Designing the METIS SCAO and LTAO systems

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ABSTRACT

METIS, the Mid-nfrared E-ELT Imager and Spectrometer, will be providing high-sensitivity imaging and high-resolution spectroscopy in the mid-infrared (3-19 micrometer) to the E-ELT. In order to achieve the exceptional performance required by its driving science cases, exoplanets and proto-planetary disks, METIS will be featuring two Adaptive Optics (AO) systems—a first-light Single Conjugate Adaptive Optics (SCAO) system, complemented by a Laser Tomographic Adaptive Optics (LTAO) system, most likely, a few years after first light. METIS, being one of the three first light science instruments on the European Extremely Large Telescope (E-ELT), will be one of the first instruments using the integrated deformable mirror of the E-ELT for its Adaptive Optics (AO) correction.

The internal SCAO system designed to maximize the performance for bright targets and has its wavefront sensors (WFSs) build inside the METIS cryostat to minimize the number of warm surfaces towards the science detectors. Although the internal dichroic will reflect all light short wards of 3 micrometers towards the WFS, only the IR light will most likely be used, mainly due to the expected improved performance at longer wavelengths for the WFS. A trade-off has been made between both visible versus infrared wave front sensing as well as Pyramid versus Shack-Hartmann, under various observing conditions and target geometries, taking into account performance, target availability, reliability and technology readiness level. The base line for the SCAO system is to minimize system complexity, thereby ensuring system availability and reliability even under first-light conditions.

Since the SCAO system will require a bright guide star near the science target, it can only be used for a limited number of targets. The LTAO system, consisting of up to 6 LGS and up to 3 low-order NGS WFS and located outside the cryostat, is designed to increase the sky coverage on arbitrary targets to >80%. Investigations are ongoing if the internal SCAO system can be used as either a Low-Order WFS or metrology system.

This paper describes the most recent developments of the SCAO and LTAO designs.

Keywords: Mid-OR, Adaptive Optics, ELT, SCAO, LTAO

1. INTRODUCTION

METIS is the mid-IR instrument for the E-ELT[1]. It is approximately one third into its Preliminary Design Phase, with the Preliminary Design Review expected by the end of 2017. Contrary to classical mid-IR instrumentation for the current

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generation of 8-10-meter class telescopes, METIS will *require* adaptive optics (AO) to reach its science goals. The METIS AO system is introduced in two phases:

- At first light of METIS, it will contain a Single Conjugate Adaptive Optics (SCAO) system. The SCAO system will be the work horse AO system and aims at high performance using bright targets. Although the SCAO system will by no means be simple, the goal is to provide a no-frills SCAO system that will work on a telescope that itself is still being tuned.
- A Laser Tomography AO system is expected to be installed at a later stage, although even at these early stages provisions need to be made that will allow the adding of the LTAO system at a later stage. The LTAO will, at cost of complexity, provide a significantly increased sky coverage (from less than 1% for random targets on the sky for the SCAO system, to more than 80% for LTAO). The goal is to provide a similar level of correction as the SCAO system under beneficial conditions. The LTAO will use the internal SCAO Wavefront Sensor (WFS) for at least system-to-system stabilization, but potentially also for low order corrections.

The main requirements for the METIS (SC)AO system are:

Description	Requirement	Goal
Strehl Ratio at 3.7 μm (m_K < 10, median seeing)	> 60%	> 80 %
Strehl Ratio at 10 μm (m_K < 10, median seeing)	> 93%	> 95%
Contrast @ 5 λ/D (m_L < 6)	$3x10^{-5}$	10^{-6}
Sky Coverage LTAO	>80%	100%

The schematic layout of METIS is shown in Figure 1, see also the paper by Agocs[2].

