The Single Laser Adaptive Optics system for the METIS

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ABSTRACT

METIS, the Mid-IR instrument for the ELT will be operating an internal Single Conjugate Adaptive Optics System (SCAO), which will be the work horse AO system and mainly serve the science cases targeting exoplanets and disks around bright stars. In order to extend the sky coverage and brightness range of targets requiring AO correction to fainter stars, a Single Laser Adaptive Optics (SLAO) system is proposed. Although SLAO systems are currently in operation on 8-10 meter class (and smaller) telescopes, extending SLAO systems to the ELT increases the challenges associated with the cone effect and the spot elongation significantly. But since METIS will be operated at L-band, the requirements on required AO correction are fortunately reduced (with respect to other ELT instruments), making a SLAO system an attractive low-cost option for METIS. The METIS SLAO system will operate using an on-axis Laser Guide Star (LGS) and re-use the internal SCAO WFS for field stabilization and low-order correction (truth sensing), further reducing cost and complexity. In this paper we will present the current state of the design of the METIS SLAO system, and will address the challenges, like the impact of the cone effect, spot elongation and design constraints on the system. We will show that this system will likely provide a >60% SR in L-band over >50% of the sky, providing an attractive addition to the METIS SCAO system.

Keywords: ELT, Laser Guide Star System, Adaptive Optics

1. INTRODUCTION

The science case for METIS focuses mainly on known targets, many of which are sufficiently bright to serve as a guide star for the wavefront sensor (WFS) [1]. However, some science areas, for which METIS would otherwise be uniquely suited, cannot be covered: brown dwarfs, fainter YSOs, most Solar System objects, and most extragalactic targets. These would require an artificial laser guide star for wavefront sensing. However, it has become clear that such a full LTAO system, using 4–6 laser guide stars, is very complex and expensive, and therefore not even on ESO's ELT instrumentation roadmap yet, likely pushing it well into the 2030ies.

As a practical alternative, the METIS team has been investigating the performance of a single, on-axis laser guide star (SLAO) system for METIS. It is clear that the AO performance of such a system would be inferior to an LTAO due to angular anisoplanatism and the LGS spot elongation, but, with METIS operating at longer wavelengths, performance might still be is sufficient to reach most science goals. In order to be added to METIS at low cost, the SLAO system would have use one of the existing lasers on the ELT, use the METIS internal SCAO WFS as tip/tilt and also truth sensor, and use the existing SCAO RTC hardware.

The purpose of this paper is to give an overview of the trade-offs and performance of the METIS SLAO (Single Laser Adaptive Optics) system as a function of system and external parameters of METIS SLAO.

1.1 Expected Science Performance

An internal study was performed to assess the impact on the METIS science case if no LTAO system becomes available. Although not providing hard requirements for a SLAO system, we derived a number of 'expectations' on the SLAO system. There are three main parameters of the SLAO system that will drive the impact of the SLAO system on the science case

- Strehl – A Strehl Ratio of 60% is assumed at 3.8 micrometer.
- Sky Coverage – Although by itself a simple parameter, it combines (mainly) two parameters; limiting magnitude and Field of View. For typical science cases a limiting magnitude of K=16 and a FoV of 10 arcsec FoV would provide a coverage of a large fraction of the potential science cases.
- Laser pick-up method – Although not explicitly indicated in the science document, it seems assumed that all METIS bands will be accessible. A variety of potential LGS pick-up methods exist and in section 3.1.1 a trade is made on several critical system parameters.

To a lesser degree, there is a strong desire to have as large as possible zenith angle range, although it is clear that for increased zenith angles the performance will drop strongly due to the increased path through the atmosphere. Currently we assume that meeting the performance down to 45 degrees zenith angle and being operational down to zenith angles of 60 degrees will allow most science observations to be performed.

2. SLAO SYSTEM HIGHLIGHTS

The SLAO system is built around a number of basic assumptions that are driven by the two main motivations for SLAO: Simplicity and Cost. The SLAO system is a combination of the SLAO module, located between METIS and the Pre-Focal-Station and the SCAO module, located inside METIS.

