How to make METIS SCAO work

Thomas Bertram[a], Olivier Absil[b], Peter Bizenberger[a], Bernhard Brandl[c], Wolfgang Brandner[a], Florian Briegel[a], María Concepción Cárdenas Vázquez[a], Hugo Coppejans[a], Carlos Correia[d, e], Markus Feldt[a], Maximilian Häberle[a], Armin Huber[a], Martin Kulas[a], Werner Laun[a], Lars Mohr[a], Daniel Mortimer[a], Vianak Naranjo[a], Andreas Obereder[f], Gilles Orban de Xivry[b], Ralf-Rainer Rohloff[a], Silvia Scheithauer[a], Horst Steuer[a], and Roy van Boekel[a]

[a]Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
[b]STAR Institute, Université de Liège, 19c allée du Six Août, bât B5c, 4000 Liège, Belgium
[c]Leiden Observatory, PO Box 9500, 2300 RA Leiden, The Netherlands
[d]Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal
[e]Center for Astrophysics and Gravitation, Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal
[f]MathConsult GmbH, Altembergerstraße 69, 4040 Linz, Austria

ABSTRACT

METIS, the Mid-infrared ELT Imager and Spectrograph, will be one of the first instruments to be used at ESO's 39m Extremely Large Telescope (ELT), that is currently under construction. With that, a number of firsts are to be addressed in the development of METIS' single-conjugate Adaptive Optics (SCAO) system:

- the size of the telescope and the associated complexity of the wavefront control tasks,
- the unique scientific capabilities of METIS, including high contrast imaging,
- the interaction with the newly established, integrated wavefront control infrastructure of the ELT,
- the integration of the near-infrared Pyramid Wavefront Sensor and other key Adaptive Optics (AO) hardware embedded within a large, fully cryogenic instrument.

METIS and it's AO system have passed the final design review and are now in the manufacturing, assembly, integration and testing phase. The firsts are approached through a compact hard- and software design and an extensive test program to mature METIS SCAO before it is deployed at the telescope. This program includes significant investments in test setups that allow to mimic conditions at the ELT. A dedicated cryo-test facility allows for subsystem testing independent of the METIS infrastructure. A telescope simulator is being set up for end-to-end laboratory tests of the AO control system together with the final SCAO hardware. Specific control algorithm prototypes will be tested on sky.

In this contribution, we present the progress of METIS SCAO with an emphasis on the preparation for the test activities foreseen to enable a successful future deployment of METIS SCAO at the ELT.

Keywords: METIS, ELT, SCAO, MAIT, Pyramid WFS, Telescope Simulator, RTC, AO Control System

