Defining the MOSAIC GLAO Image Quality Budget

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ABSTRACT

MOSAIC is the ELT wide-field spectrograph capable of observing over 200 targets simultaneously within an AO-corrected 7.4 arcminute diameter field of view (FoV) across a wavelength range of 400-1800nm. The requirements for the AO correction are specified in terms of enclosed energy (EE) improvement across the field, with an improvement of 1.4 in H-band EE is expected within a 600 milliarcsecond aperture when AO correction is applied in poor seeing conditions. Ground-layer adaptive optics (GLAO) is used to provide this correction. Due to the partial AO correction provided by GLAO and the size of the aperture, the sum of individual wavefront error terms cannot be used to provide an estimate of system performance or used to define performance requirements relating to image quality or stability for instrument subsystems. In this paper we describe the method that will be used to determine the MOSAIC image quality budget, using the results of Monte-Carlo simulations of GLAO performance at the ELT to investigate the limitations of the proposed approach which show that a convolution of the AO corrected PSF with a high-order PSF representing instrumental and non-AO effects is sufficient to determine encircled energy for the MOSAIC instrument.

Keywords: Adaptive optics, Ground layer, Error budgets, ELT

1. INTRODUCTION

MOSAIC is the multi-object spectrograph for the ELT. It will be capable of observing over 200 objects simultaneously within a field of view of over 7.4 arcminutes in diameter across the VIS to NIR wavelength range. MOSAIC has recently moved from the conceptual (Phase A) to preliminary design phase (Phase B), with an expected first light date in the early-mid 2030's. The major architectural change during this phase was the change from multi-object AO used within the Phase A system, to ground-layer AO that will be used in Phase B.

Figure 1 shows the MOSAIC instrument in its Phase B GLAO configuration on the ELT Nasmyth platform. The MOSAIC GLAO system uses four laser guide stars to provide the high-order control signals required to drive the ELT M4 and M5 mirrors in GLAO mode.

The MOSAIC focal plane is about 2m in diameter and contains up to 300 hexagonal tiles, each with its own independently steerable pickoff arm containing an optical relay. At the output of this 1:1 optical relay behind the focal plane, there is a fibre bundle comprising 7 fibres that can be used to observe a single object. Each fibre bundle is designed to optimally couple the GLAO corrected PSF with either a 600 milliarcsecond diameter aperture for NIR wavelengths, or a 700 milliarcsecond diameter fibre for VIS wavelengths. Each pickoff arm also contains a steerable mirror that can be used to direct light towards the 4 x NGS WFS and 8 x mini-IFUs that sit at the perimeter of the tiled MOSAIC focal plane. Key parameters for the MOSAIC system are listed in Table 1.

The residual errors and residual structure present in the GLAO-corrected PSF, even over a long exposure, place the AO performance in regime where the classical wavefront error-based image quality budget used in the most diffraction-limited AO system designs cannot be used. Additionally, there is no strong link between the FWHM and encircled energy within a fibre aperture. In this proceeding we describe the expected MOSAIC performance and detail the approach MOSAIC will be taking to determine image quality in terms of EE during the instrument design phase.

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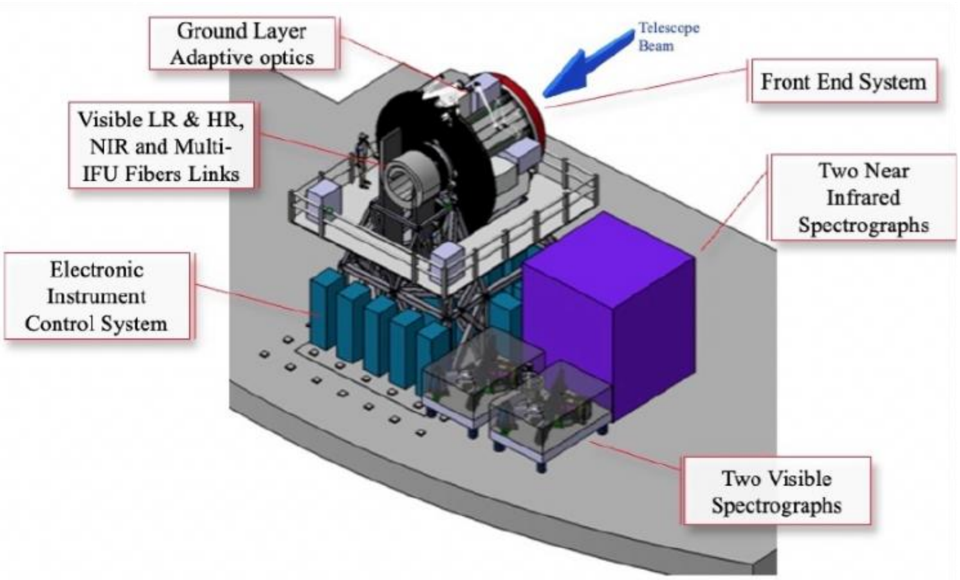

