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METIS instrument: status of the IMAGER, the SCAO and MITESI

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Abstract

METIS, the powerful Mid-infrared Imager and Spectrograph for the Extremely Large Telescope (ELT), an ELT's first-generation instrument, passed its system final design review in November 2022. It is currently in its Manufacturing, Assembly, Integration and Verification (MAIV) phase, with first light currently planned for 2029. The Max Planck Institute for Astronomy (MPIA) is the second largest consortium partner and is responsible for the Imager (IMG) and the Single-Conjugate Adaptive Optics (SCAO). The MPIA is also building a "MIni" ELT TElescope SImulator (MITESI) to validate ELT instrumentation. In this contribution, we present the current status of these three systems: the optics design, the final opto-mechanics and their ongoing MAIV.

1 Introduction

METIS is a first-generation instrument for the ELT, Europe's next-generation 39-metre ground-based telescope for optical and infrared wavelengths, which is currently under construction at the European Southern Observatory (ESO) site at Cerro Armazones in Chile. METIS is a multi-tool instrument that will offer diffraction-limited imaging, low/medium-resolution slit spectroscopy and coronagraphy for high contrast imaging between 3 and 13 microns (IMG) and high resolution integral field spectroscopy between 3 and 5 microns (LM Spectrograph). Imaging and spectroscopy can be combined with coronographic modes for high contrast imaging. The main scientific objectives of METIS are the detection and characterisation of exoplanets, the study of proto-planetary disks, and the formation of planets. The instrument current status is presented in [3], and its evolution and science drivers have been reported in previous SPIE proceedings (i.e. [4]).

METIS consists of two science modules: (1) A diffraction-limited Imager (IMG) with two wavelength channels, one for the LM bands and one for the N band, and (2) an Integral Field Unit (IFU)-fed, diffraction-limited, high-resolution LM-bands spectrograph (LMS) with a field of view of half a square arcsecond and a spectral resolving power of 100,000.

The light from the ELT enters the METIS cryostat, and passes through the common fore optics (CFO), which provides image de-rotation, pupil stabilisation and chopping capability, and serves the both science modules (science beam 2.9 – 13.5 microns), as well as the Single-Conjugate AO pyramid wavefront sensor (SCAO) module (1.4 – 2.4 microns) ([1]). The warm calibration unit (WCU) subsystem is located on top of the cryostat, and operates at the ambient temperature ([7] and [8]).

Figure 1, on the left shows the functional diagram of the METIS optical system, including all functional optical components, where the IMG is represented on the top right and the SCAO on the bottom left. Figure 1, on the right illustrates the location of the IMG and SCAO subsystems within the METIS cryostat. Both subsystems, IMG and SCAO, will be fully integrated and tested at MPIA, in Heidelberg, Germany, before being integrated at METIS, in Leiden, the Netherlands.

