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AO for MOSAIC, the E-ELT Multiple Object Spectrograph

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ABSTRACT

MOSAIC is the proposed multiple object spectrograph for the E-ELT that will eventually combine two AO observing modes within a single instrument. MOSAIC will contain up to 20 open-loop multiple object AO channels feeding NIR IFUs in addition to up to 200 seeing-limited (or GLAO corrected) VIS – NIR fibre pickoffs. Wavefront tomography will be implemented using a combination of LGS and a few high-order NGS distributed across the field with the wavefront correction applied in a split open/closed loop configuration. MOSAIC will be the only E-ELT instrument planned that can utilize the full 10 arcminute diameter field of view, enabling highly efficient observing modes for this workhorse instrument. Use of the full E-ELT field inevitably requires a closer integration between the telescope control system and the instrument AO systems, however this can bring several potential benefits to overall system performance. Here we present the initial design concept and baseline performance of the MOSAIC instrument and AO system(s) taking advantage of the CANARY on-sky results and inheriting from the previous Phase A study of EAGLE. Finally, we will highlight areas of system performance and calibration that will require further analysis and trade-off during the course of the upcoming Phase A study.

Keywords: Adaptive Optics, Multiple Object Spectroscopy

1. INTRODUCTION

The first light instrumentation suite for the European Extremely Large Telescope (E-ELT) will have a diffraction-limited imaging system (MICADO[1]), an integral-field unit spectrograph (HARMONI[2]) and a mid-IR imager (METIS[3]). Each of these systems can and will make use of Adaptive Optics (AO) correction to take advantage of combination of the unprecedented spatial resolving and light-gathering power of the ~39m diameter aperture of the E-ELT. The E-ELT has however been designed to provide a diffraction-limited 10 arcminute diameter field of view that none of the first light instruments will be able to make full use of, although the full field may be required to find the natural guide stars required for telescope operations.

Efficient *scientific* use of the full field of view provided by the E-ELT can only (currently) be achieved using a Multiple-Object Spectrograph (MOS). The ability to observe up to hundreds of targets across the field brings a huge multiplex advantage and thus increase in observational efficiency. This latter aspect is always a major consideration for any observatory, and is even more critical for a unique facility such as the E-ELT.

During the initial Phase A E-ELT instrument design studies (2007-2009), several MOS instruments were proposed. Two of these proposed instruments, OPTIMOS-EVE[4] – a seeing-limited fiber-fed visible/near-IR MOS, and EAGLE[5] – an AO-corrected image-slicer based near-infrared MOS, between them covered almost the full range of potential science cases identified for the E-ELT however they required very different levels of AO performance. The MOSAIC consortium was built from the combination of the OPTIMOS-EVE and EAGLE consortia to design a single MOS

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instrument that combined features of both precursor studies to investigate whether the combined instrument could enable better and more efficient observations.

1.1 Top Level Requirements

The top level scientific requirements for MOSAIC have been designed with a broad range of science cases in mind and are in the process of being iterated with the instrument technical team. The initial science requirements are listed in Table 1. These science requirements reflect the heritage of the Phase A instruments, with the High Definition Mode (HDM) mode targeting principally the original EAGLE science cases, and the High Multiplex Mode (HMM) covering principally the OPTIMOS-EVE science cases. The InterGalactic Medium (IGM) mode is targeted at IGM tomography specifically.

Table 1. MOSAIC top-level science requirements (as of 22/01/16)