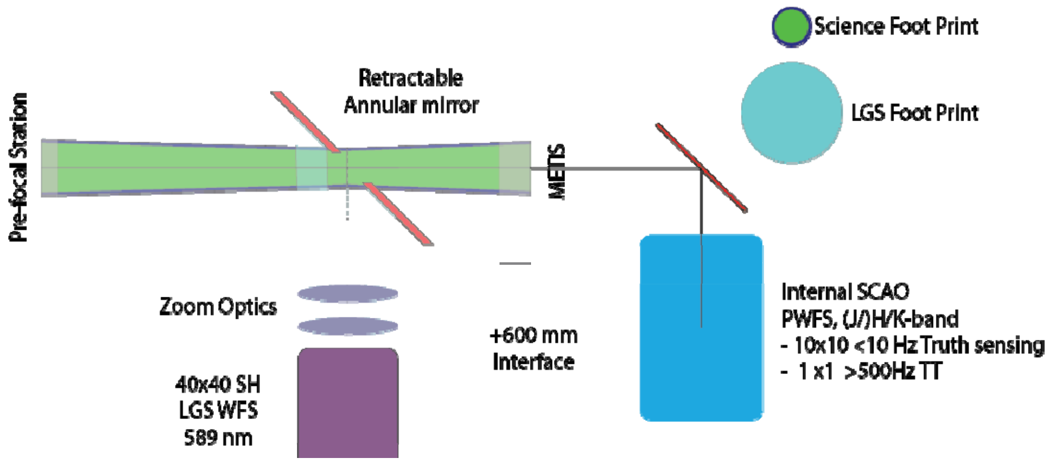

Figure 1. Layout of the full SCAO system. Note that only the external component (i.e., the SLAO Module) needs to be built to add the SLAO capabilities to METIS. The SCAO module, including its Real Time Control system is already a component of the METIS Baseline.

1. The SLAO system will make use of ONE Laser Guide Star (LGS) and ONE Natural Guide star. Minimizing the number of (L/N)GS will result in a large reduction of the hardware cost.
2. The LGS will be picked up ON-AXIS to minimize the number of moving components. Any de-rotation (i.e. of an interaction matrix/control commands) will need to be done in software
3. For NGS pick-up, the SCAO system will be used. This has the benefit that the NGS pick-up is done deep inside METIS, minimizing NCPA and residual motions and that the cost impact is expected to be minimal. An added benefit is that—theoretically—the NGS can be picked up in the full field of METIS, although the choice of LGS pick-up can/will limit the final pick-up field.
4. The LGS pick-up will be done at the focal plane, or very close to the focal plane of the ELT (i.e. ~1 meter behind the Pre-Focal Station (PFS) interface). At this location the size of the science field is minimal, minimizing potential conflicts between the LGS pick-up and the available scientific FoV.

5. The SLAO system will fit within the space initially reserved for a full LTAO system. Although the space around that location is tight, SLAO should be able to fit and not conflict with other subsystems which also require access to this volume.

3. 3 SYSTEM TRADE-OFFS

Although the majority of the choices were already made before exploring the parameter space for SLAO, see section 2, several choices still remain. These mainly involve how to pick-up the LGS, which wavelength range to use for the Truth and Tip-Tilt Sensing. These are expanded in the following sub-sections.

3.1 LGS Pick-up

3.1.1 Dichroic versus Annular mirror

As seen in Figure 1, the optimal location for picking up the laser guide star light is close to the focal plane of the ELT, between the Pre-Focal Station (PFS) and METIS. Currently two options are considered viable for the LGS pick-up. Since METIS is a thermal infrared instrument, the number of warm optics in the optical path needs to be minimized. Especially warm dichroic optics are considered to be very bad, since they contribute a large part of their thermal radiation to the instrument background, and are detrimental to N-band performance. In an earlier design study for a full LTAO system for METIS [2], one of the requirements to the LTAO system was to maintain a fully un-obstructed Field of View towards the METIS science cameras. But since for SLAO the main objective is cost, not immediately performance, a simple trade is made between two options:

1. Inserting a dichroic that reflects the sodium light (589 nm) and transmits all wavelengths longer than ~600 nm.
2. An annular mirror that reflects the light towards the LGS WFS and transmits the science light through a central opening. This option uses the difference in focus location between the science target (located at infinity) and the LGS (located between 90 and ~180 km). This difference causes the light from the LGS to be completely defocused at the location of the science focus, showing a pupil image. The central obscuration in this pupil image has no information regarding the wavefront and a hole at this location can be used to transmit the science light. The projected size of the central obscuration in the pupil changes with zenith angle, see trade-off in section 3.1.2.

The impact of the choice of pick-up mirror is summarized in Table 1.