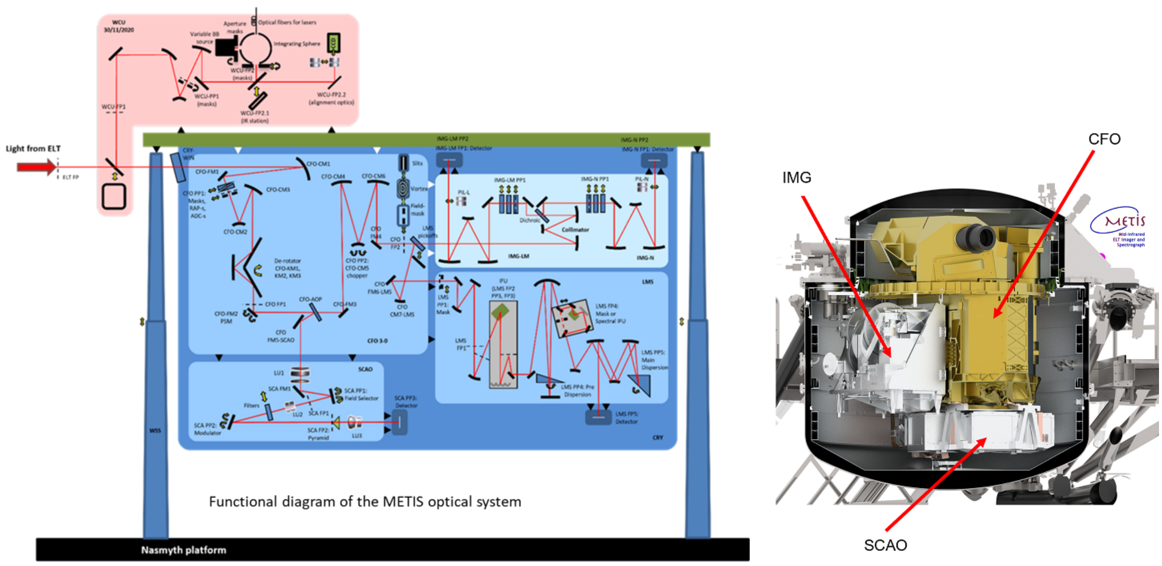

Figure 1: Left: Functional diagram of the METIS optical system. All functional optical components are represented here, the beam is reduced to the optical axis. Right: Overview of the mechanical design of the METIS cryostat. The IMG, SCA and LMS (not shown in this view) are mounted to the sides and bottom of the cold central structure and the CFO.

2 The IMG: Final optical and cryo-optomechanical design

The IMG subsystem provides diffraction-limited imaging capabilities and low/medium resolution grism spectroscopy in two channels: the first covers the atmospheric L and M bands with a field of view of 11x11 arcsec, the second covers the N band, with a field of view of 14x14 arcsec. Each channel is equipped with a HAWAII-2RG detector for the LM band and a GeoSnap detector for the N band.

The summary of the IMG specification is shown in Fig. 2, left. The optical solution consists of a collimator serving two cameras, all reflective optics and athermal design (optical quality does not change with temperature). The collimator and the two cameras are Three-Mirror Anastigmat (TMA) systems. All mirror surfaces are freeform, defined as Zernike surfaces polished directly on bare aluminium. In short, in the final optical design (Fig. 3 left), following the direction of the light coming from the CFO FP2, there is the collimator which collimates the light and feeds the two cameras: LM channel and N channel. In the collimated section, the LM and N bands are split by a dichroic element that reflects the longer wavelengths and transmits the shorter ones. The dispersive elements for long slit spectroscopy, grisms, are introduced into the collimated beam at the location of the cold stop pupil. The optical design also incorporates a precise pupil re-imaging optics for each channel, allowing the positioning of high contrast imaging masks for coronographic applications (Fig. 2, right).

IMG			
Working temperature 40 K			
Collimator			
Optics	TMA Common for both channels		
Input F#	17.75		
Wavelength range	2.9 – 13.5 µm		
Field of View	14 x 14 arcsec		
Focal length	800 mm		
Pupil diameter	45 mm		
Dichroic			
Input wavelength 2.9 – 13.5 µm			
Transmitted wavelength range	L&M bands	Reflected wavelength range	N band
Camera LM channel		**Camera N channel**	
Optics	TMA	Optics	TMA
Input beam diameter	45 mm	Input beam diameter	45 mm
Wavelength range	L: 2.9 - 4.2 µm M: 4.5 - 5.2 µm	Wavelength range	N: 7.5 – 13.5 µm
Imaging Field of View	10.85 x 10.85 arcsec	Imaging Field of View	13.925 x 13.925 arcsec
Focal length	793 mm	Focal length	639
Output F#	17.64	Output F#	14.2
Pixel sampling	5.47 mas/px	Pixel scale	6.67 mas/px
Detector	Hawaii-2RG 2048 x 2048 px 18 µm/px	Detector	GeoSnap 2048 x 2048 px 18 µm/px
$R \geq 200$ slit spectroscopy	L band → R_{max} 1500 M band → R_{max} 3500	$R \geq 200$ slit spectroscopy	N band → R_{max} 400
Pupil viewing capability	L band @ 4 µm	Pupil viewing capability	N band @ 9.1 µm

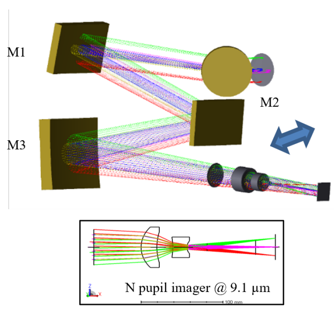

Figure 2: Left: IMG optics specifications in a nutshell. Right: Optical layout of the pupil re-imaging optics.