Parameter	**Value**	**Tolerance**
High Definition Mode (HDM)		
IFU field of view	2.0" x 2.0"	Minimum
Multiplex	10	Minimum/no maximum
Spatial pixel size	75mas	40-80mas
Ensquared Energy	30% (inside 2x2 spaxels)	Minimum: 25%
Spectral resolving power (R)	5000	No maximum
Total operating bandwidth	0.8 to 2.5 microns	1.0 to 1.8 microns mandatory
Single observation bandwidth	One photometric band at R=5000	
Instrument field	40 arcmin^2	Maximum: 78 arcmin^2
High Multiplex Mode (HMM)		
Sub-field	0.6" in NIR and 0.9" in VIS	
Multiplex	200	No maximum
Spectral resolving power (R)	5000 in VIS and NIR, 15000 in VIS	15000 in NIR desirable also
Total operating bandwidth	0.4 to 1.8 microns	
Single observation bandwidth	One photometric band at R=5000. 400Å at R=15000	
Instrument field	40 arcmin^2	Maximum: 78 arcmin^2
InterGalactic Medium (IGM)		
Sub-field	3.0" x 3.0"	Minimum 2.0" x 2.0"
Multiplex	30	Minimum 10
Spatial pixel size	0.25"	0.2" to 0.3"
Spectral resolving power (R)	5000	3000-5000
Total operating bandwidth	0.37 to 1.0 microns	0.4 to 0.8 microns
Single observation bandwidth	0.38 to 0.6 microns and one photometric band at wavelength >0.6 >1000Å at R=3000	
Instrument field	40 arcmin^2	Maximum: 78 arcmin^2

In terms of adaptive optics requirements, here we see a clear split between the HDM, and HMM/IGM modes. HDM requires high-fidelity AO correction over the widest possible field of view of the E-ELT. The only AO technique currently thought capable of providing this level of Ensquared Energy (EE) performance across the full 10 arcminute E-ELT field of view is Multiple Object AO (MOAO)[6].

HMM and IGM modes require much lower levels of correction, and are targeted primarily at seeing-limited observations. However, the process of providing even a seeing-limited PSF across the full field of view of the E-ELT is not trivial, requiring the use of multiple wavefront sensors, operating at fast update rates to control both gravitational flexure and distortion, as well as aberrations introduced by wind loading and vibrations within the telescope itself.

Of the two of these operating modes, the HDM is obviously more challenging from an AO perspective, however with the AO infrastructure required to implement MOAO, it may be possible to implement Ground Layer AO (GLAO) for 'free'. GLAO would potentially enable a modest reduction in the NIR spectrograph size, which is attractive option for obvious reasons.

2. MOSAIC ARCHICTECTURE

Several iterations of combined architecture have been studied that provisionally meet the top level requirements, and the baseline design that will be investigated during the Phase A study is shown in Figure 1. MOSAIC will sit at the Nasmyth 'B' platform of the E-ELT. The ~2m diameter focal plane of MOSAIC is populated by a number of hexagonal tiles. These tiles will each contain a steering mirror to direct light to the Natural Guide Star (NGS) WaveFront Sensors (WFS), HDM MOAO channels, and potentially IGM fibres that will be situated around the edge of the focal plane. Each tile will also contain the seeing-limited fibre bundles for the NIR and VIS observations in HMM mode. Each tile will be aligned to compensate for the focal plane curvature and non-telecentricity that can introduce coupling losses within the fibres.