Property	Dichroic mirror	Annular mirror
L/M-band performance	Likely minimal loss in performance	Likely no loss in performance
N-band performance	Likely very bad transmission/high emission	Likely no impact on performance
Sky Coverage	Not impacted	Potentially decrease due to limited FoV
Operational Zenith Angle	Not impacted	Potentially decreased due inner diameter of annular mirror
Technical feasibility and cost	High cost and risk due to expensive material (IR transmission) and expensive coating	Low risk and cost – simple mirror with standard coating
Impact on the science focus and optical quality	Significant change in focus due to thickness of the dichoric and introduction of astigmatism due to optic in	No impact on system focus
Calibration	Close to the focal plane, so any variation in emission will have significant impact on calibration.	No or minimal impact on calibration (some edge might protrude in science FoV)
Chopping	No impact on Chopping	Might reduce the available Chopping Range.

Table 1. Overview of the main impact of the choices for picking up the laser guide stars by the SLAO system. Color coded are how 'very bad' (=orange), 'bad' (=yellow) or good (=green) a certain choice is for a certain key property of METIS.

From Table 1 it follows that there are several key properties of METIS will be severely impacted by a dichroic in the optical beam. Therefor our current base line is using an annular mirror. The next section discusses the size of the hole in this annular mirror.

3.1.2 Pick-up size annular mirror and operational Zenith angle Range

The size of the annular mirror is determined by four main trades:

1. Available Zenith Angle. The smaller the central hole, the larger the range of available zenith angles will be.
2. Spot truncation. As the size of the hole increases, for certain viewing angles the spot will be truncated.
3. Available Science FoV. The larger the central hole, the larger the available FoV will be. This is a combination of the available chopping throw and clear science FoV.
4. Sky coverage. The larger the central hole, the larger the FoV for picking up the Truth/TT star, which will increase the sky coverage.

Note that for the latter two points, there is a natural limit due to the detector size (10x10" + 5" chopping, totaling 27" diameter) and the pick-up range of the SCAO system (27", equal to the transmitted FoV of the CFO), while for the first point, the hole size is limited to the projected central obscuration at a zenith angle of 60 degrees (with some decrease in performance being accepted to 70 degrees. The spot truncation is currently not included in the trade, but is taken into account in the performance estimates and truth sensing.

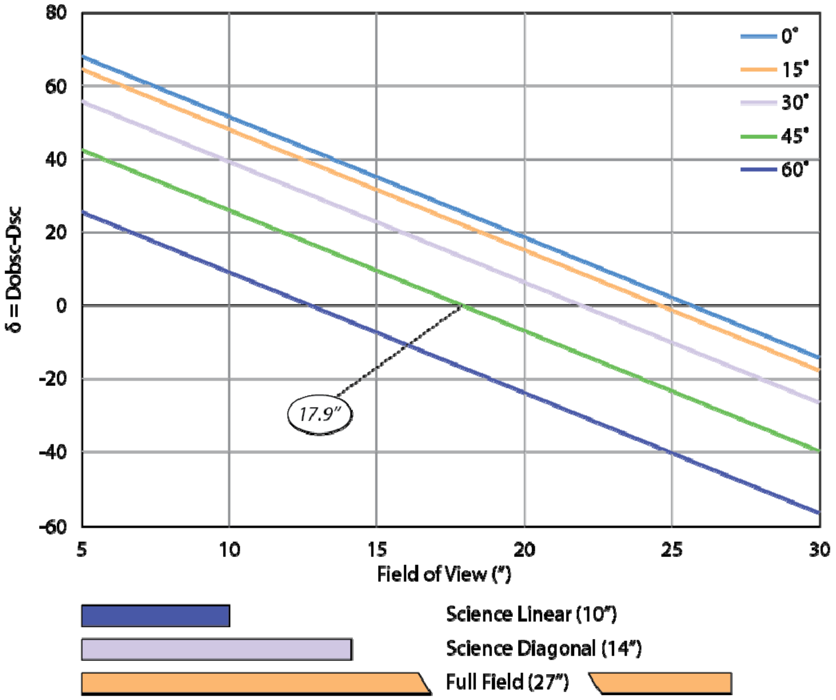

Figure 2. Difference between size of secondary obstruction and size of science beam versus field of view for various zenith angles. For a positive difference, the obstruction size is larger than the science beam and an annular mirror can be used without losing laser light. For negative differences, the science beam is smaller, which means that you either lose science light or laser light when splitting off the light at that location. The three color bars on the bottom indicate three important diameters within the METIS scientific field of view. The top bar is the linear science field, the middle bar the science field as taken over the diagonal and the bottom bar the full field, including the range for chopping. From the figure follows that for a zenith angle of 45 degrees, the secondary obscuration has a size of 17.9", allowing for the transmission of a 17.9" field towards the science detector, which means that the full science detector remains available, but the chopping range is limited. This is then automatically the pick-up field for the SCAO WFS/truth sensor.