Figure 1 Updated MOSAIC Phase A conceptual design showing key subsystems and instrument installed on the ELT Nasmyth platform.

Table 1. MOSAIC Phase B instrument key parameters.

Parameter	**Value**
Number of targets	Up to 300 objects & 8 IFUs
Technical field of view	Ø 7.5 arcmin
Wavelength range	0.39 – 1.8 μm
Spectral resolution	Low Resolution > 4000, High Resolution > 18000
IFU sampling	2.5” with 150 mas spaxels
Fibre aperture diameter	Visible: 0.7”, Near infrared: 0.6”
AO performance	1.2-1.4 H-band EE improvement across full field of view

2. GLAO PERFORMANCE

The MOSAIC AO implementation has gone through many iterations since the project inception. The scientific impact of reduction in sampling and aperture losses was a key trade-off study performed during the conceptual design phase and resulted in an increase in IFU spaxel size from 85 to 150 mas. At this spaxel scale the performance benefit of MOAO over GLAO in terms of enclosed energy within an aperture is now minimal. Subsequent discussions after the conceptual design phase was complete also prioritized the system multiplex over the high-spatial resolution performance. As such, GLAO was adopted as the baseline operating mode for MOSAIC moving forward[1]. In this section we describe the GLAO performance of the ELT with MOSAIC and assess how these relate to the MOSAIC top-level performance requirements.

The top-level performance requirement on the GLAO system specifies a ~1.4x increase in H-band Enclosed Energy (EE) within the 600mas NIR fibre aperture when GLAO correction is applied compared to the PSF delivered natively by the telescope. Figure 2 shows simulations 1650nm GLAO and NoAO PSFs within a 600 milliarcsecond diameter aperture for the poor seeing conditions (JQ4 describing the 75th percentile conditions[2]) that MOSAIC is required to operate in.

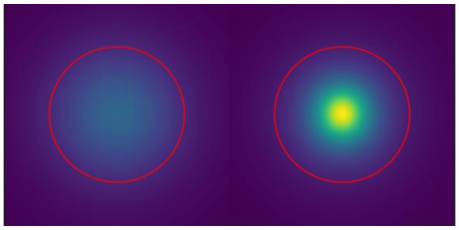

Figure 2 Simulated 1650nm on-axis NoAO (left) and GLAO (right) ELT PSFs with 600 milli-arcsecond circular aperture.

However, the ELT is not designed to natively provide AO correction across such a wide field as is required by MOSAIC. Figure 3 shows pupil mis-conjugation of the ELT adaptive M4 mirror by between 1.8 to 2.1 meters. This is equivalent to a mean M4 conjugation altitude of approximately 600m above the ground. This non-pupil conjugation results in a ±1.75% pupil shear over the 7.5-arcminute technical field of view of MOSAIC which introduces significant field-dependent errors within the AO corrected field of view, even with the large 600 milliarcsecond aperture.