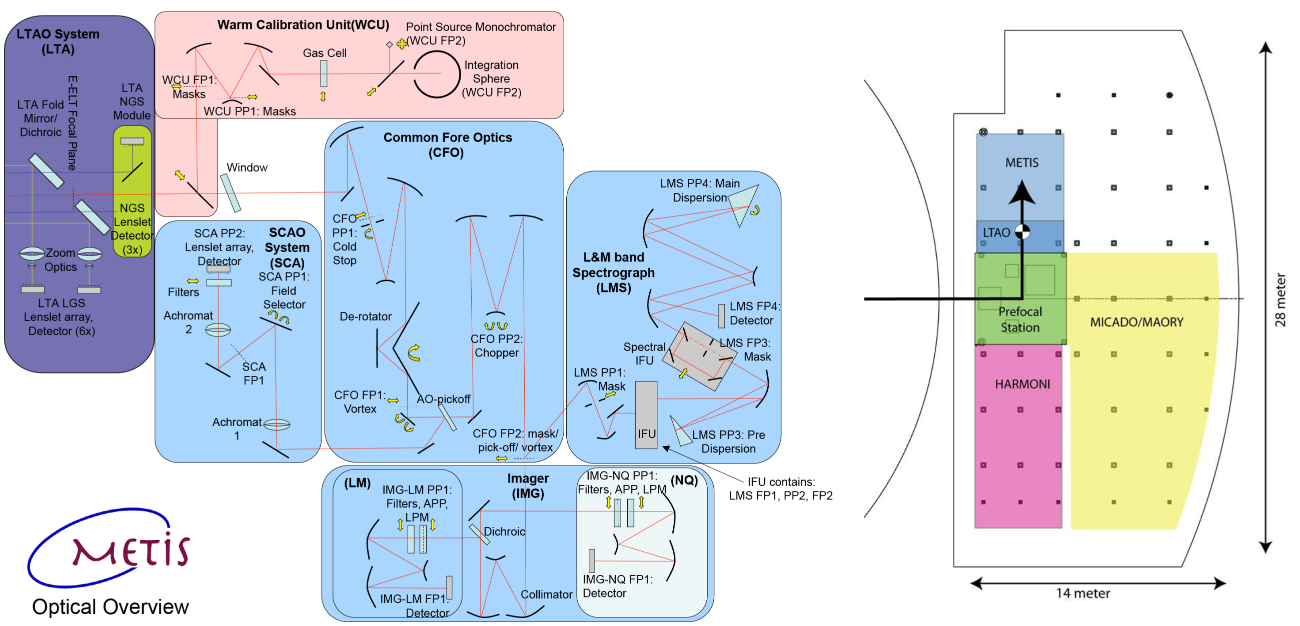

Figure 1. Schematic Layout of METIS and its LTAO system. Both the LTAO system as well as the warm calibration unit are located outside a cryostat, while all other components, including the SCAO WFS are inside the cryostat.

The optical layout of METIS provides for all sub-systems inside the cryostat, with only the LTAO system and the Warm Calibration Unit (WCU) outside the cryostat. The SCAO WFS is located inside the cryostat, which means that all components need to be compatible with a cryogenic environment. The light for the SCAO WFS is picked-off as far as possible downstream in the optical path to minimize non-common-path aberrations (NCPA). Specifically, it allows for correction of the bearing run-out of the de-rotator, greatly simplifying the complexity of this de-rotator. Since the LTAO system is outside the cryostat, there will be significant image motions between the LTAO output focal plane and the METIS entrance focal plane. We intend to use either the SCAO WFS for low-order WFS or, when using a set of Natural Guide Star (NGS) low-order sensors in the LTAO system, use the signal from the SCAO WFS to compensate for residual image motion between METIS and the LTAO system.

2. SINGLE CONJUGATE ADAPTIVE OPTICS

The SCAO system is an integral part of METIS, located in the cryostat to minimize thermal background due to a dichroic pick-up, to minimize residual motion between the SCAO-corrected focal plane and the METIS detector focal plane and to minimize residual NCPA. A first order trade-off study was made to reduce the number of options that needs to be studied in detail for the SCAO wavefront sensor. Table 1 shows the trade-off matrix, comparing pyramid WFS versus Shack-Hartmann wavefront sensor, under various geometries and observing conditions, using a grid of simulations performed using YAO[3].