To maintain the stable low temperatures required for good performance at mid-infrared wavelengths, the IMG operates at 40 Kelvin to provide detector-limited performance in both bands, while the METIS CFO operate at 70 Kelvin. A kinematic mount has therefore been implemented to allow for the temperature difference while keeping the optics aligned to the demanding accuracy required for high contrast imaging. Challenging requirements suitable for high contrast imaging require a thorough integration and verification, especially considering the size, complexity and the operating temperature of the instrument.

The optomechanical design (Fig. 3 right) consists of three optical units, the Collimator, Camera LM and Camera N. They are built externally in close collaboration with the Fraunhofer Institute for Applied Optics and Precision Engineering (IOF), in Jena, Germany. As part of this cold optics procurement, the mechanical design, manufacturing and verification at ambient environment will be carried out by IOF in Jena, and the units verification at the working environment (i.e., 40 Kelvin), will be carried out in the IMG test cryostat in Heidelberg in collaboration with the MPIA. The final optical and opto-mechanical design and manufacturing is described in [5], while the IMG assembly, integration and verification is described in [2].

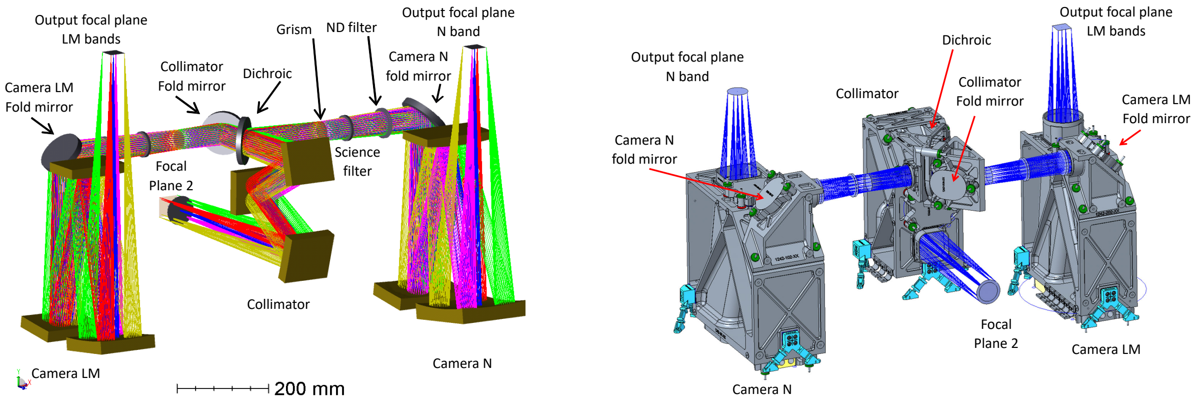

Figure 3: Left: IMG optical layout. Right: Cryo-optomechanical design.

3 The METIS SCAO subsystem

To reach diffraction-limited performance, METIS will use a single-conjugate adaptive optics system to compensate for atmospheric turbulence. METIS SCAO is the real-time wavefront control system that enables diffraction-limited observations. To achieve the scientific goals of METIS, a Strehl Ratio >93% at 10 μm and >60% at 3.7 μm is required. SCAO will be used for all observing modes, with High Contrast Imaging imposing the most challenging requirements on its performance. To achieve the desired (post-processed) contrast level (contrast $< 3 \cdot 10^{-5}$ for an angular separtion of 0.02 arcsec and λ= 3.7 μm), 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.

The wavefront control system for METIS is based on several distributed entities: on the SCAO Module and the AO Control System in the instrument domain, as well as on the corrective optics (M4 and M5) and the Central Control System in the telescope domain. The SCAO Module is a pyramid wavefront sensor operating in the K-band (H is also supported) with a spatial sampling of

90 × 90 subapertures and a SAPHIRA detector. It is in-built inside METIS, in the 70 K cryogenic environment. It has optomechanical actuators for field selection and modulation (up to 1 kHz) of the natural guide star in the accessible field of view of 27 arcsec on-sky provided by the CFO.

