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CANARY: The NGS/LGS MOAO demonstrator for EAGLE

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Abstract. EAGLE is a multi-object 3D spectroscopy instrument currently under design for the 42-metre European Extremely Large Telescope (E-ELT). EAGLE will use open-loop Multi-Object Adaptive Optics (MOAO) to provide partial AO correction across a wide (5-10 arcmin) field of view. The novelty of this scheme is such that on-sky demonstration is required prior to final construction of an E-ELT instrument. The CANARY project will implement a single channel of an MOAO system on the 4.2m William Herschel Telescope. The CANARY project is undergoing a phased development plan that starts with demonstration of low-order open-loop AO correction using first NGS then Rayleigh LGS tomography, moving to a demonstration of high-order open-loop AO correction using LGS tomography. This final stage will also include 2 DMs in a woofer-tweeter configuration similar to that of EAGLE when installed at the E-ELT. We describe the requirements for the various phases of MOAO demonstration, the corresponding CANARY configurations and capabilities and the current designs of the various subsystems.

1 Introduction

Multi-Object Adaptive Optics (MOAO)[1] is a technique allowing simulataneous Adaptive Optics (AO) correction for several small target fields (typically 2-4arcsec in diameter) within a wider Field of View (FOV). Each target sub-field is corrected by an independent deformable mirror (DM) providing AO correction along a given line-of-sight only. Providing AO correction in this manner improves AO performance compared to other wide-field AO techniques such as Multiple Conjugate AO (MCAO)[2], because the correction need not be optimised for the entire wide FOV simultaneously.

The technical FOV of an MOAO system is typically of the order of 2-10 arcminutes in diameter, although in practice this technical FOV is only limited by the availability of guide stars and the telescope FOV. To provide AO correction across this wide FOV tomographic wavefront sensing is required. Multiple Natural Guide Stars (NGS) or Laser Guide Stars (LGS) are observed in order to map the distribution of turbulence above the telescope primary aperture. The real-time control system then slices a column through the mapped turbulent volume in the direction of a target object and applies a correcting signal to the relevant DM. In order to correct for multiple objects, multiple columns are sliced through the turbulent volume and applied to several independent DMs.

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The critical difference between MOAO and other more established AO techniques is that the DMs are controlled in open loop such that the WaveFront Sensors (WFSs) do not observe the correcting signal provided by the DMs. In such a system, accurate system characterisation and calibration is critical to ensure performance. Without this, the true system performance cannot be fully characterised. The principal advantage of running the DMs in open-loop is that one need not have a single guide star per target. Indeed, the number of guide stars (either LGS or NGS) is completely independent of the number of corrected fields within the system, allowing a highly modular and apaptable system design. This adapbility is demonstrated by the fact that open-loop MOAO solutions have been proposed for both diffraction-limited narrow to moderate FOV correction [3] as well as wide-field lower angular resolution instruments (see Sect. 1.1 below). Open-loop control also improves the temporal response of the system as the open-loop gain, by definition, must be set to unity. This should allow the WFSs to use longer exposures and provide similar levels of correction to a closed loop system, whilst running on fainter guide stars.

MOAO as a technique has been extensively demonstrated within simulations, using laboratory testbenches, and to a limited extent, on-sky as well. When compared to the more established wide-field AO technique of MCAO, it is clear that a successful demonstration of a full tomograhpic WFSing open-loop AO system is required to demonstrate that a facility-class instrument design is feasible using current technology. The CANARY instrument will provide this demonstration, as well as gaining critical experience of the on-sky operation of such an MOAO system.

This paper describes the design of CANARY, then moves on to the functionality of various sub-systems within CANARY. Results of Monte-Carlo simulations of the NGS-only phase of CANARY are then presented, along with some early results from CANARY subsystem testing.