The available FoV as a function of zenith angle is indicated in Figure 2. Even for 60 degrees zenith angle, the available FoV will still reach ~12.5", which is significantly larger than typical science targets for METIS, leaving sky coverage as the main trade-off factor. At 45 degrees, the FoV is 17.9", while at 60 degrees the FoV is 12.8". These translate in sky coverage fractions as seen in Figure 3.

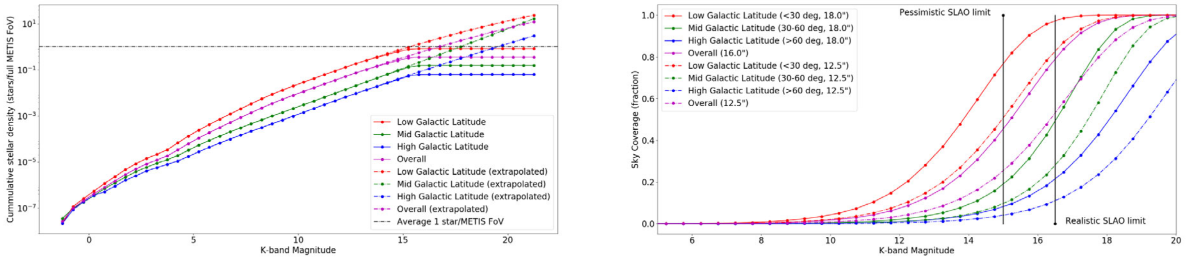

Figure 3. [left] Cumulative stellar densities as a function of K-band magnitude. For K-band, the SDSS saturates at K~15 and we extrapolated the power law in stellar densities seen between K~10-15 to retrieve reasonable numbers at slightly fainter magnitudes. [right] The stellar density converted to probability of finding at least 1 star of given brightness or brighter in two potential FoV for the METIS SLAO NGS pick-up (18" and 12.5"). Indicated in with vertical lines are pessimistic and realistic estimates of the sensitivity of the SCAO internal WFS.

The global achievable sky coverage varies from ~20% for a pessimistic magnitude limit of K=15 and a field corresponding to 60 degrees zenith angle, up to ~80% for a realistic magnitude limit of K=16.5 and a pick-up filed corresponding to 45 degrees zenith angle. Note that even with an aperture compatible with 45 degrees zenith angle, this translates to a limited loss in information towards the LGS WFS. The impact is not yet studied in this document. As a baseline, the LGS pick-up will be done using an annular mirror, which is expected to reflect the laser light and transmit the science and NGS light through the central hole. The annular mirror will transmit 18 arcseconds, corresponding to the projected size of the central obscuration at 45 degrees.

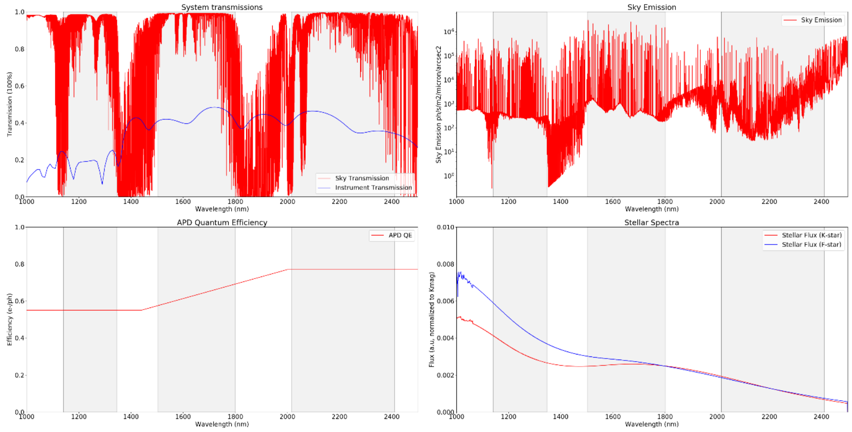

Figure 4. Input for guide star brightness at the SCAO WFS. Upper left: Atmospheric and system transmission (telescope + instrument) to SCAO WFS. Upper right: Emission by the atmosphere. Lower left: SCAO WFS Quantum Efficiency and lower right: assumed stellar brightness for two typical stars.