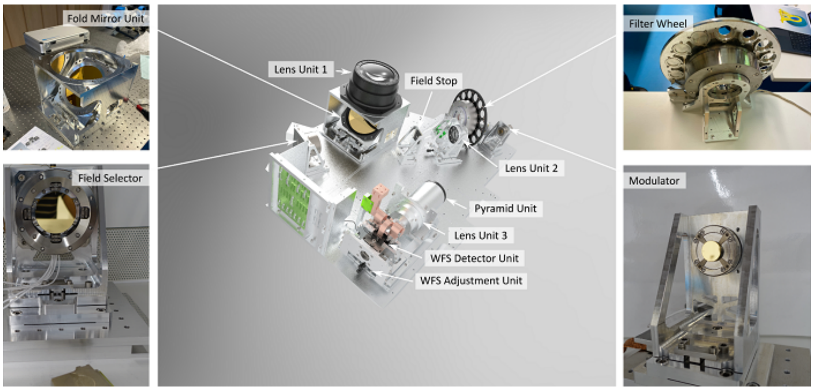

Figure 4: SCAO module optical design (center). Detail of units already built (left and right).

The more recent description of the METIS SCAO can be found in [1]. Figure 4), center, shows the optomechanical design of the SCAO Module, and, on the sides, some of the already manufactured units, such as the Filter Wheel and the Fold Mirror unit, and the actuators, Field Selector and Modulator.
For the cryogenic verification of the METIS SCAO requirements, MPIA has built a dedicated test cryostat to ensure a smooth assembly in METIS during the final system integration in Leiden (Netherlands).

4 MITESI: a "MIni" ELT TElescope SImulator

A telescope simulator will be used for comprehensive testing of the SCAO subsystem. The MITESI project comprises of both, an optomechanical system and a software component. It is described elsewhere in [6]. Its objective is to produce hardware with dedicated functionalities that will allow to test and verify requirements of instruments for the ELT in the laboratory prior to the installation on the telescope.

The optomechanical setup mimics a number of features of the ELT, such as the unique pupil shape, a deformable mirror (ELT M4), a field steering mirror (ELT M5) and means to introduce a diffraction-limited light source on SCAO Module. It provides the complete accessible field of view that METIS supplies to SCAO (diameter 27 arcsec on-sky). Different disturbances can be introduced: temporally and spatially variable phase distortions, pupil image motion, M4 image motion (relative to the entrance pupil). An ALPAO 820 deformable mirror and a pupil steering mirror substitute are used to compensate for these disturbances (and also to introduce them). Figure 5) on the left, shows the optical layout of the telescope simulator, and on the right, MITESI placed in front of the SCAO test cryostat. MITESI will be also used at METIS system level testing in the Leiden integration facility to test the overall Adaptive Optics performance of the METIS instrument before shipment to the ELT.

Acknowledgments

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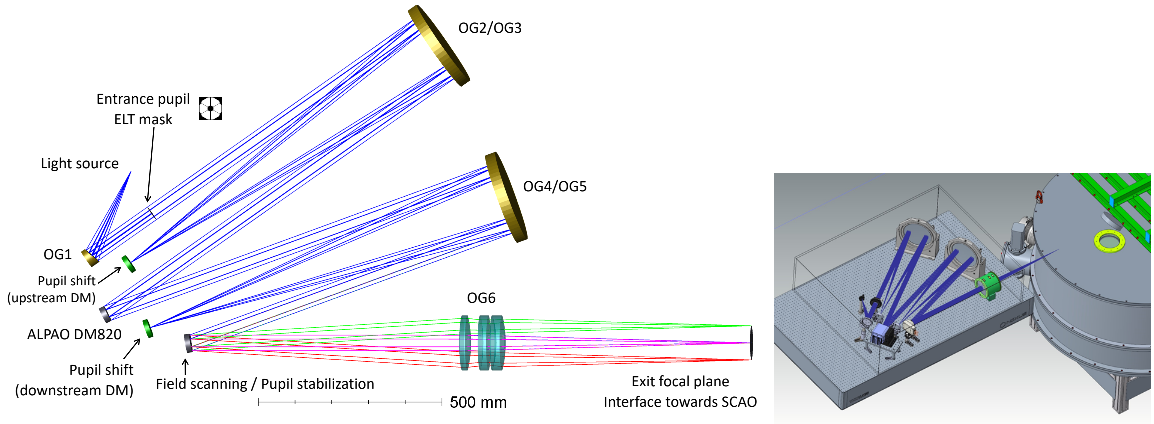

Figure 5: Left: MITESI optical layout. The six Optical Groups (OGs) of MITESI with their functionality described in the captions. Right: MITESI will be placed in front of the SCAO test cryostat.

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