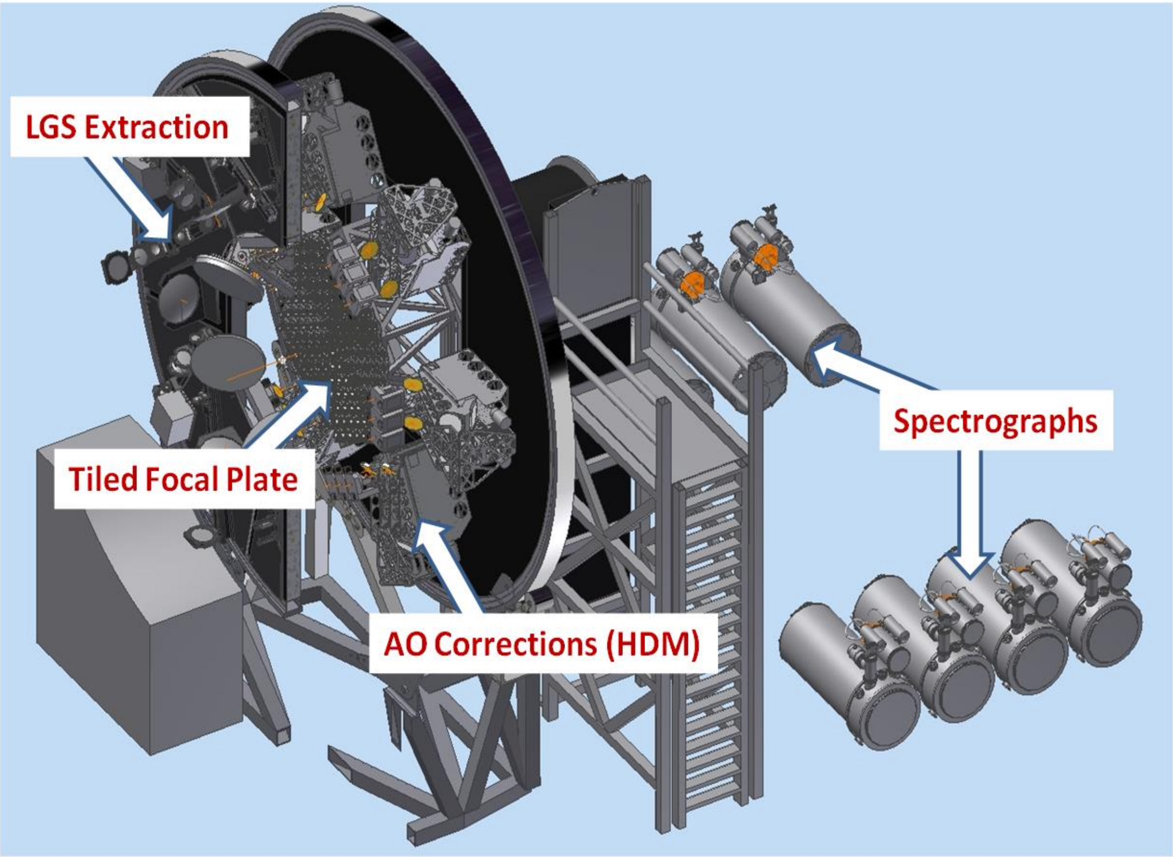

Figure 1. Initial concept design for MOSAIC instrument showing location of key elements within the system and the 8 planned spectrographs (5 VIS and 3 NIR) required for the number of fibres/multiplex.

Due to the physical size of the seeing-limited/GLAO-corrected E-ELT PSF, each seeing-limited fibre is actually a mini-IFU of 7-19 fibres. Each tile will be able to place either the pickoff mirror or fibre bundle on a target however it will not be possible to use both at the same time. Current conceptual designs allow up to 4 fibre/mirror pickoffs to be clustered for crowded field observations.

At the output of the MOAO-corrected HDM channel the reimaged 2x2" field of view will be coupled into a fibre IFU. All fibres (HMM, HDM and IGM) will then be routed to the VIS and NIR spectrographs that will be mounted on the Nasmyth platform. HDM and HMM NIR modes will share the same spectrographs and can be swapped between using a slit-exchanger. IGM and HMM VIS modes will likely share the same spectrographs also for cost reasons. Whilst this limits the full functionality of the system, the possibility remains of mixing observing modes with for example, HDM and HMM VIS observations occurring at the same time. Operationally this will obviously be challenging, but once again, overall efficiency will be enhanced if this operating mode can be delivered.

2.1 AO architecture

As stated, the most challenging AO mode in terms of performance is the MOAO. This concept has been validated on–sky using both NGS and LGS thanks to the CANARY demonstrator at the 4.2m W. Herschel Telescope in the Canary Islands[7][8].The baseline MOAO design resembles that of the EAGLE MOAO system, although with a reduced telescope diameter (42m to 39m), and relaxed EE requirements (30% in 80mas to 25-30% in 150mas). This has allowed some of the component specifications to be relaxed to the point where existing commercially available components can be used within the system. This has not only reduced some of the major technical risks associated with EAGLE MOAO, such as the requirement for an 84x84 actuator open-loop capable DM, but also allowed us to potentially reduce the number of WFS subapertures also.

The MOSAIC MOAO baseline, inherited from the EAGLE phase A study[9], uses 6 off-axis laser guide stars in combination with several bright NGS to sense the full volume of turbulence above the E-ELT. The 6 LGS are positioned in a ring ~7.3 arcminutes in diameter and in the concept presented here are picked off in front of the infinity focal plane. The possibility to place the LGS WFS behind the focal plane will be investigated during the Phase A study. At least three, and up to 6 NGS WFS will also be positioned around the edge of the focal plane. 10 or more MOAO (HDM) channels, dependent upon cost per channel and channel size will be positioned around the edge of the focal plane.