3.2 NGS Wavelength Range

The NGS pick-up is done using the internal SCAO WFS, as explained in Section 2. The SCAO WFS is based on a Saphira detector, operating in the infrared. The base line is to use the H- and K-band, but potentially can extend down to J-band. For NGS sensing, an extension of the wavelength range is considered, to include the full IR wavelength range. The trade-off is:

1. The wider the wavelength range the more light you collect.
2. Towards the longer wavelengths, the sky background increases, making it more beneficial to shift the band width to shorter wavelengths.
3. Towards the shorter wavelengths, the transmission of the optical system towards the SCAO WFS decreases.
4. Typical guide stars will become more red(dened) as the limiting magnitude is increased, favoring longer wavelengths.

In order to find the optimal wavelength range, the predicted transmission of sky, telescope and METIS up to the SCAO WFS is taken, together with the expected sky emission. The inputs for these simulations are shown in Figure 4.

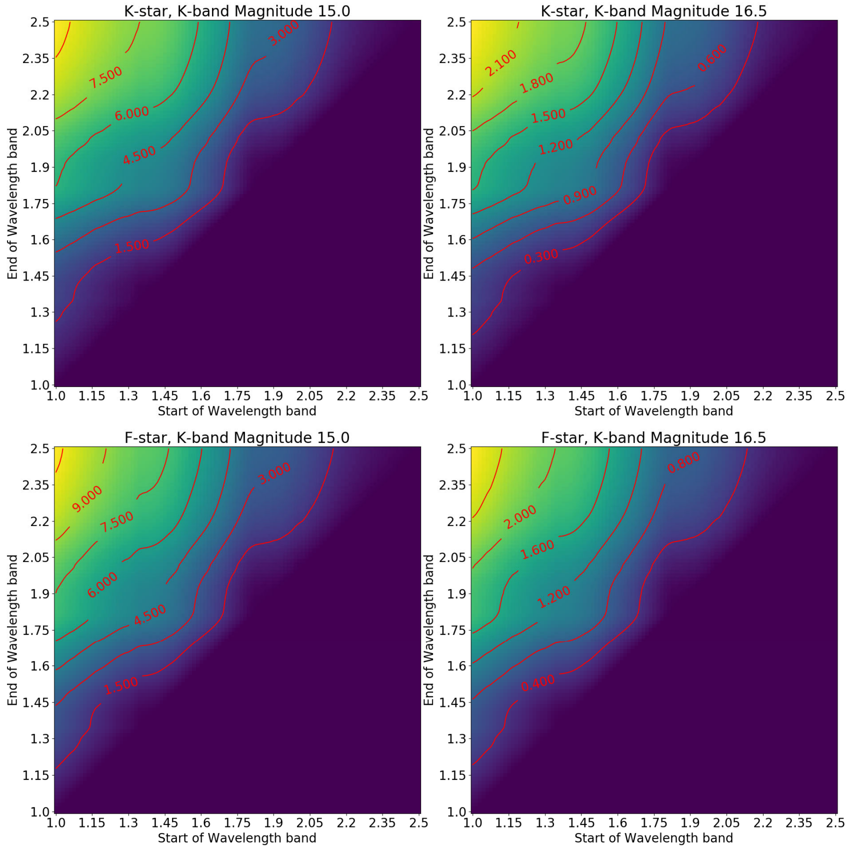

Figure 5. Overview of the 4 different configurations of stellar brightness and type, each showing the expected signal-to-noise ratio as a function of starting wavelength (horizontal) and ending wavelength (vertical).

These inputs have been taken to compute the signal-to-noise (SNR) per sub-aperture, per time step on the (binned) SCAO WFS. As follows from Figure 5, the configuration with the highest SNR is J/H/K band combined, but there is only a minimal loss when only taking the H/K band as is the current base line for the SCAO system. There is no significant difference between using an F-type star or a K-type star of the same K-band brightness, so for these simulations we assume a K-type star. For the rest of the simulations we assume a SCAO WFS with starting wavelength of 1.0 µm and an ending wavelength of 2.4 µm. For further simulations we assume a K-type star, leading to a total of ~2.1x103 photons/frame/sub-aperture on the SCAO WFS at a K-band magnitude of 15.