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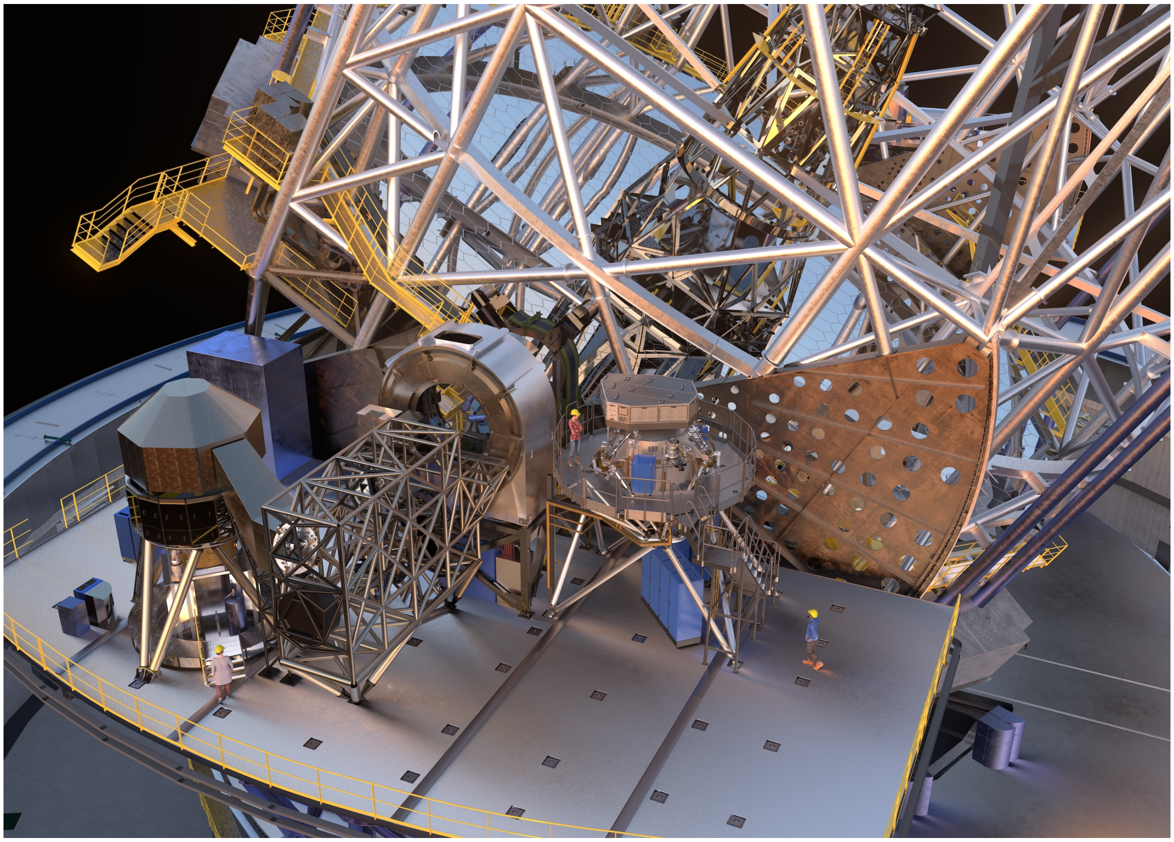

Figure 1. METIS will be located on the front facing (here: right) side of Nasmyth platform B of the ELT. At a height of 6m above the platform the light coming from the telescope enters the METIS cryostat, which hosts the entire optical path of the instrument down to the science detectors. It provides a very stable cryogenic environment, suppressing the thermal background emission. The SCAO wavefront sensor also resides within the cryostat. Image credit: ESO/L.Calçada

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.[1,2] Figure 1 shows a rendering of METIS on Nasmyth platform B of the ELT.

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
- 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.

To limit the impact of thermal self emission it is essential for the instrument to be realized within a stable cryogenic environment.

Each observing mode of METIS is designed to make use of the diffraction limit of the ELT's 39m aperture.

Send correspondence to T. Bertram (E-mail: bertram@mpia.de, Telephone: +49 6221 528-441)

The METIS SCAO System[3] 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 *SCAO Module* and *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.

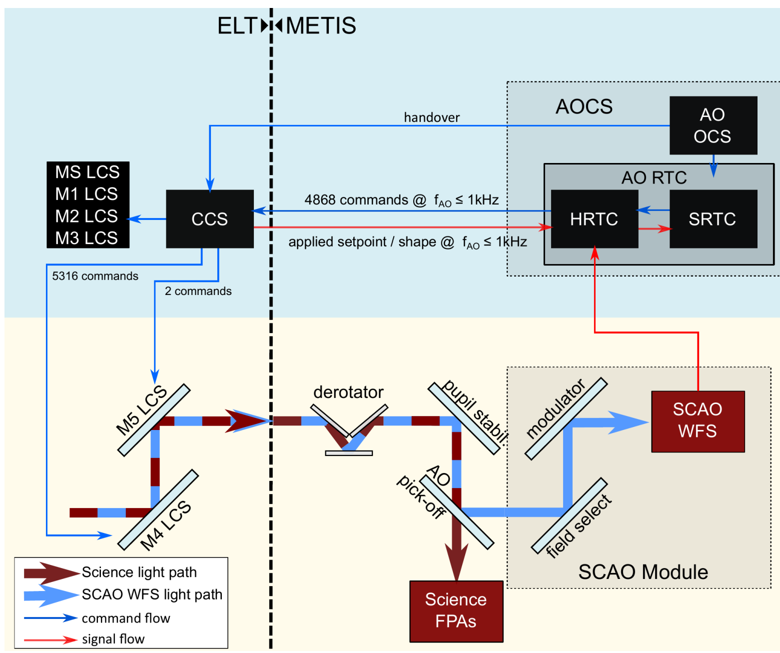

Figure 2. Simplified block diagram of the METIS SCAO system: The AOCS and the SCAO Module (shaded boxes) are the entities of the SCAO system that belong to the instrument domain. The key entities for the real-time correction of the incoming light of the 'ELT' domain are located on the left side of the 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 *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.[4] 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. MANUFACTURING, ASSEMBLY, INTEGRATION AND TESTING

