal space and the control space of the DM: the registration of the DM to the PWFS. Flexure of the telescope structure causes the image of M4 on the PWFS to shift, a continuous rotation of the image is introduced due to the location of the instrument on the Nasmyth platform. These effects need to be considered in order to avoid misregistration.

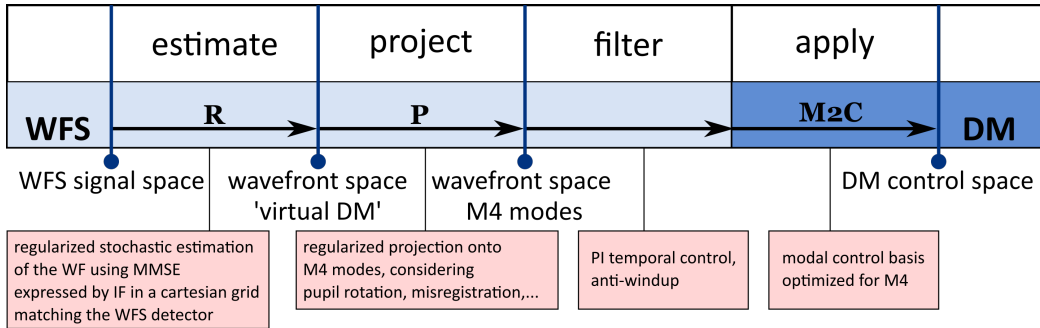


Figure 3. The wavefront control scheme for METIS SCAO consists of 4 logical steps: a stochastic wavefront estimation into a “virtual DM” space, a projection step onto the control modes for M4, time filtering using a PI control law, and applying the correction by converting the requested modes into actuator commands of the adaptive mirrors M4 and M5. The last step is executed by the telescope’s CCS. The “virtual DM” has a Cartesian layout that matches the subaperture arrangement of the WFS.

In METIS, reconstruction, DM fitting (encompassing a change of the control space) and time-filtering are functionally disentangled. This is achieved by an intermediate step in which the wavefront is decomposed into reconstruction basis functions of a “virtual DM” – using a reference frame that is fixed with respect to the WFS (cf. Figure 3). This basis can be chosen independently from the M4 control basis [12] in the modes-to-commands matrix (M2C)! Thus, the WFS response to wavefront perturbations can be decoupled from the DM response. The optimal projection [10] onto the M4 control basis is the successive logical step, before a temporal filtering is introduced by the controller.

In practice, the wavefront control pipeline in the HRTC will not compute each intermediate step individually. The reconstruction and the projection are done through a single matrix-vector multiplication using a command matrix (cf. Figure 4). The “Command Matrix Optimizer”, an application in the Soft Real-Time Cluster (SRTC), monitors the registration and the illumination on the PWFS, computes both the reconstruction and the projection based on the current situation, combines them into the command matrix and updates the corresponding wavefront control pipeline parameter on-the-fly.

The majority of the lateral misregistration is prevented by stabilizing the pupil. Another application in the SRTC monitors the lateral position of the pupil image on the PWFS [4]. This information is used to stabilize the pupil for the complete instrument by applying corrections with a tip/tilt mirror in the common path (cf. Figure 2).