4. AO SIMULATIONS AND THE SODIUM LAYER

The SLAO system is supposed to serve the METIS system, which has a relatively small field of view and operates at long wavelengths; anisoplanatism is not very important and in the simulations, equivalent to on-axis SCAO simulations, where the exact distribution of the turbulence in the atmosphere is not important. Furthermore, the requirements for the SLAO system are ‘diffraction limited,’ but nowhere near the performance requirements for the METIS internal SCAO system. The main WFS parameters are given in Table 2. For the main simulations we assumed a seeing of 0.65”, an outer scale of 25 meters, a typical zenith angle of 30 degrees, a sodium density of $6\text{x}10^9/\text{cm}^2$ and a V and K band sky background of 21.4 and 13.0 per square arcsec respectively.

Nature of WFS	**LGS WFS** **(high-order sensing)**	**NGS WFS – Tip/Tilt** **(low-order sensing)**
Type	Shack-Hartmann	Pyramid
Sub-apertures	40 x 40	SCAO 80x80 Truth Sensing 10x10 Tip-tilt 1x1
FoV - field stop	10”	2”
Pixel scale – Number of pixels (if SH-WFS)	0.5"/pix, 20x20 pixels	0.5"/pix
Wavelength of sensing λ	589 nm	1.4 – 2.2 µm
Noise:	RON = 1e$^-$, DC = 1000 e$^-$/s η_{opt} = 0.56	RON = 3e$^-$, DC = 1000 e$^-$/s η_{opt} = 0.56
Integration time (cycles)	1.4 ms (1 cycle)	1.4 ms (1 cycle) for Tip-Tilt 140 ms (100 cycles) for Truth Sensing
Other parameters:		Modulation points: 8, 4λ/D Padding: 2

Table 2. Overview of the main LGS, tip-tilt and truth sensing parameters.

Due to spot elongation and spot truncation, the main parameter of interest was the Sodium profile, as changes in the profile will lead to time-varying offsets in the centroiding, which in turn leads to (slowly) changing WFE. A typical set of Sodium profiles is shown in Figure 6.

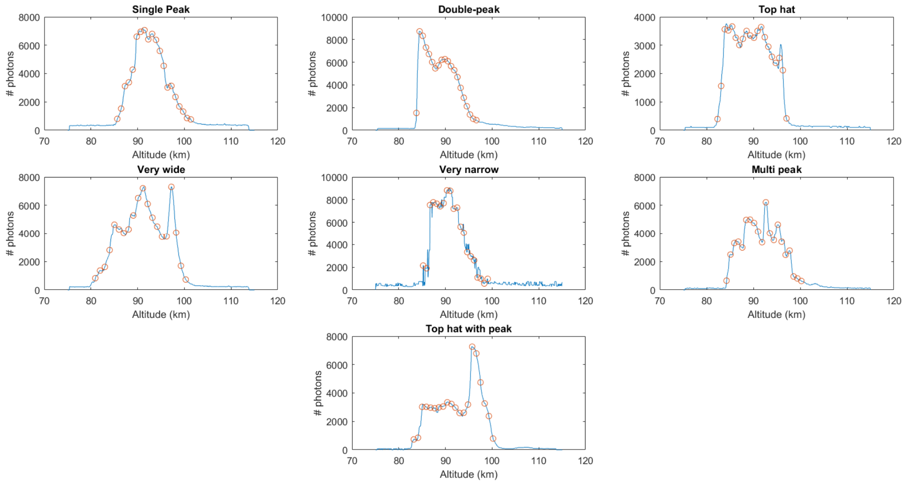

Figure 6. Distribution of the sodium concentration regarding altitude [3]. The blue curve represents the actual data, the orange dots the points used in our simulations. These profiles have approximately the same probability of occurrence.

The simulations were performed mainly in the YAO simulation package [4], coupled to post-processing in Matlab and Python. A basic AO simulation, using the parameters indicated above, was set up in YAO. We tried to implement the truth sensing fully in YAO, but did not obtain useful results. In the end we save the residual phase maps and used a dedicated CURED reconstructor [5] in Matlab to compute what a 10x10 truth sensor would have seen and subtracted this from the residual wavefront map. This gave an indication of how well the wavefront distortions due to the Na WFS could be corrected, and its correction level dependence on the guide star magnitude. In order to study the full dynamical behavior of the truth- and tip/tilt sensing, we need to implement this loop in YAO, or use another E2E simulation package. The typical residual WFE maps, before correction by using the Truth Sensing, for the different Na-profiles are shown in Figure 7.