Sensor Type		Pyramid WFS				Shack-Hartmann WFS											
Band		V		NIR		V						NIR					
Subaperture Diameter		0.5m	1.0m	0.5m	1.0m	0.5m			1.0m			0.5m			1.0m		
# Pix per Subaperture		2	2	2	2	2	4	6	2	4	6	2	4	6	2	4	6
Brightness	Seeing																
Strehl at 3μm																	
Very Bright	good	0.95	0.88	0.97	0.82	0.95	0.95	0.96	0.85	0.87	0.88	0.93	0.95	0.96	0.84	0.87	0.88
	median	0.90	0.73	0.94	0.84	0.89	0.90	0.92	0.70	0.75	0.77	0.87	0.91	0.92	0.67	0.75	0.77
	bad	0.62	0.27	0.83	0.61	0.74	0.79	0.79	0.32	0.52	0.53	0.68	0.79	0.81	0.37	0.49	0.51
Bright	median	0.90	0.72	0.94	0.83	0.88	0.90	0.91	0.69	0.74	0.76	0.86	0.90	0.90	0.69	0.74	0.75
	bad	0.61	0.27	0.83	0.60	0.73	0.78	0.78	0.31	0.50	0.51	0.68	0.77	0.78	0.35	0.47	0.49
Faint	median	0.90	0.70	0.82	0.73	0.85	0.86	0.85	0.64	0.63	0.61	0.70	0.66	0.50	0.53	0.53	0.37
	bad	0.59	0.26	0.67	0.44	0.66	0.64	0.66	0.22	0.28	0.30	0.49	0.45	0.35	0.22	0.24	0.19
Contrast at 3μm, at 3λ/D (x 10-4)																	
Very Bright	good			0.19	0.18							0.16	0.42	0.43	0.18	0.32	0.35
Residual Tip-tilt performance (mas)																	
Very Bright	good			0.15	0.14							0.47	0	0	0.82	0.19	0.03
Technology Readiness																	
Field Selector		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
WFS Detector		8	8	8	8	4	4	4	8	8	8	4	4	4	8	8	8
Modulator		3	3	3	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pyramid Prism		TBD	TBD	TBD	TBD	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Lenslet Array		N/A	N/A	N/A	N/A	8	8	8	8	8	8	8	8	8	8	8	8
ADC		TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
# Pix per Subaperture		2	2	2	2	2	4	6	2	4	6	2	4	6	2	4	6
Subaperture Diameter		0.5m	1.0m	0.5m	1.0m	0.5m			1.0m			0.5m			1.0m		
Band		V		NIR		V						NIR					
Sensor Type		Pyramid WFS				Shack-Hartmann WFS											

Table 1. Summary of a simulation grid on optimal WFS geometry under a variety of observing conditions. The brightness refers to the brightness of the central Natural Guide star and correspond to 10 (faint), 100 (bright), and 10,000 (very bright) counts per sub-aperture per loop cycle. The seeing refers to good (0.44"), medium (0.68") and bad (1.2") seeing, using a zenith angle of 30 degrees. The AO loop frequency is for these simulations fixed at 1 kHz, with a loop delay of 2 frames. The outer scale was set at L_0 = 25 m. Indicated in green are configurations that meet the METIS requirements, while red numbers indicate incompatible configurations.

An IR WFS is preferred as METIS is expected to observe a significant number of embedded sources, which are much brighter in the IR than in the visible. Both the Pyramid WFS as well as the Shack Hartmann (SH) perform well using 0.5 meter sub-apertures, operating in the IR. METIS SCAO favors an infrared e-APD detector (Selex Saphira), which currently only exists with a format of 320x256 pixels. This means that the SH, using an existing detector, is limited to 2x2 pixels per sub-aperture, but developments are ongoing to develop 512x512 pixel devices, up to 1024x1024, allowing for 4x4 and 6x6 pixels per sub-aperture configuration. For the Pyramid, the main technical challenge is the modulator, a ~50 mm mirror that moves the PSF a few times per integration time, by a few diffraction limits over the pyramid to increase the dynamical range and decreasing the sensitivity to large fluctuations in tip-tilt. This modulator is currently not available and several potential suppliers have already indicated that such a device will not be available in the near future. Alternatively, a diffuser could be employed with similar function, but this either requires a set of diffusers to allow for varying conditions or a significant loss in performance. Furthermore, this technique has not yet reached sufficient level of maturity to make it a baseline choice. Therfore, the current baseline for the METIS SCAO WFS is a Shack-Hartman WFS, with 0.5 meter sub-apertures (~74 sub-apertures over the diameter of the pupil), operating at infrared wavelenghts.