In May 2024, METIS officially passed the final design review (FDR). With reaching this milestone the project fully entered the manufacturing, assembly integration and testing (MAIT) phase. Figure 3 shows the development tracks of the AOCS and the SCAO Module. METIS SCAO activities span all phases of instrument development up to commissioning.

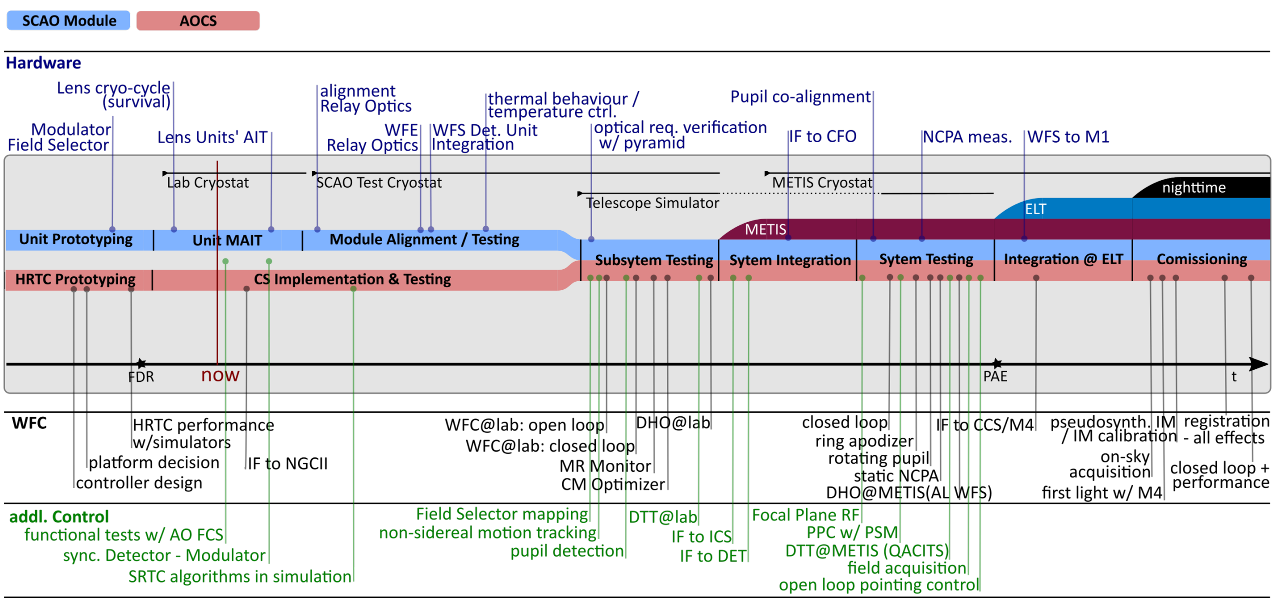

Figure 3. SCAO development tracks: The development of the AO Control System (AOCS, red) and the SCAO Module (blue) is done in parallel. Each MAIT phase represents a higher level of integration. Dedicated test setups, such as the SCAO test cryostat or the telescope simulator will be used in the corresponding test phases. Key tests for the hardware, the main wavefront control (WFC) pipeline and for auxiliary control tasks are indicated.

2.1 AO Control System

The implementation of the AOCS (Figure 4) has already started before the FDR. A more detailed overview of its design and implementation status is provided separately.[5] The GPU-based hard real-time core (HRTC) is the heart of AOCS. The wavefront control pipeline has been prototyped and tested. It fulfills the requirements in terms of RTC computation time and jitter.[4]

The implementation of the soft real-time cluster (SRTC) components has started. These components are based on the RTC toolkit, that is developed by ESO, and provide numerous auxiliary control functions as well as the required parameters for the main wavefront control loop.