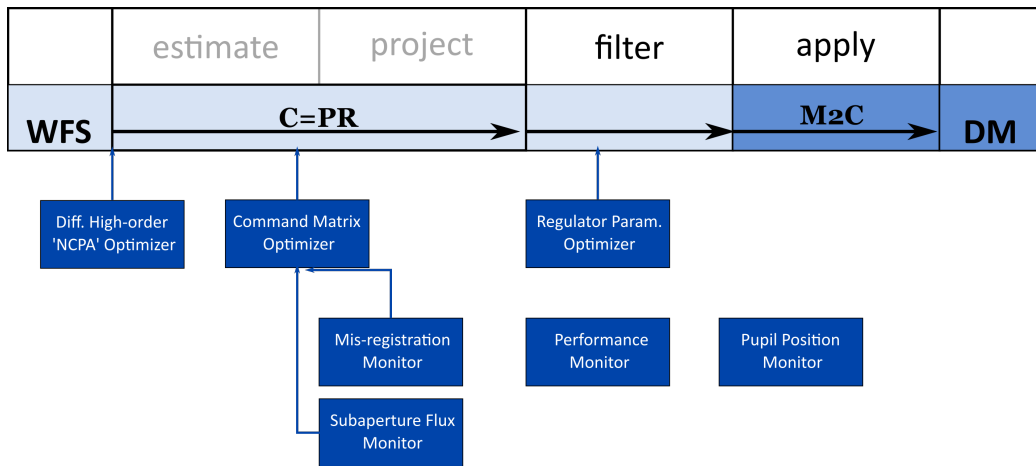


Figure 4. The logical separation of the wavefront reconstruction into an estimation step and a projection step is maintained outside of the wavefront control pipeline. For the Hard Realtime Core (HRTC) the two steps are combined in a Command Matrix, allowing for a single matrix-vector multiplication. A Soft Real-Time Cluster (SRTC) optimizes and updates the parameters of the wavefront control pipeline on the fly.

The primary Wavefront Control (WFC) loop of SCAO provides the bulk of the wavefront correction for METIS, using its Pyramid Wavefront Sensor to obtain the required measurements in real-time. This sensor, however, does not probe the exact electromagnetic field that produces the image on the science detectors. Some effects have been identified to produce a wavefront error (WFE) component that is not sensed by the WFS and ends up as residual WFE in the science instrument, degrading the science performance. Such unseen effects would need to be compensated through a secondary wavefront control stage. Among these effects is Water Vapor (WV) turbulence and variable Non-Common Path Aberrations (NCPA). Due to the chromatic nature of WV disturbances a feedback is required at the observing wavelength. Within METIS, such a feedback is available only in the science focal planes. A secondary wavefront correction stage, fed with science focal plane measurements (Figure 5), is foreseen for HCI observations [11].

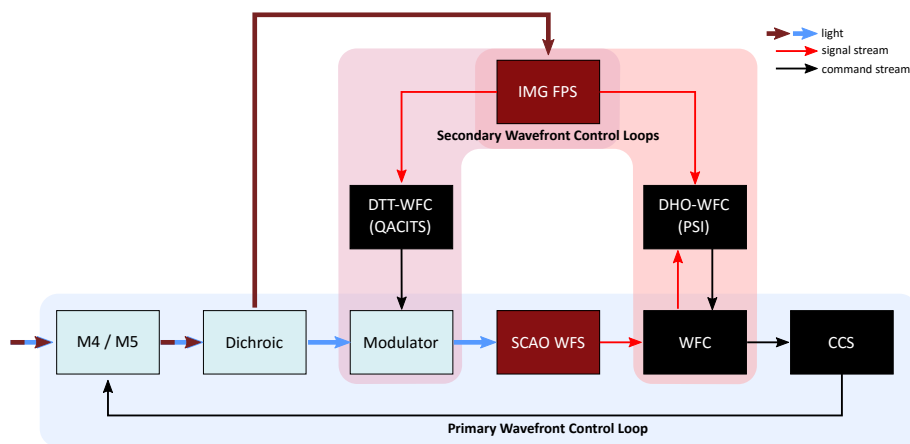


Figure 5. Simplified block diagram of the wavefront control loops. The entities in the in the blue area form the primary wavefront control loop, which is driven by the real-time measurements of the SCAO WFS. Both secondary wavefront control loops, highlighted in red, provide a differential correction on top of the primary control loop, to minimize the wavefront error in the science optical path. Both use the Imager Subsystem (IMG) detectors as Focal Plane Sensor (FPS) to retrieve phase information. Both secondary control loops are coupled to the primary control loop: in the case of the differential tip/tilt loop (DTT WFC), the correction is introduced through the modulator, in the case of the differential high order wavefront control loop (DHO WFC) the correction is introduced as signal offsets for the primary WFC.

2.1 Real-time Computer

The METIS SCAO RTC is the core component of the AO Control System. A more detailed description of the RTC is provided in a separate paper [9]. It is developed at the Max Planck Institute for Astronomy, drawing from the heritage of previously developed AO RTCs, but it is not based on a pre-existing platform. This approach allows the RTC to be tailored to the METIS SCAO application in the software framework defined by ESO. Only commercial off-the-shelf components are foreseen for the RTC. Also, for the software development special care was taken to avoid a reliance on proprietary technologies, 3rd party licensing issues or vendor lock-in.