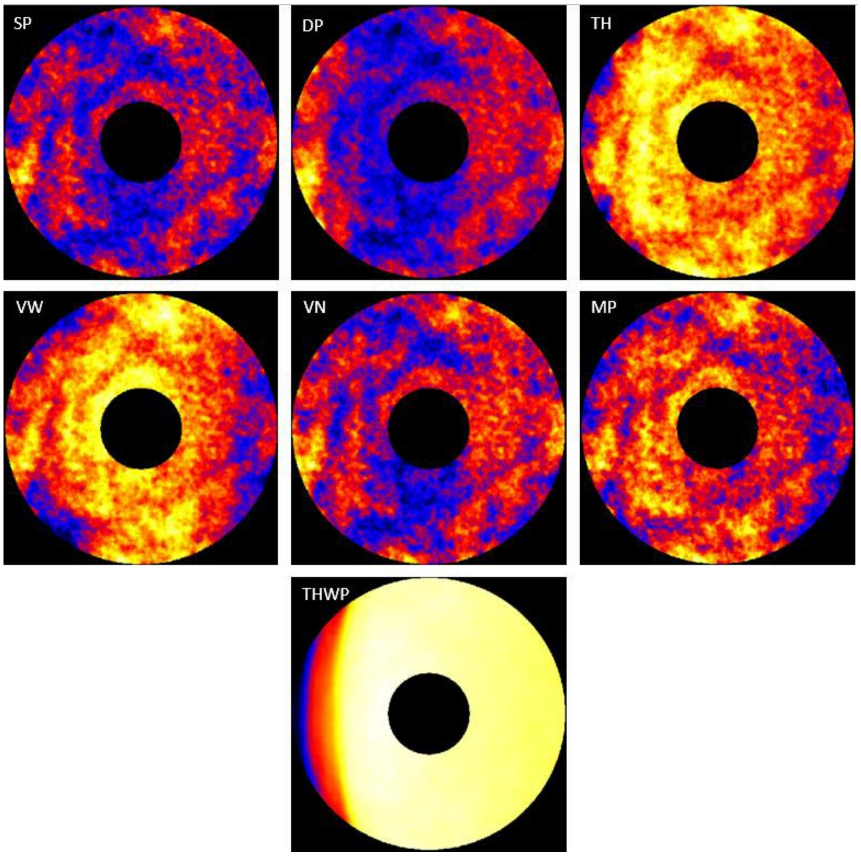

Figure 7. Residual low wavefront maps, corresponding to the turbulence profiles given in Figure 6. Note that for the THWP (top-hat with peak) and TH (Top-hat) profiles, the spot truncation basically leaves no structure for the WFS to trigger on.

The truth sensor stabilizes the instantaneous Strehl Ratio and provides a significant correction. Since the truth sensing correction is currently implemented after the closed loop simulations, it cannot fully prevent, but was able to correct, the instability as sensed in the 'Top-Hat With Peak' profile. For a true comparison, we need to implement the truth sensing inside the closed loop simulations. Furthermore, the current simplistic approach is that the Truth Sensor waits for 0.1 seconds, instantaneously computes the correction and applies this with gain = 1 to the next 0.1 seconds. It is clear that this is not the optimal implementation and we believe that with improved control, the residual temporal errors can be minimized. The resulting Strehl ratios, before and after truth sensing correction are given in Table 3. The resulting Strehl Ratios have—with the truth sensing implemented—now all stabilized at the 0.50-0.55 level, regardless of the Sodium profile.

Profile	Single Peak	Double Peak	Top Hat	Very Wide	Very Narrow	Multi Peak	Top Hat With Peak
Strehl Ratio *before* correction	0.58	0.36	0.38	0.27	0.50	0.49	Unstable
Strehl Ratio *after* correction	0.56	0.48	0.51	0.50	0.54	0.54	0.49

Table 3. Long exposure L-band (3.0 µm) strehl ratio, before and after correction using an a-posteriori 'truth sensing' using a binned SCAO Pyramid WFS.

In the optimal situation for bright guide star and fast Truth Sensing (i.e. at full rates of 500-1000 Hz instead of 10Hz), the truth sensing would be able to correct also some low-order terms not sensed due to the cone effect and the effective Strehl might become higher than the highest values obtained here, of 0.56 @ 3.0 µm.