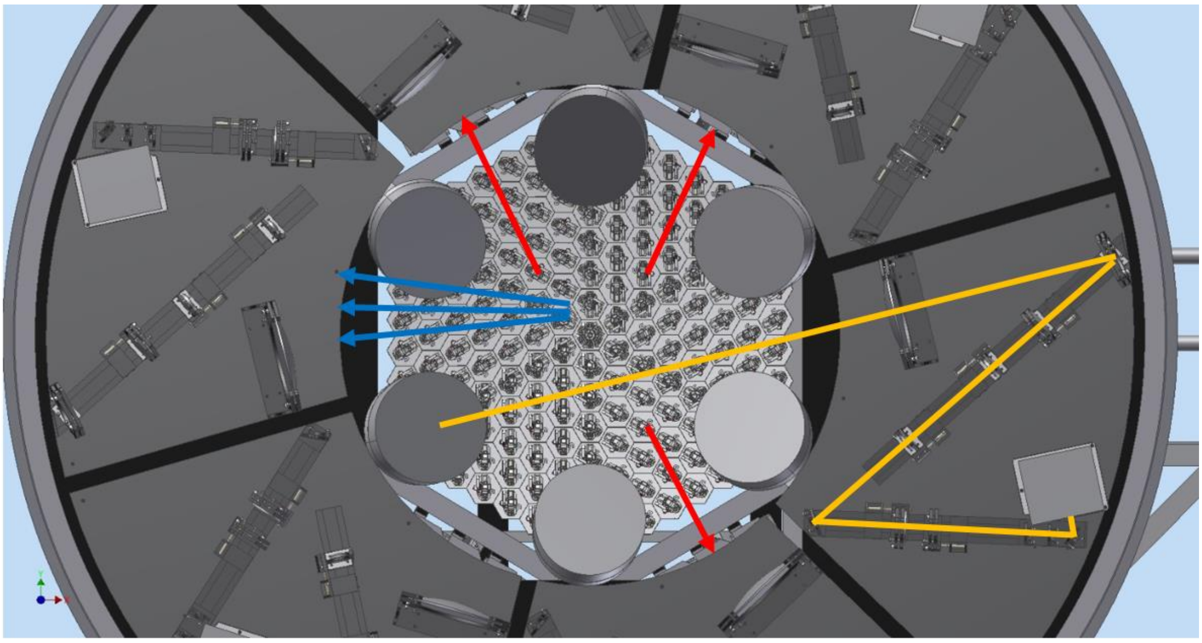

Figure 2. MOSAIC focal plane as seen from the E-ELT. HDM/IGM pickoff paths are shown in blue showing a single pickoff mirror addressing one of three (potential) channels. NGS WFS pickoff paths are shown in red, and the LGS WFS pickoff in yellow that is directed across the focal plane.

Irrespective of the AO architecture ultimately selected, the use of the full 10 arcminute field of view of the telescope is required to meet the instrumental field of view requirements. This means that *at the very least* MOSAIC must recreate the basic telescope functionality required to provide seeing-limited correction and perform telescope acquisition functions. Full details of the E-ELT control scheme have not been released at this stage, but it is likely that the NGS WFS within MOSAIC will have to mimic these functionality.

3. PHASE A AO DESIGN STUDY

A 20 month Phase A study is planned to run from April 2016 to December 2017. During this study, we aim to perform all the major architectural tradeoffs, define an instrumental design that meets the top level requirements, and identify the major technical risk issues with the conceptual design that can be addressed at later project phases. We also have to provide an accurate cost estimate for the system.