The baseline for the METIS optical design is shown in Figure 2.

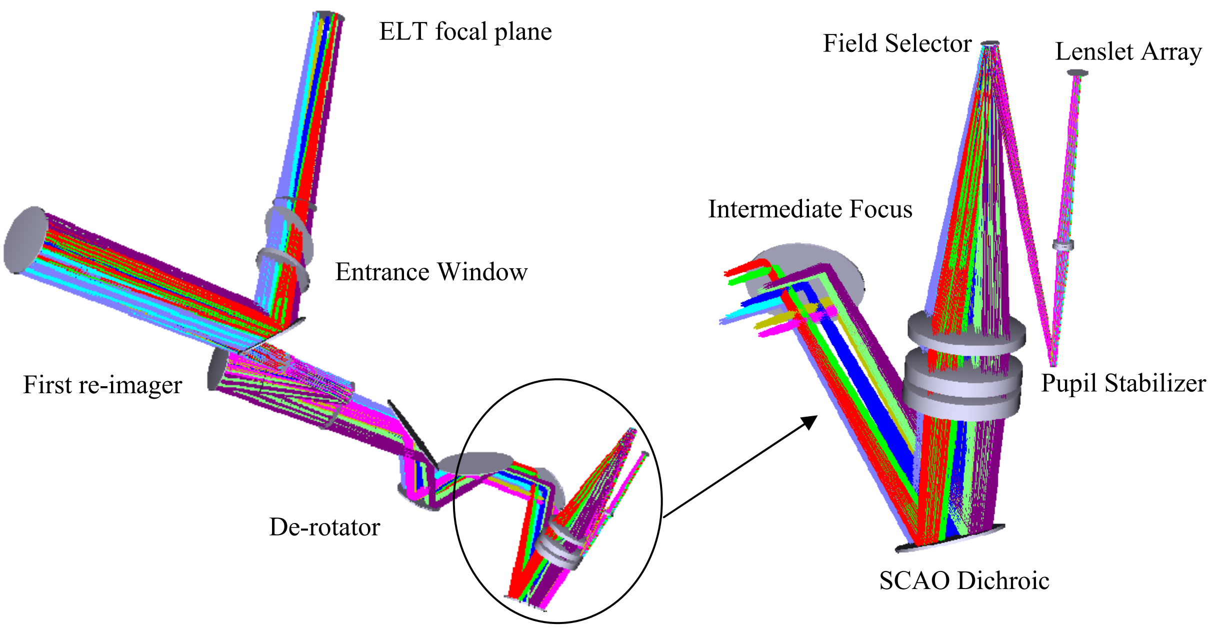

Figure 2. The optical design of the METIS Common Fore Optics (CFO), showing the optical path to the SCAO WFS. In the left image the full CFO are shown, with on the right a zoom into the SCAO WFS. Individual components have been labeled.

The SCAO WFS features a field selector, for selecting (off-axis) guide sources, a pupil stabilizer—stabilizing the relative positions of actuators with respect to the sub-apertures of the wavefront sensor—and a ~74x74 lenslet array to sample the pupil with 0.5 meter sub-apertures. No optical pupil de-rotation is foreseen and the interaction matrix is de-rotated in software.

We're expanding our simulations for the selected configuration to include the effects of the (large) spiders, truncation of the pupil by the internal cold-stop, the control loop for the pupil registration and pupil control for the science channel. Furthermore, the E-ELT provides a rather dynamic environment with both telescope as well as instrument vibration, a periodic low-order optimization of the telescope and relative large offsets between the focus provided by the telescope with respect to where METIS expects the focus, leading to a requirement for secondary guiding. METIS will require the ability for guiding on extended sources; many sources that are still unresolved on 8-meter class telescopes will become resolved on the E-ELT. Lastly, interaction with the science camera is required to provide estimates on the residual NCPA. Measurement and correction of the NCPA will be very important in achieving the ultimate contrast with METIS.