The RTC hardware consists of a single HRTC node, a number of SRTC nodes and network infrastructure. In an extensive comparison study a Graphics Processing Unit (GPU) based server solution was identified as the hardware platform for the HRTC. In addition, various SRTC applications with a high computational load will make use of GPU acceleration. This is especially true for the “Command Matrix Optimizer”, which, in some instances needs to compose an updated $13k \times 5k$ command matrix at a frequency of 0.5 Hz.

The main wavefront control pipeline is executed on the HRTC. A large number of computations must be performed in less than $909 \mu s$ for each loop cycle, resulting in a minimum computing power of 137 GFLOP/s and a memory throughput of 276 GB/s.

A prototype of the WFC pipeline for METIS was implemented and used to test the computer performance of the HRTC itself (cf. Figure 6) as well as a number of other aspects, such as the data transfer between WFS, HRTC, CCS and SRTC. The requirements on the computation performance are well met by the chosen hardware platform.

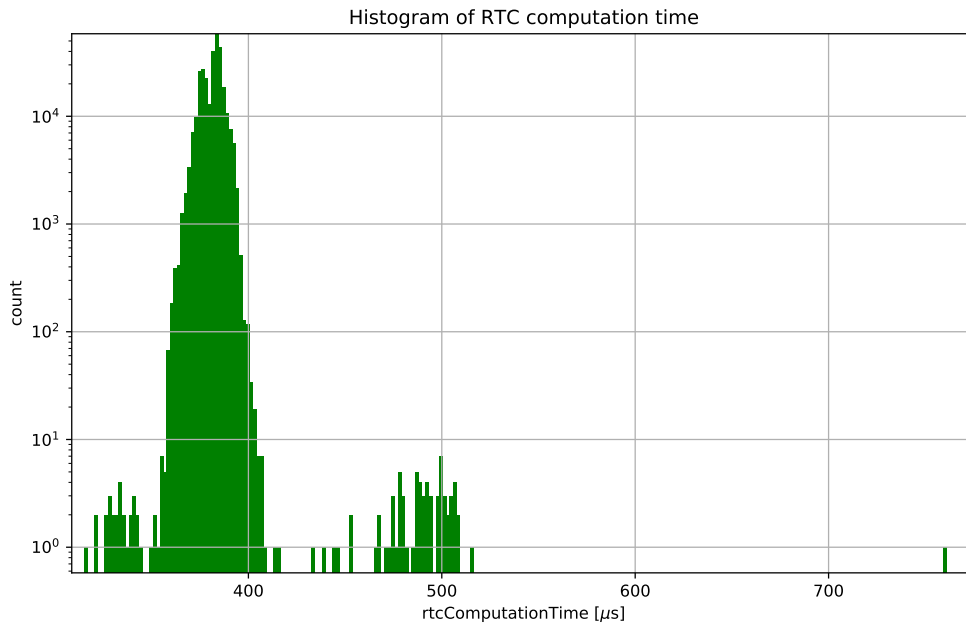


Figure 6. Histogram of the RTC computation time, determined with the HRTC prototype. For a set of 300,000 samples a median computation time of $382 \mu s$ was achieved. All samples were below the limit of $909 \mu s$. See [9] for further details.

The HRTC prototype was also integrated into our end-to-end simulation setup [9] to demonstrate that the HRTC pipeline produces the same results as the WFC pipeline that is used to analyze the expected performance of METIS SCAO.

2.2 Performance Analysis

Extensive studies of the expected AO performance were carried out in the phases that led to the FDR. Numerous topical analyses and assessments of the overall performance considering the presence of all anticipated disturbances and conditions were done with the help of an end-to-end numerical simulation setup. A detailed description of the simulation setup and the obtained results is provided in a separate paper [6].

The simulation setup continues to be a valuable tool for the development of the METIS SCAO control system and will be actively maintained. It is based on COMPASS [8], extended by a number of additional modules, in which the specifics of the METIS wavefront control strategy are implemented. The development of the METIS RTC will make use of these additional modules. The simulation setup is also used to generate long sequences of residual phase screens for the analysis of the HCI performance [1].

A number of different metrics in addition to the Strehl Ratio are required for the assessment of the performance of METIS SCAO. The AOSAT tool [7] is used for a consistent calculation of the key metrics on PSF, contrast, phase and pupil fragmentation.