The AO architecture (including replication of required telescope functionality for ‘seeing-limited’ operation) is one of the main analyses to be performed at this study. Initial studies will investigate:

- The impact on AO operations, performance and instrument design on allowing the LGS to rotate with respect to the field, or remain fixed with respect to the pupil. The latter is the baseline operation mode for the first light instruments, but the tomographic control scheme can become complicated when the rotation between the NGS and LGS varies.
- Number of required NGS/LGS vs. sky coverage. With the open-loop nature of the MOAO correction, we can make a tradeoff between the number of required NGS and the LGS configuration (number of LGS used and asterism diameter). As we reduce the number of LGS, we must increase the number of NGS to compensate for the loss in sampling, which will reduce sky coverage. However reducing the number of LGS increases the unvignetted NGS focal plane, allowing more NGS to be picked off. Requiring greater numbers of NGS may dramatically reduce sky coverage however. This is a complex tradeoff balancing overall instrument performance against cost and scientific functionality.
- NGS and LGS WFS configuration. The optimal NGS configuration covering wavefront sensor type (Pyramid/Shack-Hartmann), operating wavelength, spatial sampling will also be studied looking at optimizing sampling against guide star magnitude. In terms of the LGS WFS, a wide-field Shack-Hartmann is proposed, but the choice of detector is still open for MOSAIC, with the slightly lower possible loop update frequencies meaning that sCMOS detectors may be a potential option as opposed to CCD detectors that will suffer from significant spot truncation.
- DM type and actuator count. HDM channel designs for two DM diameters of approximately 20mm and ~80mm will be developed, broadly equating to the choice between MEMS and piezo/magnetic DMs. The number of actuators will be varied from 16x16 up to 64x64, but we are limiting the project to selecting only DMs that are currently commercially available, or currently being prototyped.

In addition to these major studies, a full AO error budget will be developed and seeing-limited/GLAO and MOAO PSFs across the full telescope field of view will be provided as inputs into the fibre-fed spectrograph design.

4. BASELINE AO PERFORMANCE

Several studies of potential MOSAIC GLAO/MOAO performance have been made prior to the Phase A kickoff and in this section we summarize these results and define the baseline system parameters. Whilst the precise system, telescope and atmospheric configuration of the studies has varied since the end of the EAGLE study, the preliminary results presented here utilize the latest E-ELT telescope design and the E-ELT nominal 35-layer C_n^2 profile.

The EE requirement is based on the EE within a spaxel *as seen at the spectrograph*. As such, the delivered MOAO performance must be slightly higher to account for the effect of the IFU, fibre and spectrograph. This is being (conservatively) estimated at a 10% increase in EE at this stage, although this value will also change as the design progresses.

4.1 MOAO performance with real NGS asterisms

As performed during the EAGLE phase A study[9], a study presented in Basden *et al*[10] investigated the performance of MOSAIC with real NGS asterism by looking at 10 random pointings within the from within the GOODS-S cosmological field. The results presented here used an approximation of the E-ELT adaptive M4 mirror that uses a 75x75 actuators with a square geometry, and an additional 75x75 actuator MOAO DM to provide directional correction. 6 LGS and 5 NGS were observed, each by a 74x74 subaperture Shack-Hartmann WFS. Further details of the simulation model used can be found in the reference.

In Figure 3, the H-band PSF for 5 pointings is shown, highlighting the variation in PSF that occurs when the NGS asterism is changed. Within a 150mas box, these simulations predicted an EE of between 42-50% in the H-band. A full 74x74 subaperture system in these configurations should exceed the EE requirements of MOSAIC, even when additional instrumental losses are also included. As such, these early simulations show that the EE requirements are attainable with the infrastructure that will be present at the E-ELT, and that there is some scope to reduce component specification (e.g. reducing MOAO actuator count to 64x64 or fewer) within the design study.

4.2 Combined GLAO/MOAO operation

It is clear from a conceptual level that if the MOAO targets are distributed over a wide field of view that the E-ELT M4/M5 adaptive/tip-tilt mirrors must be providing something that optimizes correction for all field angles. This may not be the case for highly-clustered MOAO targets, but for the majority of expected observations, M4/M5 should effectively be providing GLAO correction. This would then allow the HMM/IGM modes to make use of the rest of the corrected field of view for observations.