3. LASER TOMOGRAPHY ADAPTIVE OPTICS

Although an LTAO system is foreseen for METIS, the development of the LTAO is delayed with respect to the rest of METIS. This means that at this point only a straw-man design of the LTAO system is being pursued in order to allow addition of the LTAO at a later stage.

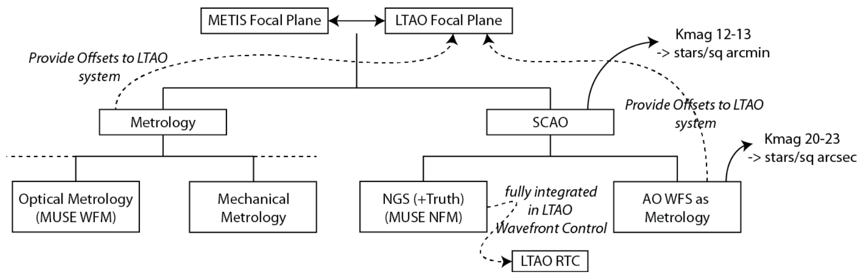

Figure 3. Options for maintaining a stable science focal plane in the light of the system separation of METIS and the LTAO system.

The main constraints on the LTAO system are:

- A goal performance close to the SCAO performance
- At least 80% sky coverage, with a goal of 100%
- Maintain a clear science field of 16.5" (including the chopping range)
- A space envelope not exceeding 4.5 meter in diameter, centered on optical beam from the Pre-Focal Station (PFS) towards METIS, and placed between the PFS space envelope (starting at 1 meter before the E-ELT focus) and the METIS space envelope (starting 0.75 meter after the E-ELT focus).
- A maximum Laser Guide Star (LGS) separation of 1.3' radius, given by the maximum transmitted field by the Pre-Focal Station.
- Minimize LGS separation for maximum performance of the tomographic reconstructors
- Minimize complexity to maximize System stability
- Maintain a stable reference between the LTAO output focal plane and the METIS detector planes (i.e. dynamic correction, including NCPA). This is indicated also in Figure 3.

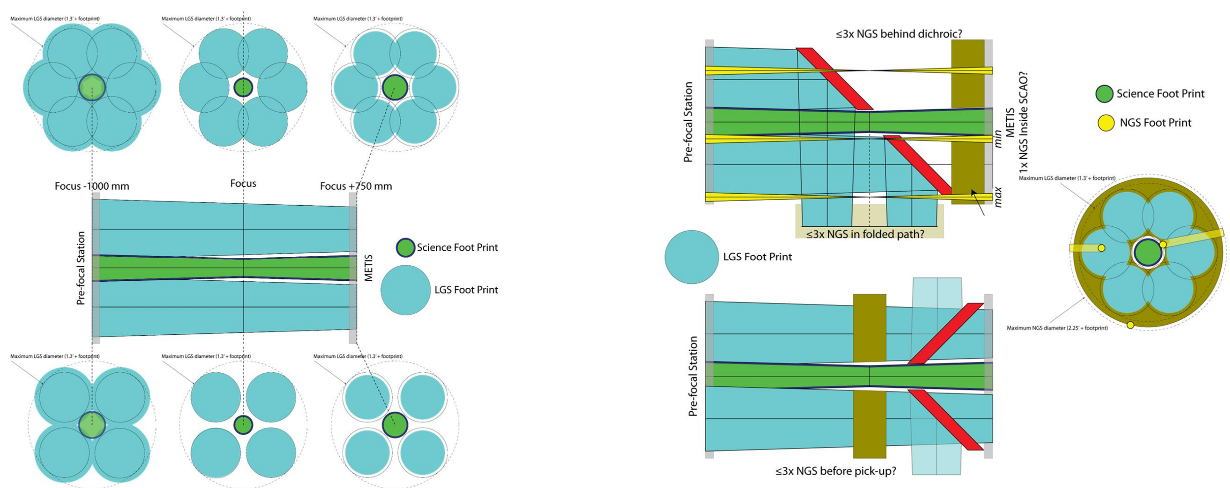

Figure 4. Left panel: Possible configurations based on the requirements from the transmitted field by the Pre-Focal station and the clearance of the science field of view. Configurations are shown for 6 and 4 lasers. Right panel: For 5 and 6 lasers, only a folding of the full field in one direction is possible; the individual laser footprints overlap in the full LTAO space envelope. For 4 or less lasers, footprints separate and the individual LGS can be picked-up directly. Depending on the required configuration of stars for the lower-order sensing, several locations are available.