4.1 Truth sensing and Tip-Tilt sensing limiting magnitudes

Both the truth sensing and the tip-tilt sensing are currently relying on the binning of the SCAO Pyramid WFS data to provide control signals. In the case of the truth sensing, each sub-aperture sums the light of 8 x 8 spatial sub-apertures and integrates over 100 time steps, while for the Truth Sensing, the summation takes place over 80 x 80 sub-apertures, with no temporal binning. Therefor both sensors sum over approximately 6400 sub-apertures and will receive very similar signal to noise values – even in K-band we're not limited by sky background noise, but by the detector noise—mainly again due to the binning over large numbers of pixels. The Dark Current used was 1000 e-/pixel/s and a Read Noise of 1 e-/pixel

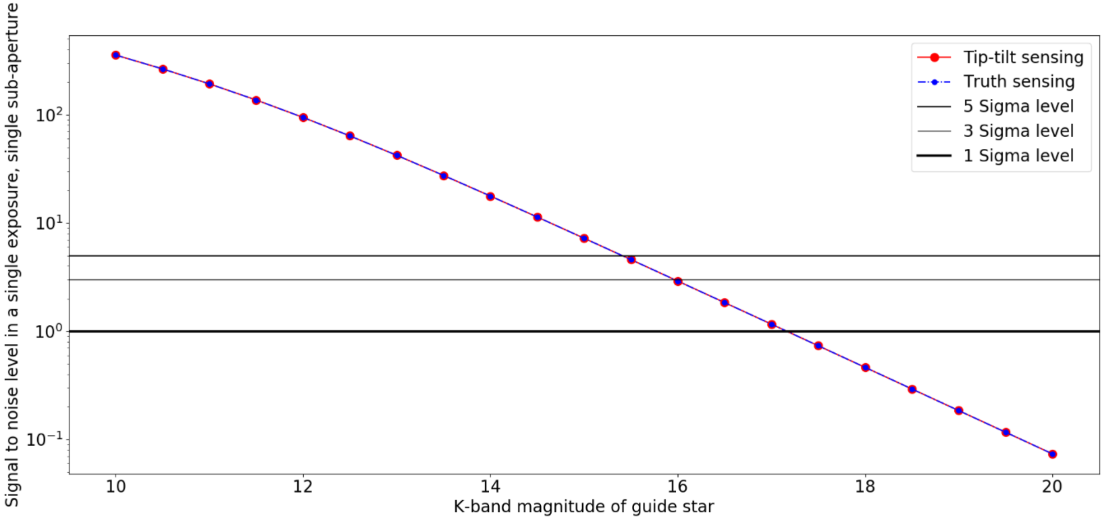

Figure 8. Resulting Signal-to-Noise ratio per aperture for truth sensing as well as tip-tilt sensing. Due to the choice of temporal and spatial binning, both SNRs are very similar.

The effective SNR drops below 1 around a K-band magnitude of 16.5-17.0. The truth sensing will likely run with a gain of 1, while the TT sensing will likely run with a slightly lower gain, making the TT probably be available until slightly lower magnitudes. Again, we need to implement full end-to-end simulations to verify these limits.

5. CONCLUSIONS

METIS will, at first light, be installed with an internal SCAO system which will give peak performance for most bright targets. In order to extend the coverage to fainter targets, especially for extra-galactic science cases, a single-laser adaptive optics system (SLAO) is proposed. Although the performance of the system is significantly hampered by the classical cone-effect and spot elongation, the performance drop due the cone effect can be shown to be acceptable for the L-band (and longer wavelengths) on the ELT, while the spot elongation effects can be largely mitigated by using an optimized truth sensing system. The currently proposed SLAO system resides (optically) in front of METIS and picks up the laser light using an annular mirror. Although this mirror potentially introduces additional spot truncation, it also minimized the thermal back ground towards METIS. Full optimization of the hole in the annular mirror, including end-to-end simulation to study the impact of the spot truncation still needs to take place, but initial estimates indicate an optimal size equivalent to 18 arcsec on-sky. Re-using the internal SCAO WFS will both provide excellent stabilization between the external SLAO system and to detectors of METIS inside the cryostat, and also offer low-cost truth sensing and an excellent opportunity for flexible re-binning, depending on the brightness of the guide star. Under typical atmospheric conditions, the performance of SLAO is expected to approach 60%, meeting our first science desire. With an expected pick-up field of ~18 arcsec diameter and an estimated limiting magnitude of K ~16 the current SLAO system provides sufficient sky coverage to open up the science for most potential METIS science targets.

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