In summary the analyses yielded a robust system with a stable performance of about 95.5% Strehl at $3.7 \mu\text{m}$ in most of the analyzed conditions. The consideration of calibration errors, misregistration and petal errors within reasonable limits, missing segments, 130nm of NCPA and other performance limiting effects resulted in only a small drop of the Strehl ratio to 94.6% (Figure 7). Even in combination, saturation management, wind-shake, missing segments, modeling errors, NCPAs, and initial petaling only have a minor impact on the system performance.

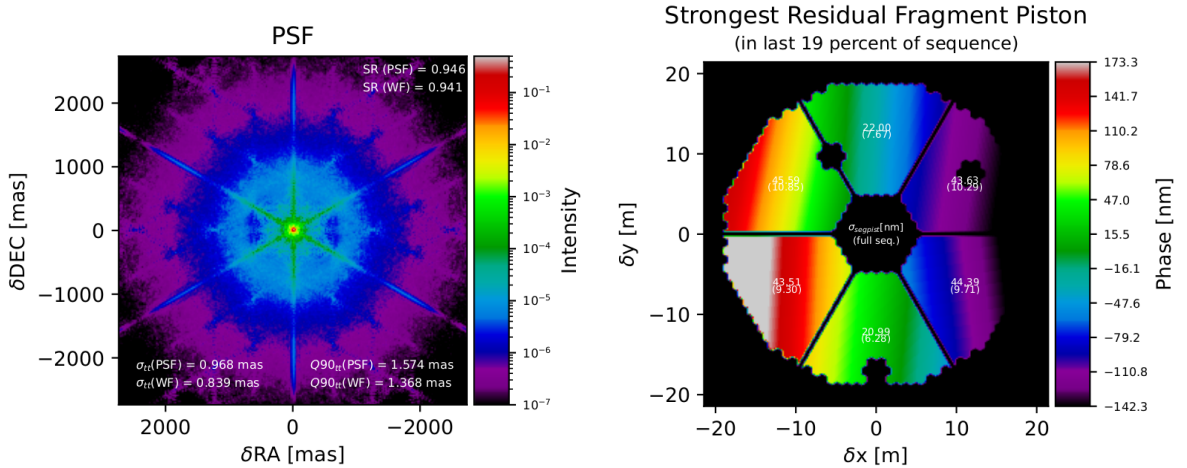


Figure 7. Simulation results: Extensive simulations were performed, considering a large number of potentially performance degrading effects. With the foreseen wavefront control strategy the Strehl Ratio remains high (PSF in the left panel). The petaling error remains small (right panel) for the assumed conditions. See [6] for a detailed description of the performed simulations.

A notable exception is wind speeds of or below 0.5 m/s in the telescope dome. The low-wind condition introduces potentially steep phase gradients that coincide with the pupil dissecting spider structures. The simulations show that the K-Band PWFS picks up phase discontinuities such as petaling errors in the given ELT pupil geometry. In closed loop these errors are corrected. However, if the phase steps exceed half of the operating wavelength of the wavefront sensor, the wavefront in each pupil fragment (also known as “petal”) will be corrected and the petals will be phase tracked but not co-phased. A quasi-stable correction of the wavefront is the result, in which one or more petals are locked with a differential piston of an integer multiple of the wavefront sensing wavelength. The SCAO team investigates the means of detecting such a cophasing error condition.

3. MAKING IT HAPPEN

The completion of the final design allows METIS to proceed into the manufacturing, assembly, integration and test (MAIT) phase. SCAO MAIT activities span the entire remaining development cycle of METIS well into commissioning. Many aspects, especially related to the AOCS, cannot be tested in the subsystem MAIT phase of METIS. Figure 8 provides a birds-eye view over the test activities and their dependencies on test setups and level of integration. The first parallel and then joint development of the SCAO Module and AOCS are shown.