Simulations of GLAO performance under median atmospheric conditions have shown that FWHM will decrease by a factor of up to 2 at NIR wavelengths, which has been reflected in the 0.6” sampling of the HMM NIR fibres. GLAO performance is highly dependent on the split in turbulence strength between ground and high-layer turbulence which can vary on a night-to-night or even hour-by-hour basis. The E-ELT structure itself may also impact the ground layer, making estimation of GLAO performance one of the more challenging tasks within the design study.

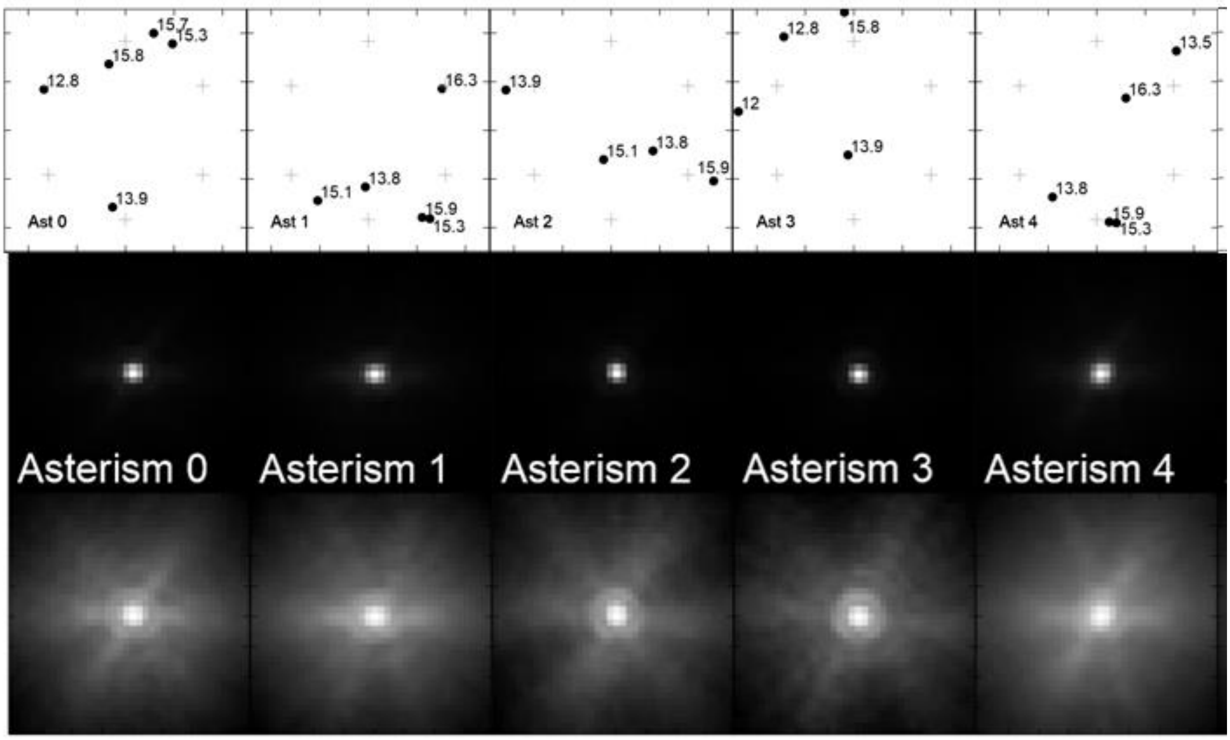

Figure 3. Linear (middle) and log-scaled (lower) H-band MOSAIC MOAO PSFs for 5 of the 10 asterisms simulated by Basden *et al*. The box size is 177mas. The upper plots show the locations and R-band magnitude of the 5 NGS within the 10 arcminute field of view and the locations of the LGS (grey crosses).

4.3 Impact of C_n^2 profile variations

The tomographic sensitivity of any multi guide star tomographic AO system is defined by the spatial scales at which the wavefront is sampled and the on-sky asterism spacing. MOSAIC uses the widest possible asterisms that can be provided by the E-ELT, making it the most sensitive tomographic system to changes in altitude. As the MOSAIC WFS geometry matches that of EAGLE, it is likely that MOSAIC will be sensitive to changes in turbulent layer altitude of approximately 150m. Whilst there exists a defined median atmospheric model for the E-ELT, encountering the precise median profile that the instrument was designed for is unlikely. Information on the profile variation at a vertical resolution approaching 150m at Cerro Armazones does not exist leading to an uncertainty in system performance under realistic (e.g. each hour over the course of a year) as opposed to statistical conditions.