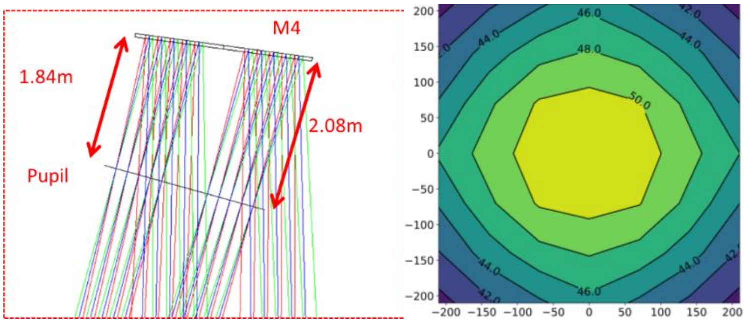

Figure 3 ELT optical design showing location of telescope pupil and tilled adaptive M4 mirror (left) and impact of M4 conjugation on the percentage encircled energy within a circular 600 milliarcseconds diameter aperture across the 400 arcsecond diameter field of view of the ELT in worst quartile seeing conditions with an r_0 of 0.097m (right).

MOSAIC GLAO performance requirements are defined in terms of the EE improvement that GLAO will make when correction is applied. ELT performance requirements state that the on-axis image FWHM shall be degraded from that of a perfect telescope by no more than 10% in median conditions, but this does not describe wide-field performance sufficiently to define MOSAIC performance requirements. Until the wide-field performance of the ELT without AO is defined, we therefore compare GLAO to the performance of the ELT without AO correction. In this paper we subsequently refer to this mode as “No AO”. Figure 4 shows the field dependence of the GLAO/NoAO EE ratio for the 5 defined ELT atmospheric conditions. The slight increase in performance at the off-axis distance of 3.5 arcminutes is due to a simulation artefact due to the diameter of the LGS asterism. The beneficial impact of GLAO is greatest in poorest seeing conditions.

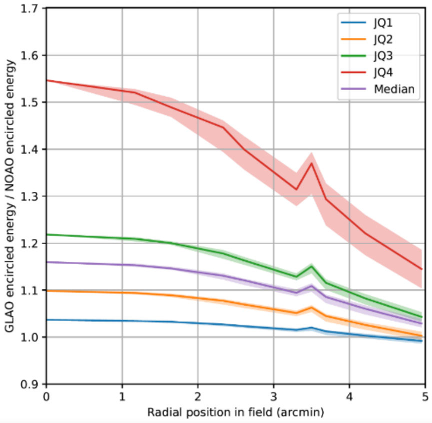

Figure 4 GLAO encircled energy improvement ratio across the corrected field of view within a 600 milliarcsecond circular aperture at 1650nm. JQ1 describing the best quartile atmospheric turbulence conditions, JQ4 being the worst quartile conditions expected at the ELT site. Error bounds show 1-sigma variation between independent simulation realisations.

3. MOSAIC IMAGE QUALITY

The GLAO performance estimated using Monte-Carlo simulations in the previous section do not include many of the instrumental errors or slowly varying effects that may impact encircled energy when MOSAIC is installed at the telescope. To convert the raw AO performance values into an image quality budget requires also considering these errors. We wish to combine the information output from the AO simulations with models of instrument performance that ***describe EE over the course of an observation***. For this, we must consider not only ‘adaptive’ errors but also errors that may vary slowly over the course of a typical 1-hour observation. Such errors cannot feasibly be included directly within the end-to-end GLAO (and NoAO) simulations therefore the goal of the image quality model is to provide an approximate model that satisfies the following criteria:

- The model must provide an estimate of the encircled energy achieved by the full MOSAIC instrument in GLAO and No AO modes.
- The model must provide a means of combining slowly varying or static instrumental errors with the AO corrected PSF
- The model must allow subsystem image quality performance budgets to be developed, tracked and updated as the AO simulations and instrument design matures.

Figure 5 describes the basic image quality model architecture, showing how errors will be combined to show the system meets the top-level enclosed energy improvement requirement. The challenge within this budget is to transition from Level 3 to Level 2, where AO simulations and instrumental performance are combined.

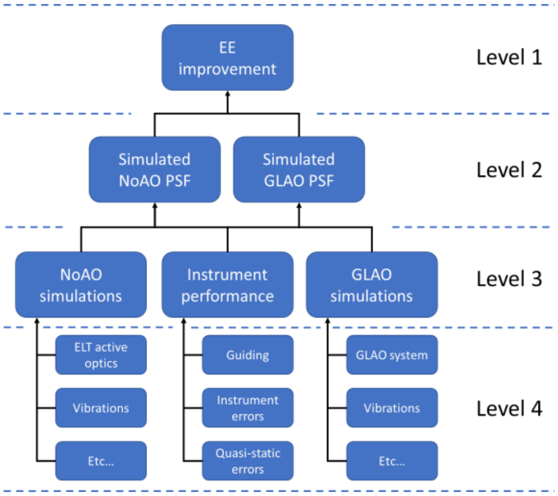

Figure 5 Image quality model architecture showing the method for GLAO and NoAO PSF estimation.