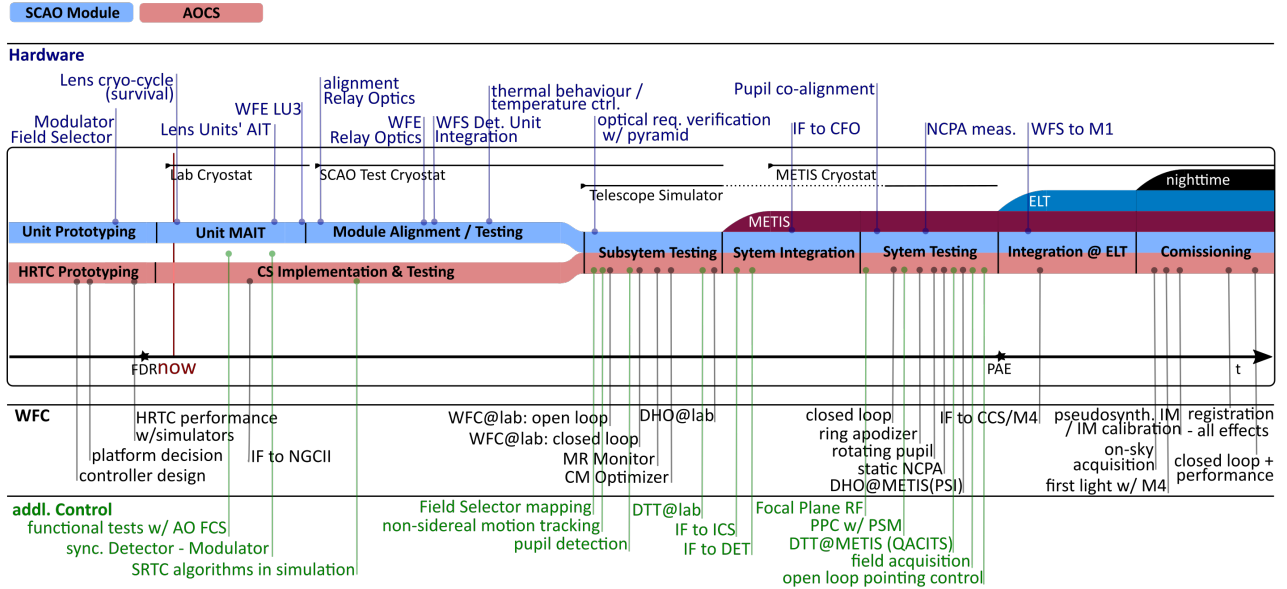


Figure 8. MAIT road map: The development of the AO Control System (AOCS, red) and the SCAO Module (blue) is done in parallel. Each MAIT phase represents a higher level of integration. Dedicated test setups, such as the SCAO test cryostat or the telescope simulator will be used in the corresponding test phases. Key tests for the hardware, the main wavefront control (WFC) pipeline and for auxiliary control tasks are indicated.

The procurement of most optical components and mechanisms of the SCAO Module has a lead time of more than 6 months. These components had been reviewed as part of a Long-Lead-Item FDR prior to the system FDR. Most of these components are available at the time of writing and ready for the integration.

As many of the core components of METIS SCAO are part of the telescope domain and available for integration and testing only at a very late stage in the development, when the instrument is shipped to the ELT site, it is important to establish environments that allow for thorough testing at much earlier stages.

The MAIT plan foresees different phases in which important parts of the wavefront control loop are tested in different contexts. The table in Figure 10 lists different contexts that provide important functionalities of METIS SCAO in six AIT phases.

The SIM phase covered the prototyping of the wavefront control strategy, using the simulation setup mentioned before. The second, currently ongoing phase covers the integration of the actual RTC in the simulation environment.

In the third AIT phase it is intended to test some of the important SRTC functionalities on sky in the context of another instrument, LINC-NIRVANA at the Large Binocular Telescope (LBT). While the AO facilities of the LBT and ELT have commonalities, they still differ in numerous ways. The AO RTC at the LBT is highly integrated into the telescope and it is neither feasible nor intended to try to test the HRTC for METIS at the LBT. But the configuration of the RTC, the detection of misregistration in the AO telemetry, updating the reconstructor in closed loop or the stabilization of the pupil on the PWFS detector are important functionalities that can be tested with LINC-NIRVANA.