2.2 Unit MAIT

The procurement process for long-lead items was started already after a dedicated optical FDR, which preceded the system FDR. All opto-mechanical components have since been manufactured and delivered or, in the case of the lenses, are in the final stages of manufacturing. A number of units could already be assembled (cf. Figure 5).

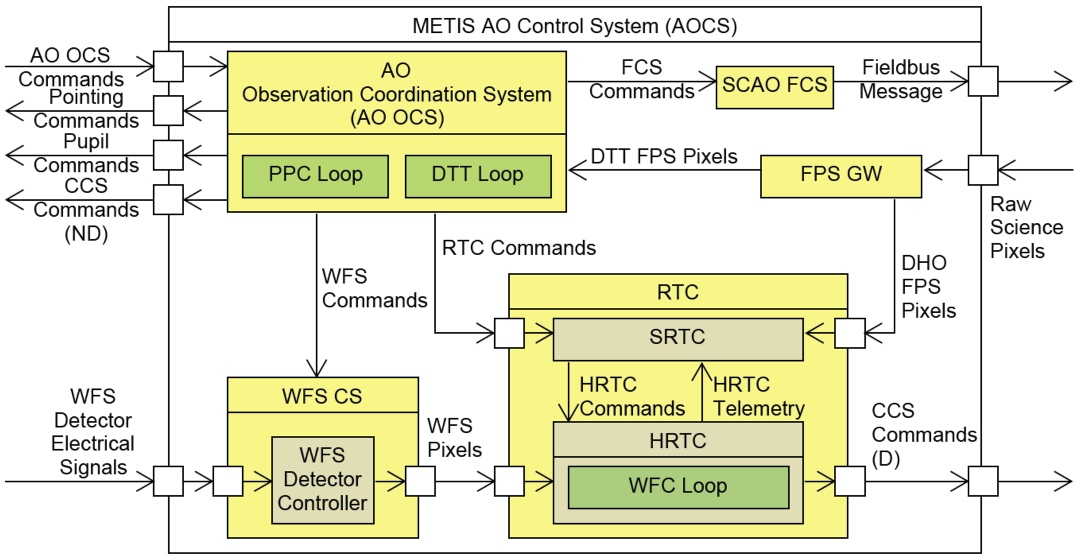

Figure 4. Overview of the main AOCS subsystems and the main data paths.[5]