For low-order tip-tilt errors, the move from Level 3 to Level 2 can simply be combined by convolution of the AO PSF with a 2D Gaussian of suitable width, providing a simple means of meeting all the model criteria and supporting the instrument design process. For higher-order residua errors caused e.g., by varying NCPA, instrument flexure, or quasi-static aberrations in the telescope optical path this convolution no longer provides an accurate estimate of the PSF, but we wished to investigate the limits of where the convolution approximation holds, and if it can provide an acceptable measure of the enclosed energy in the specific case of MOSAIC at the ELT.

Now we compare the EE predicted by this approximation to that measured from the ‘actual’ H-band GLAO PSF. To generate the actual PSFs, several sets of random static aberrations are added directly to the GLAO-corrected wavefront. To generate the estimated GLAO PSF, the GLAO corrected PSF is convolved with an empirically derived Gaussian convolution kernel that approximates the impact on EE of the static aberration. Random Zernike aberrations up to 5th radial order have been considered within the model to date, but these will be refined at later stages once we have better estimates of instrument performance. Figure 6 plots both these comparisons for 12 sets random low-order aberrations added to the GLAO corrected wavefront. We can see that the addition of large aberrations even up to 1000nm RMS results in minimal degradation in the encircled energy, and we also note that there is less than a 1% error between the EE measured from both the actual and convolution "estimated" models.

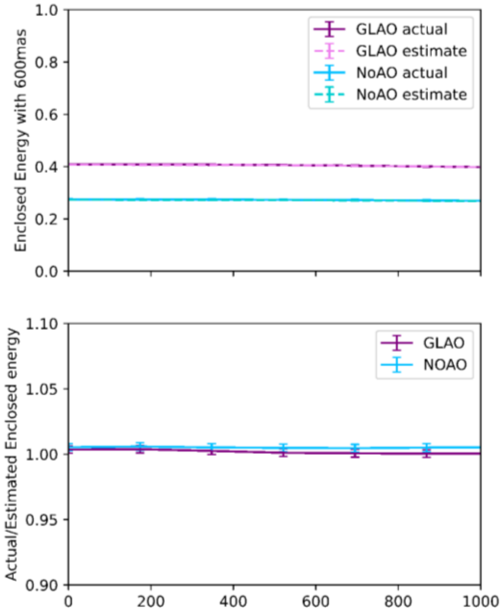

Figure 6 H-band EE within **600mas** between actual PSF and convolutional model estimate in **JQ4** conditions for NoAO and GLAO (top) and the EE error between these two models (bottom). Error bars show the 1-sigma deviation in values derived for 12 random sets of Zernike modes simulating residual low order errors present outside of the AO simulation.

We can also investigate the validity of this model when looking at the finer spaxel scale within the mini-IFUs of 150 milliarcseconds. In this regime we expect to be more sensitive to errors in the estimated PSF due to the finer sampling of the PSF. It is feasible to consider that the mini-IFU will be used in better seeing conditions than the single-object fiber bundles, therefore we consider their performance in median conditions.

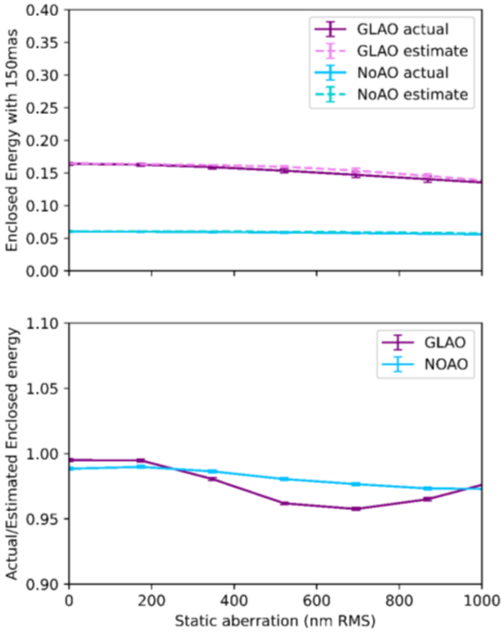

Figure 7 H-band EE within **150mas** between actual PSF and convolutional model estimate in **median** conditions for NoAO and GLAO (top) and the EE error between these two models (bottom). Error bars show the 1-sigma deviation in values derived for 12 random sets of Zernike modes simulating residual low order errors present outside of the AO simulation.