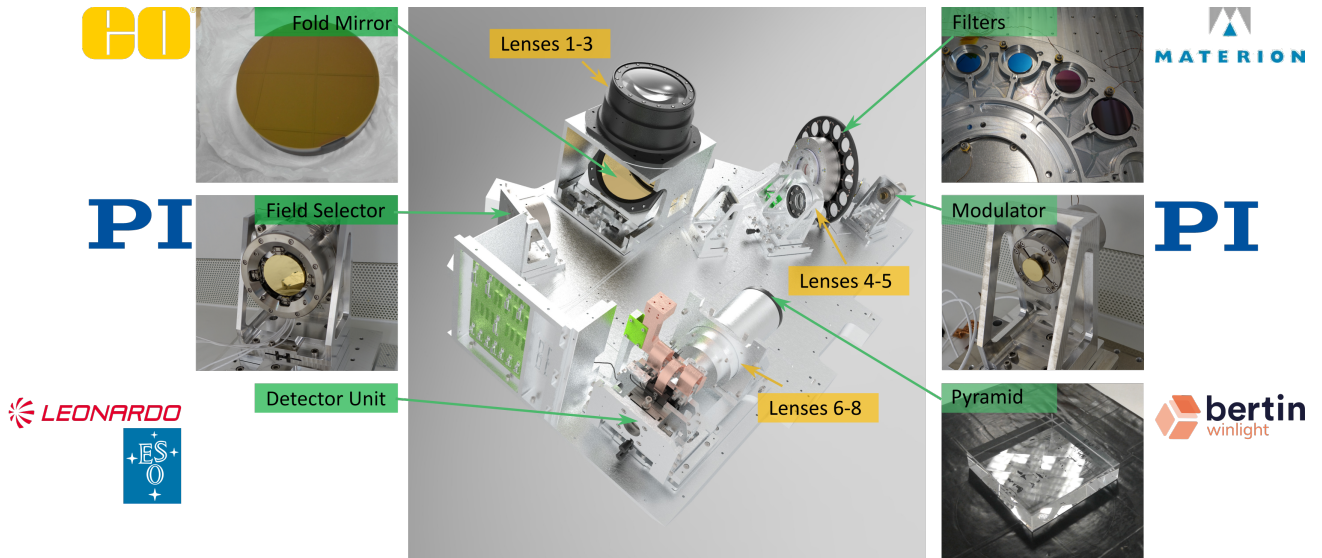


Figure 9. Components within the SCAO Module: All opto-mechanical components with a long delivery time were procured after having passed a combined optical- / long-lead item design review. Most of these components are now in the lab at MPIA, ready to be integrated and tested.

	AIT/V Phases					
	SIM	RTC & SIM	@LBT	@Lab	@METIS	@ELT
Disturbances	SCAO SIM	SCAO SIM	Telescope	Telescope Simulator	Telescope Simulator	Telescope
Pupil	SCAO SIM	SCAO SIM	Telescope	Telescope Simulator	Telescope Simulator	Telescope
DM	SCAO SIM	SCAO SIM	Telescope	Telescope Simulator	Telescope Simulator	Telescope
P-WFS	SCAO SIM	SCAO SIM	LINC-NIRVANA	SCAO Module	SCAO Module	SCAO Module
WFC loop	SCAO SIM	HRTC	LINC-NIRVANA	HRTC	HRTC	HRTC
CCS	SCAO SIM	SCAO SIM	Telescope	Telescope Simulator	Telescope Simulator	Telescope
Core Functionality						
configuration / Calibration	SCAO SIM	SRTC	SRTC	SRTC	SRTC	SRTC
modal basis	SCAO SIM	SRTC	SRTC	SRTC	SRTC	SRTC
diagnostics	SCAO SIM	SRTC	SRTC	SRTC	SRTC	SRTC
registration	SCAO SIM	SRTC	SRTC	SRTC	SRTC	SRTC
System Parameter Estimation			SRTC	SRTC	SRTC	SRTC
Pupil Pos. Control PPC			AOCS	AOCS	AOCS	AOCS
DTT (QACITS)					AOCS	AOCS
DHO (PSI?)					AOCS	AOCS
Supervision				AOCS	AOCS	AOCS
Function Control (ICS)				AOCS	AOCS	AOCS
WFS Control (Detector)				AOCS	AOCS	AOCS

Figure 10. Testing the AO System in different contexts: Different settings are used to test core functionality as early as possible in the development. End-to-end simulations were used to develop the wavefront control strategy. Next phases include “hardware in the loop”, an integration of the HRTC into the simulations, SRTC component tests with LINC-NIRVANA at the Large Binocular Telescope, and closed loop tests with a telescope simulator, both before and after integration into the METIS instrument. The final phase is the commissioning at the ELT.