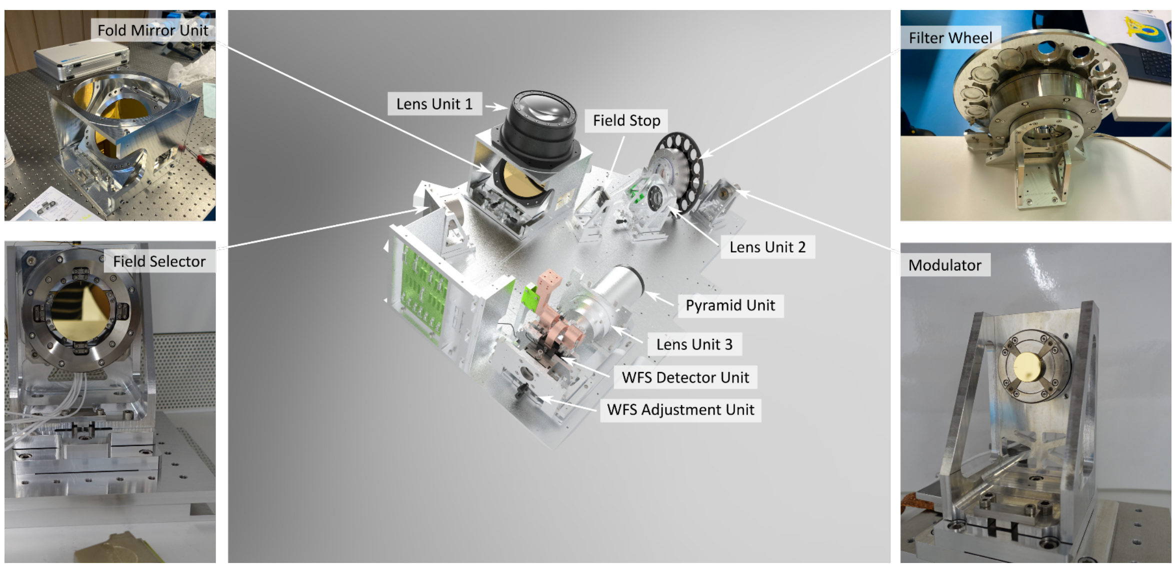

Figure 5. Assembled units of the SCAO Module. The Fold Unit, Field Selector, Filter Wheel and Modulator are assembled and undergo unit testing.

2.3 Test Cryostat

A dedicated test cryostat (Figure 6) was built to be able to test the SCAO Module under operating conditions already at subsystem level. With an outer diameter of 1835mm it provides sufficient space to host the SCAO Module. The cryostat provides the optical interfaces to the telescope simulator. Additional windows allow to place additional optical test equipment which will be used to measure the wavefront error in the optical path of the SCAO Module at the operating temperature of 70 K.

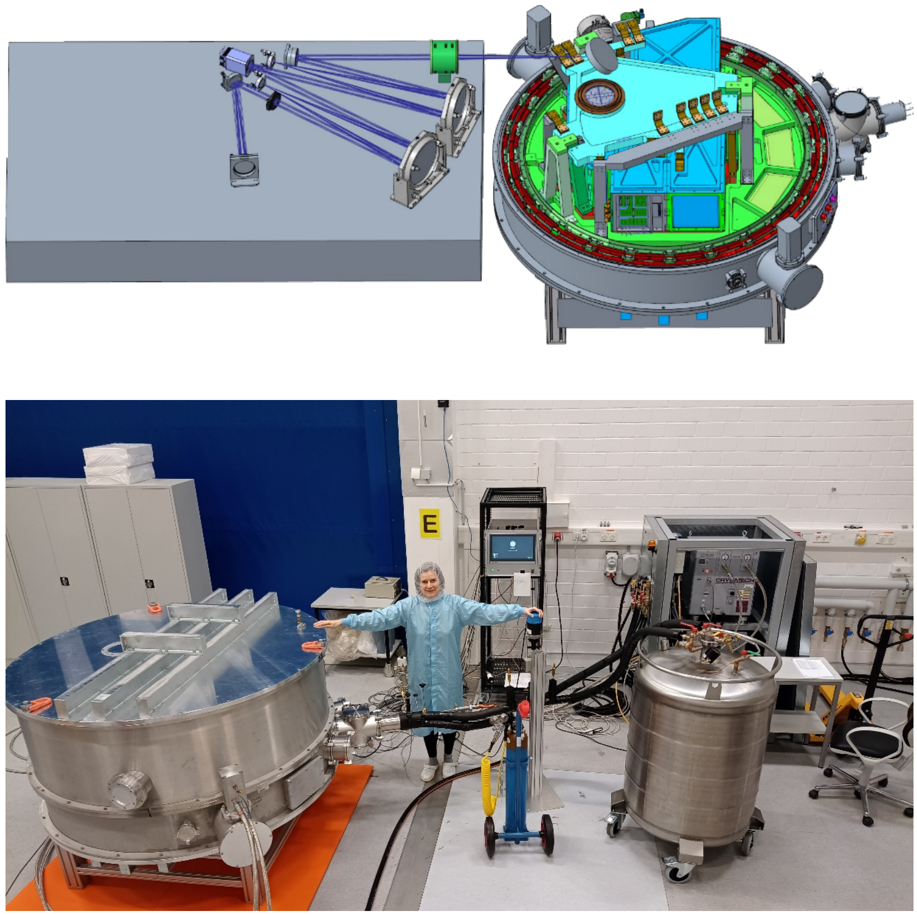

Figure 6. The SCAO test cryostat. It provides the operating environment for the SCAO Module prior to the integration into the METIS cryostat. The cryostat is fully operational and will be used in the subsystem test phase. It forms a test setup in conjunction with the telescope simulator (top left).