When operating at finer spaxel scales, and with a better corrected PSF, both the estimated EE and error between the two models become more sensitive to the amplitude of the random aberrations. We note that the EE measured from the estimated PSF provides a pessimistic estimate of the EE, building some inherent conservatism into the model. When feeding the mini-IFU the wavefront errors must be more tightly controlled and it is likely that this aspect will provide the main driver of instrument optical performance.

The MOS image quality budget shown in Table 2 tracks the encircled energy within a 600mas MOS aperture over the course of a 1-hour observation. This has to include slowly-varying errors that introduce offsets between fibres and the object, such as telescope plate scale variations and guiding errors. Known optical aberrations greater than 300nm RMS must be included within the GLAO simulation to maintain the applicability of the convolutional model when applied in mini-IFU mode. It is therefore likely that a wavefront error model of the variation of ELT off-axis errors will have to be included directly within the AO simulations. We note that the EE reduction factors are derived directly from analysis of the model PSF.

Table 2. Preliminary MOSAIC H-band Phase B GLAO image quality budget combining high-order error terms and impact of slow instrumental error on encircled energy within 600 milliarcsecond aperture in median conditions.

Parameter	**Value**	**EE/EE reduction**	**Comments**
AO simulations	1200 *(1256)* nm		Telescope field aberrations are not currently included in off-axis simulation. Requires model of ELT quasi-static aberrations.
GLAO residual (JQ4 seeing)	1200 nm	52% (on-axis)	
Telescope field aberrations	*(360 nm)*		
Instrument/Quasi-static high-order	300 nm		
Instrumental + ELT high-order errors	274 nm	x0.99 EE	
Other (including margin)	120 nm		
Fibre aperture offsets	56 mas		[1] Assumes that telescope field distortions can be offloaded to pickoff system
Telescope plate scale distortions[1]	30 mas		
Guiding errors[2]	30 mas	x0.978 EE	[2] Initial estimate – factor of 10 better than ELT PFS/telescope guiding
Pickoff positioning	15 mas		
Other (incl. margin)	33 mas		
TOTAL		**50% (on-axis)**	

The authors would like to note that the results presented in this text have been updated since the poster was presented. The updated analyses shown in Figure 6 and Figure 7 have shown that the 600 milliarcsecond apertures are less sensitive to aberrations than originally thought. The conclusion that instrumental errors must remain below 300nm RMS is still true, however this requirement is now driven by mini-IFU performance.

4. CONLCUSION

We have presented an initial Encircled Energy (EE) image quality budget for the MOSAIC instrument that combines the output of Monte Carlo AO simulations of GLAO system performance with slower non-AO errors. This includes errors such as guiding, higher-order static and higher-order quasi-static errors that will be encountered at the telescope. These non-AO error sources are combined with GLAO PSF through convolution with a Gaussian convolution kernel. The preliminary analyses presented here show that this approach results in a small under-estimate in the expected end-to-end EE compared to a full end-to-end model (1-3% EE for errors < 300nm RMS). One major benefit to this approach is that the instrument high-order optical performance budget becomes completely independent of the GLAO simulation, and at the 300nm RMS level, can be allocated using a classical wavefront-error based system. However higher-order wavefront errors with contributions greater than 300nm RMS, such as quasi-static field aberrations, must be included within the

AO simulation. This approach is an approximation but will be checked periodically with end-to-end modelling to confirm instrument top-level requirements.

ACKNOWLEDGEMENTS

This work is funded in the UK under STFC grants ST/S001360/1 and ST/X002284/1. The authors would like to thank all the members of the MOSAIC AO system team, past and present, for their contributions to the MOSAIC AO system design.

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