Phase four and five involve the usage of a telescope simulator. This is an opto-mechanical setup that mimics a number of features of the ELT, such as the unique pupil shape, a deformable mirror (M4), a field steering mirror (M5) and means to introduce a diffraction limited light source. This setup will be used first for subsystem tests of the SCAO system, involving the SCAO Module and the AOCS alone. It will allow to close the AO loop with the final PWFS inside the SCAO Module. For this purpose a dedicated test cryostat is being built (cf. Figure 11), which provides operating conditions for the SCAO Module, before it is finally integrated into METIS itself. The telescope simulator is reused for final tests of SCAO within METIS in a phase before the shipment of the instrument to Chile. The final integration and test phase will be part of the installation and commissioning at the ELT.



Figure 11. Test cryostat: A dedicated test cryostat is being set up for the tests of the SCAO Module. It will provide the operating environment of the SCAO module and allow for extensive testing before the integration into the METIS instrument.

4. SUMMARY

The final design of METIS and its SCAO system has been reviewed in fall of 2022 and METIS has since entered the MAIT phase. Core components of the SCAO Module are manufactured and ready for integration. The Wavefront Control Strategy has been extensively studied and promises outstanding robustness and performance for the conditions under which METIS SCAO is anticipated to operate.

A phased approach to testing will allow to develop METIS SCAO with increasing level of integration until the Preliminary Acceptance Review, which is scheduled for end of 2027, and beyond. Part of this phased approach is the development of dedicated test setups to mimic the final operating conditions: a telescope simulator and a test cryostat.

References

- [1] O. Absil. “Final design and estimated performance of the ELT/METIS high-contrast imaging modes”. In: *Adaptive Optics for Extremely Large Telescopes*. Vol. 7. 2023.
- [2] B. Brandl et al. “METIS: The Mid-infrared ELT Imager and Spectrograph”. In: *The Messenger* 182 (Mar. 2021), pp. 22–26. DOI: [10.18727/0722-6691/5218](https://doi.org/10.18727/0722-6691/5218). arXiv: [2103.11208](https://arxiv.org/abs/2103.11208) [[astro-ph.IM](#)].
- [3] Bernhard R. Brandl et al. “Status update on the development of METIS, the mid-infrared ELT imager and spectrograph”. In: vol. 12184. Proc. SPIE. 2022, 1218421. DOI: [10.1117/12.2628331](https://doi.org/10.1117/12.2628331).
- [4] Hugo Coppejans et al. “Subpixel pupil tracking on METIS for ELT”. In: *Adaptive Optics for Extremely Large Telescopes*. Vol. 7. 2023.
- [5] Carlos M. Correia et al. “ELT METIS wavefront control strategy”. In: vol. 12185. Proc. SPIE. 2022, 1218512. DOI: [10.1117/12.2630096](https://doi.org/10.1117/12.2630096).
- [6] M. Feldt et al. “Simulating METIS’ SCAO System”. In: *Adaptive Optics for Extremely Large Telescopes*. Vol. 7. 2023.
- [7] M. Feldt et al. “The adaptive optics simulation analysis tool(kit) (AOSAT)”. In: *Adaptive Optics Systems VII*. Ed. by Laura Schreiber, Dirk Schmidt, and Elise Vernet. Vol. 11448. Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. Dec. 2020, 114483S, 114483S. DOI: [10.1117/12.2561404](https://doi.org/10.1117/12.2561404).
- [8] D. Gratadour et al. “COMPASS: status update and long term development plan”. In: *Adaptive Optics Systems V*. Vol. 9909. SPIE. July 2016, 990971, p. 990971. DOI: [10.1117/12.2232681](https://doi.org/10.1117/12.2232681).
- [9] M. Kulas et al. “The RTC for METIS SCAO”. In: *Adaptive Optics for Extremely Large Telescopes*. Vol. 7. 2023.
- [10] A. Obereder et al. “Finally, let’s use all the modes!” In: *Adaptive Optics for Extremely Large Telescopes*. Vol. 7. 2023.
- [11] G. Orban De Xivry et al. “Non-Common Path Aberrations Strategy for the METIS High Contrast Imaging Modes”. In: *Adaptive Optics for Extremely Large Telescopes*. Vol. 7. 2023.
- [12] C. Vérinaud and C. Correia. “Eigen-Bases for force-constrained position control of adaptive shell mirrors”. In: *Astronomy and Astrophysics (accepted)* (2023).