High-vertical resolution C_n^2 profilers (such as the Stereo-SCIDAR instrument[11] developed to support the CANARY AO demonstrator system on La Palma) will become available from Cerro Paranal over the course of the study allowing an estimation of system performance, at least for the high altitude layers that define wide-field performance.

The impact of short timescale variations in altitude also impacts the rate at which the system control scheme requires updating to meet performance levels. This can have a large impact not only on the way in which the system is operated, but also the amount of processing required to maintain performance over the course of an observation. An estimate of the non-real time processing requirements, as well as the entire operational and calibration scheme will be developed throughout the course of the Phase A study.

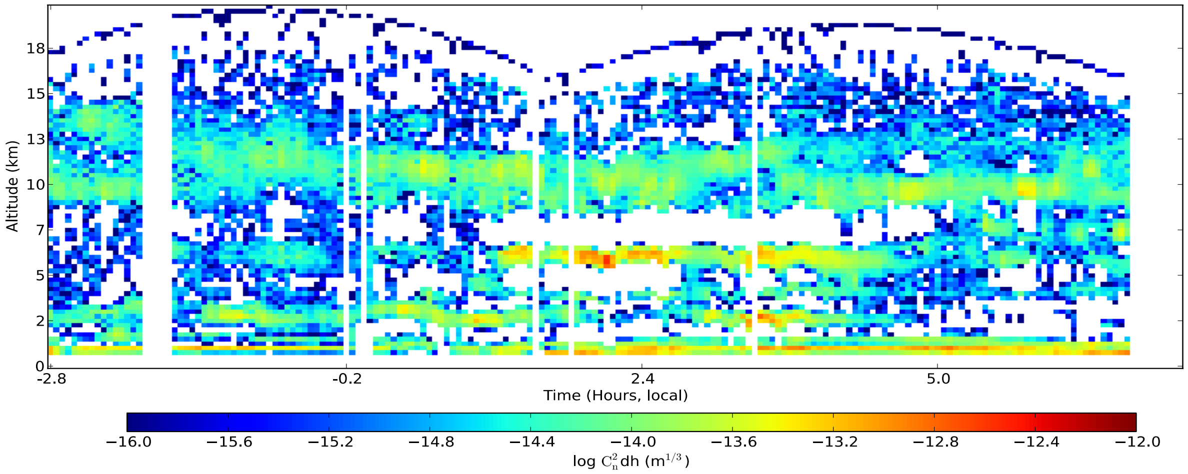

Figure 4. Optical turbulence profile recorded using the Stereo-SCIDAR instrument on the 1.2m JKT telescope on La Palma on the night of 15th September 2013. Taken from Shepherd *et al*[11]. The vertical resolution of the profile is approximately 250m, approaching that required for MOSAIC. Note the rapid variation in layer altitude and strength e.g. starting at approximately 01:00 @ 6km, or 03:45@ 10km that will be observed by MOSAIC, and thus affect system performance.

5. CONCLUSIONS

The MOSAIC instrument is entering its Phase A (conceptual) design phase that will last until December 2017. In these proceedings we have introduced the initial conceptual design that will form the basis for a range of performance trade-off studies. We have described the top-level instrument scientific requirements, and described the baseline AO operating concept. We have also highlighted the initial AO tradeoffs that can have a major impact on not only AO system performance, but the entire instrument architecture, including the issue of LGS field or pupil tracking, the impact of reducing the number of LGS on performance and sky coverage, and the MOAO DM characteristics (particularly diameter).

Finally we have highlighted some early published simulation results that show the baseline MOAO architecture can meet, or even exceed, the top-level requirements for the HDM mode. This provides some scope within the design to reduce risk and/or cost. AO and telescope performance for the HMM mode will also be investigated, which will be particularly sensitive to the split in turbulence strength between ground and higher-altitude turbulence.

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