2.4 Telescope Simulator

To be able to test the AOCS together with the SCAO Module already at subsystem level, the core AO components (M4 and M5, CCS) in the telescope domain need to be substituted. It is not feasible to mimic all the numerous conditions that affect the temporal and spatial wavefront distribution at the focal station of the ELT on a test bench. The telescope simulator provides the core functions the ELT will eventually provide to operate METIS SCAO in closed loop.

Figure 7 shows the opto-mechanical design of the The MIni ELT TElescope SImulator (MITESI), which foresees an ALPAO DM820 as wavefront corrector. A more detailed discussion of the requirements and the design of MITESI is provided in a dedicated presentation.[6] It will be used to verify functional requirements during subsystem level as well as during system level testing. For subsystem tests it will feed its light into the test cryostat (Figure 6), while for system level testing MITESI will be installed in front of the METIS cryostat.

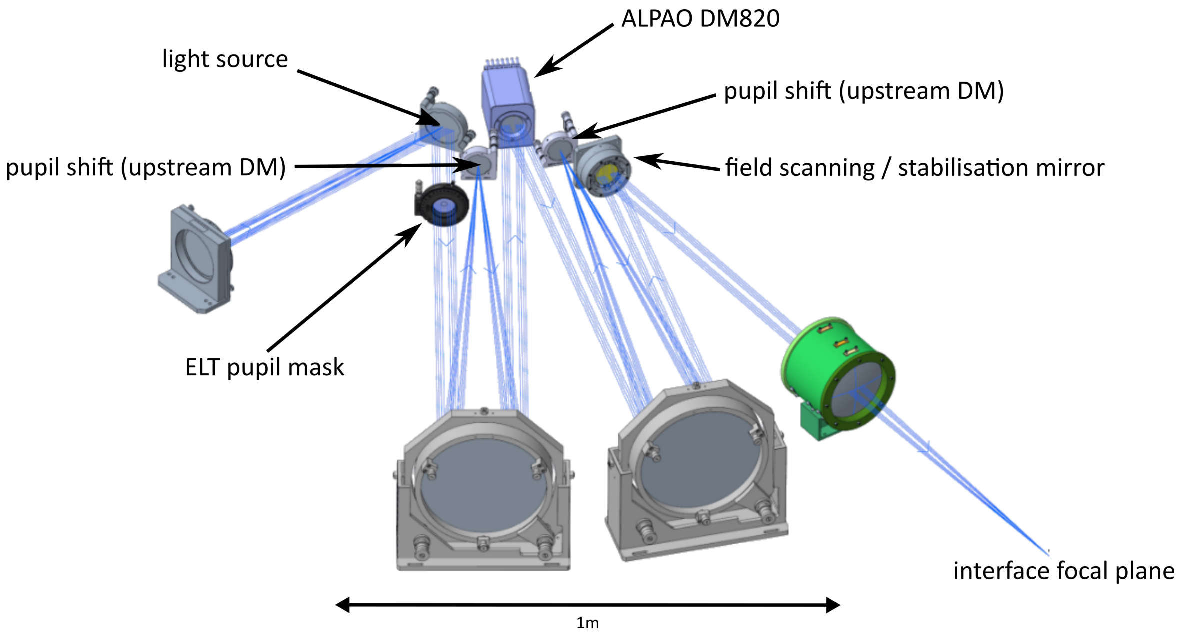

Figure 7. The telescope simulator MITESI[6] is used for subsystem and system tests.

3. SRTC VERIFICATION AT THE LBT

In the course of the implementation and testing of the SRTC the RTC development team has the opportunity to test mission critical software components on-sky before METIS is actually commissioned at the ELT. This is possible with the instrument LINC-NIRVANA at the Large Binocular Telescope (LBT). Figure 8 shows LINC-NIRVANA without its cover, when it was installed at the LBT in 2016.