The standard E-ELT configuration features 6 Laser Guide Stars. Using the above constraints on minimum (clear science field) and maximum (transmitted FoV by PFS) LGS radius, only a very limited range in LGS separation is available to the METIS LTAO system (1.25-1.30 arcminute radius for 90 km distance towards the sodium layer), see also Figure 4. For this configuration the LGS footprint only clears the science footprint at ~300 mm before the focus, severely limiting the options for the LGS pick-up, when assuming that the *full* LGS footprint needs to be transmitted. Using 5-6 lasers, the individual laser foot prints do not separate within the LTAO space envelope and only a full annular mirror or annular dichroic mirror can be used to deflect the LGS until they can be separated. For 4 or less LGS, individual lasers can be deflected, making it easier to multiplex, although de-rotation becomes significantly more challenging.

The performance of the LTAO system, based on a perfect sensing of the lower orders by an external NGS WFS is shown in Figure 5. For the given constellation, the performance is well within the requirements and even meets the goal as specified for the SCAO system. Keep in mind that this is for a configuration near zenith for median seeing conditions and that performance will drop significantly when observing away from zenith. The exact performance versus zenith angle is still under investigation.

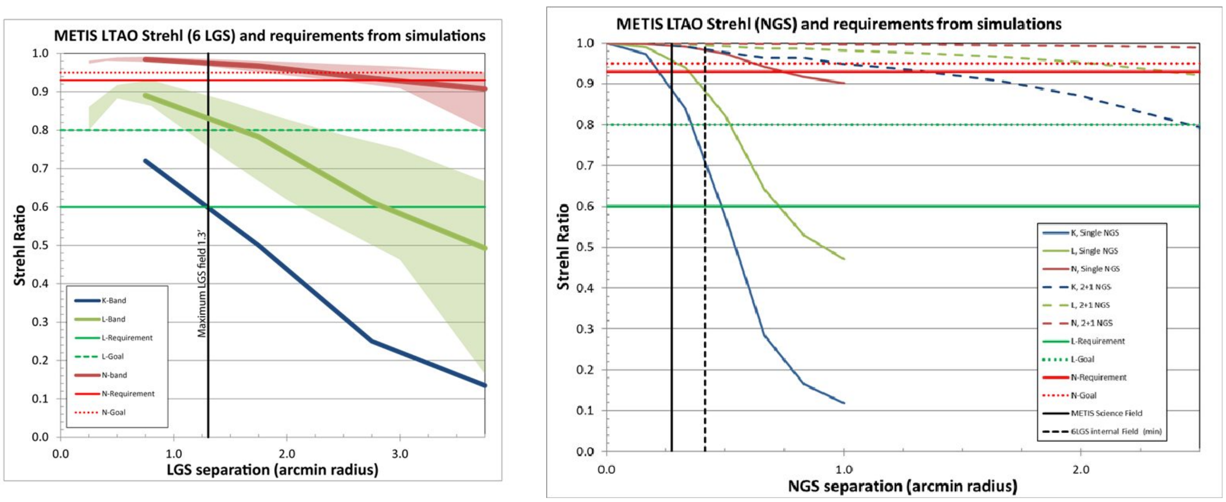

Figure 5. Left: Performance of the LTAO system based on perfect sensing of the low-order modes, using 6 LGS under median seeing conditions and using a K-band wavefront sensor. The solid lines indicate the performance of the system in from top to bottom, the N-, L- and K-bands. The bands surrounding these lines indicate the results from several different models, indicating the uncertainty in the simulations. Horizontal lines indicate the requirements (solid) and goals (dashed) for N-band (top, red) and L-band (green, bottom). The vertical solid line indicates the LGS constellation radius for METIS. Right figure indicates the relative performance using a single low-order sensor (solid) and triple (2x tip-tilt, 1x tip-tilt-focus) low order sensor. Solid vertical line indicates the maximum range for the METIS internal SCAO system, while the vertical dashed line indicates the minimum pick-up field for an NGS in LTAO module.