The LBT operates adaptive mirrors as part of the telescope's bulk optics in a similar way as is foreseen for the ELT. The adaptive secondary mirrors (ASM) represent an earlier generation of the kind of mirrors that also get deployed as M4 at the ELT. LINC-NIRVANA provides a total of four wavefront sensors for multi-conjugate adaptive optics. It is quite versatile and is intended to be used as a platform for AO assisted technical demonstrations.[7,8] Among other options, it can be configured to work as an SCAO system. Such a configuration would provide a single on-axis pyramid wavefront sensor and wavefront correction with the ASM.

While the AO facilities at the LBT and at the ELT differ significantly, there are a number of similarities that can be taken advantage of to run technical demonstrations of SRTC components. It is not possible to replace the wavefront control loop itself. However, both LINC-NIRVANA and METIS recurrently adjust the command matrix, one of the core parameters of the wavefront control loop. It is derived from a (partially) synthetic calibration and takes into account the rotation of the pupil image on the wavefront sensor.[9] For METIS SCAO, the command matrix is generated by the Command Matrix Optimizer.[10] This is one example of an SRTC component that can be tested with LINC-NIRVANA. Other examples are the Pupil Position Monitor and the Misregistration Monitor. The experiment does not rely on but would benefit from upgrade paths of LINC-NIRVANA as a AO platform in the effort to extend the AO observing capabilities at the LBT.[8]

4. SUMMARY

METIS SCAO is in the subsystem MAIT phase. The implementation of the AO Control System and the integration of hardware units for the SCAO Module is ongoing. The integration and testing activities of METIS SCAO span all remaining development phases of METIS. To test many wavefront control tasks early on, a subsystem test setup, consisting of a dedicated cryostat and a telescope simulator is developed. Core SRTC tasks, the Command Matrix Optimization and misregistration monitoring, will be tested at the LBT.