For the low-order wavefront sensing there are two main configurations that are being investigated:

1. Using the internal SCAO WFS as low order (and truth) sensor. In this configuration there is a natural stabilization between the LTAO system and the METIS focal plane (assuming a near-perfect stabilization between the SCAO focal plane and the METIS focal plane). With the low-noise detectors, we are investigating to use the Shack-Hartmann with simple binning to provide lower-order slopes for the low-order sensing and slower-cadence for the truth sensing.
2. Using a set of up to three low-order WFS over a larger field of view inside the LTAO unit. A single low-order sensor at larger radius will suffer from significant degradation in the performance due to tilt-isoplanatism, see Figure 5. Note that in this case the low-order sensors can be either visible or infrared. In this case the internal SCAO WFS is still require to perform slow, low-order correction of the residual motion between METIS and its LTAO system, but the required guide star brightness is significantly lower.

The resulting sky coverage for these configuration is given in Figure 6. The performance remains well below the 3 mas requirement up to magnitude 16 for a single star in K and, assuming an equal distribution among the multiple low-order stars, up to magnitude 16.5 in K for three low-order sensors in an extended field. With a single low-order guide star in the science field, the sky coverage is improved to ~5%, well below the required 80%. For three low-order stars in a much wider field the sky coverage increases to well above 80% for the chosen configuration. From this we conclude that an LTAO system for METIS will require the configuration #2 as specified above to achieve its requirement on sky coverage.

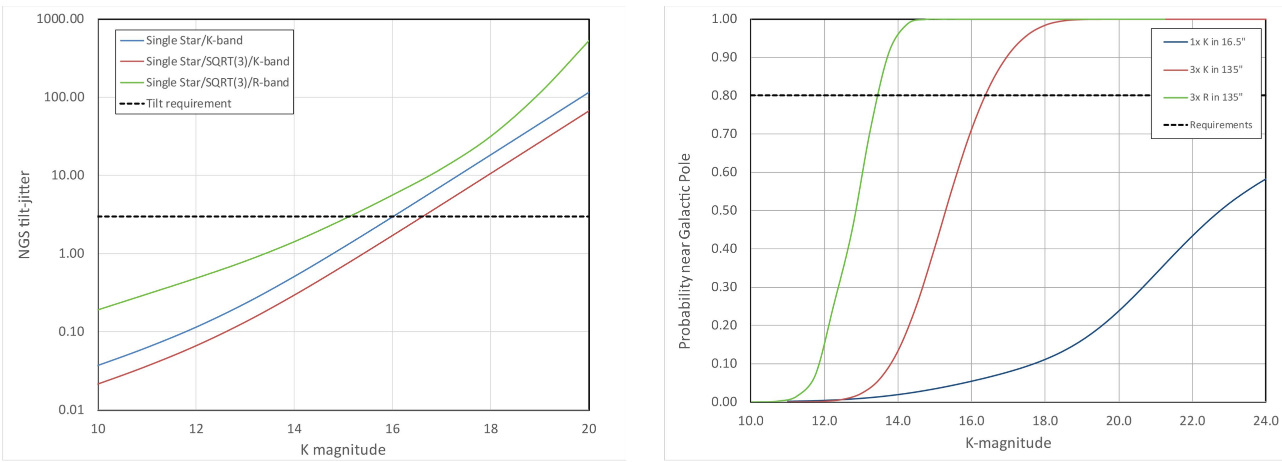

Figure 6. Left: the residual rms jitter as a function of magnitude of the low-order tip-tilt star. Right: Sky coverage as a function of guide star magnitude. The IR counts are based on star counts in high-galactic latitude Hubble fields[4], while the R-band counts are based on the USNO-B catalogue[5].

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