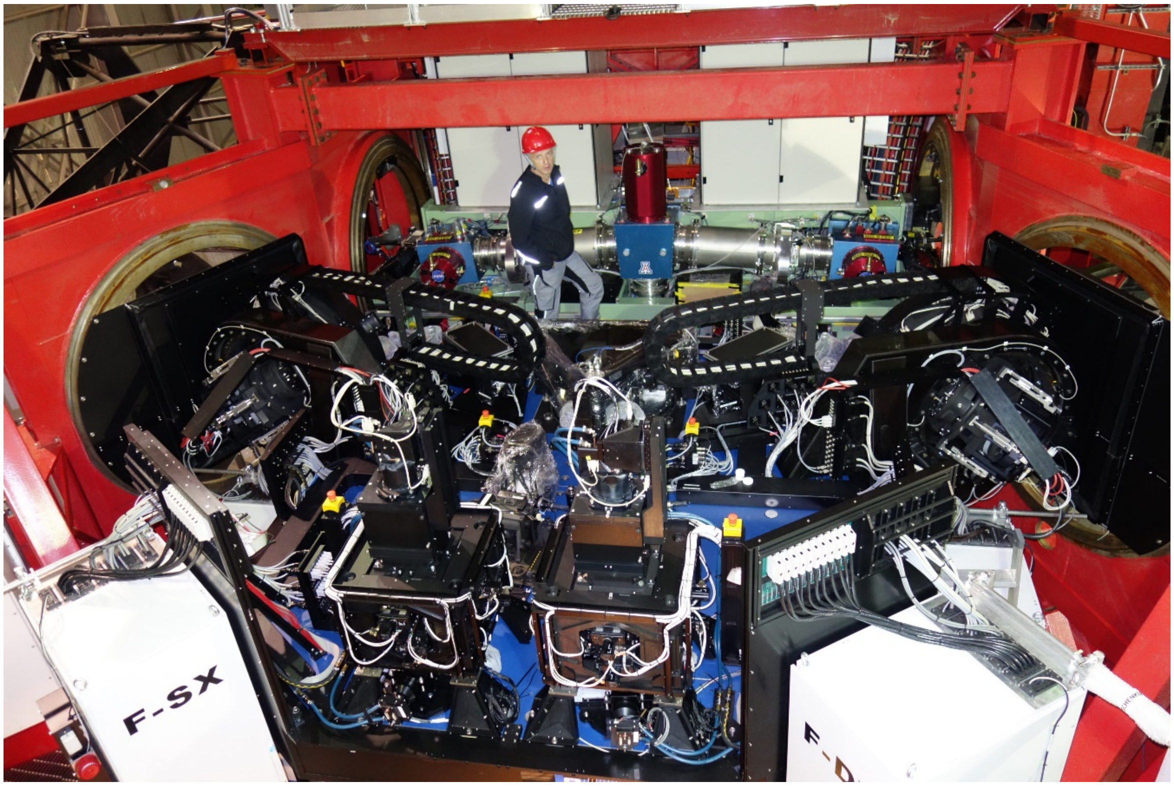

Figure 8. LINC-NIRVANA during the installation at the LBT.

REFERENCES

[1] Brandl, B., Bettonvil, F., van Boekel, R., Glauser, A., Quanz, S., Absil, O., Amorim, A., Feldt, M., Glasse, A., Güdel, M., Ho, P., Labadie, L., Meyer, M., Pantin, E., van Winckel, H., and METIS Consortium, "METIS: The Mid-infrared ELT Imager and Spectrograph," *The Messenger* **182**, 22–26 (Mar. 2021).

[2] Brandl et al., B., "Final design and status of the Mid-Infrared ELT Imager and Spectrograph, METIS," *Proc. SPIE*, 13096–38 (2024).

[3] Bertram, T., Bizenberger, P., van Boekel, R., Brandner, W., Briegel, F., Cárdenas Vázquez, M. C., Coppejans, H., Correia, C., Feldt, M., Henning, T., Huber, A., Kulas, M., Laun, W., Mohr, L., Naranjo, V., Neureuther, P., Obereder, A., Rohloff, R.-R., Scheithauer, S., Steuer, H., Absil, O., Orban de Xivry, G., Brandl, B., and Glauser, A. M., "METIS SCAO – implementing AO for ELT," in [*Adaptive Optics for Extremely Large Telescopes (AO4ELT7)*], 23 (June 2023).

[4] Kulas, M., Hugo, C., Steuer, H., Bertram, T., Correia, C., Neureuther, P., and Briegel, F., "The RTC for METIS SCAO," in [*Adaptive Optics for Extremely Large Telescopes (AO4ELT7)*], 27 (June 2023).

[5] Kulas, M., Absil, O., Bertram, T., Briegel, F., Coppejans, H., Correia, C., De Mester, W., Feldt, M., Naranjo, V., Obereder, A., Orban de Xivry, G., and Steuer, H., "METIS AOCS at the beginning of MAIT," *Proc. SPIE*, 13101–145 (2024).

[6] Mortimer, D. J., Cárdenas Vázquez, M. C., Bertram, T., Bizenberger, P., Häberle, M., Huber, A., and Scheithauer, S., "Building an ELT simulator in the lab for subsystem testing of METIS/SCAO," *Proc. SPIE*, 13097–137 (2024).

[7] Bergomi, M. e. a., "NirvanaVIS, exploiting ground-layer AO correction for speckle holography at visible wavelengths," *Proc. SPIE*, 13096–359 (2024).

[8] Ragland, S. e. a., "Emerging adaptive optics facility at the Large Binocular Telescope Observatory," *Proc. SPIE*, 13097–20 (2024).

[9] Arcidiacono, C., Santhakumari, K. K. R., Viotto, V., Bergomi, M., Briegel, F., Bertram, T., Marafatto, L., Herbst, T., Farinato, J., Ragazzoni, R., Hofferbert, R., Kürster, M., Kittmann, F., Berwein, J., and Baumeister, H., "The calibration procedure of the LINC-NIRVANA ground and high layer WFS," in [*Adaptive Optics Systems VI*], Close, L. M., Schreiber, L., and Schmidt, D., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10703**, 107034R (July 2018).

[10] Steuer, H., Feldt, M., Bertram, T., Correia, C., Obereder, A., Coppejans, H., Kulas, M., Scheithauer, S., Cardenas Vazquez, M. C., Mortimer, D., Orban de Xivry, G., and Absil, O., "Evolving the METIS soft real-time control system out of the simulation environment," *Proc. SPIE* (2024).