1.1 MOAO with EAGLE

EAGLE[4] (Extremely large telescope Adaptive optics for GaLaxy Evolution) is a proposed MOAO-based multiple Integral Field Unit (IFU) spectrograph for the European Extremely Large Telescope (E-ELT). EAGLE will provide medium spectral resoution R-K band 3D spectra of up to 20 independent 2 arcsec diameter sub-fields within an effective technical FOV of 7 arcmin diameter. EAGLE will use up to five NGS and six LGS to tomographically map the turbulence above the 42m diameter aperture of the E-ELT. In addition to the E-ELT adaptive secondary mirror (designated M4 within the E-ELT design) of 84 by 84 actuators, EAGLE will contain 20 open-loop MOAO DMs each containing a similar number of actuators to that of the E-ELT M4. This configuration means that EAGLE will operate as a woofer-tweeter system, with M4 removing large scale aberrations common to all target fields, while the MOAO DMs will provide correction specific to a given line-of-sight. One complexity of this arrangement is that M4 will operate in closed-loop, while the MOAO DMs operate in open-loop. The combined open and closed loops will require careful control in order to optimise system performance. The combined loops also provide redunancy in case of system failure (an MOAO system can still provide limited functionality if either M4 or the MOAO DMs are inoperable) as well as providing useful calibration capabilites.

The WFSing requirements in terms of number of WFSs for EAGLE are no more complicated than that required by an equivalent wide-field MCAO system, while each AO path is greatly simplified due to the narrow FOV. The only complexity of the AO path design is that it must be replicated 19 times. This modularity means that any MOAO demonstrator system need only recreate a single AO corrected channel in order to demonstrate the feasibility of the MOAO concept.

2 CANARY Design

CANARY is a single channel MOAO demonstrator that will be deployed at one of the Nasmyth foci of the 4.2m William Herschel Telescope (WHT) at the Roque de Los Muchachos Observatory on the island of La Palma. CANARY is a three phase project, each phase increasing system complexity, leading up a system that closely resembles the proposed implementation of EAGLE on the E-ELT.

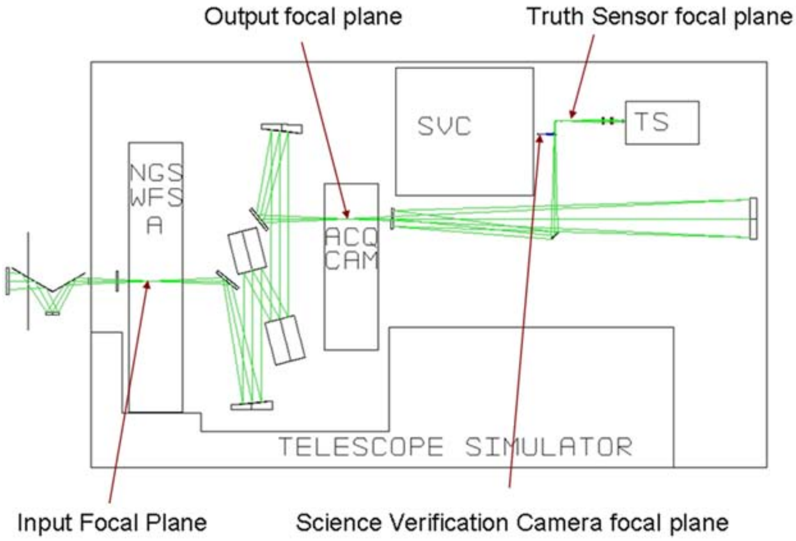

Fig. 1. CANARY phase A optical layout showing locations of principal subsystems around the main AO optical path (in green). Acq. Cam = Acquisition Camera. SVC = Science Verification Camera. TS = Truth Sensor.

CANARY phase A will use three NGS WFSs and a low-order 8x8 actuator open-loop DM. Phase B of the project will use four Rayleigh LGS for tomographic WFSing to provide a correcting signal to the same low-order DM. Phase C will then introduce the closed-loop woofer, open-loop tweeter configuration that will be encountered within EAGLE. The tweeter DM at phase C will be of a higher-order than the single DM used at phases A and B, with up to 32x32 actuators. In order to reconfigure the system between the three phases, the optical design is based around a set of interchangeable optical modules that could be moved around a central AO beam path that contains the correcting elements. The on-sky demonstration of phase A is planned for June 2010, with phases B and C planned for 2011 and 2012 respectively.

As a demonstrator system, the principal aim of the system is to fully understand and characterise the on-sky system performance. With this in mind, a telescope simulator and comprehensive diagnostics package have been included within the CANARY design. The telescope simulator provides critical alignment and calibration functionality, as well as allowing complete characterisation of the system when under testing in the laboratory (see Sect 2.4). The diagnostics package is described in further detail in Sect. 2.3.

2.1 Phase A Design

At phase A, three NGS will be selected within a 2.5 arcmin diameter FOV. A central on-axis star will be used as a wavefront reference for the diagnostics package. The phase A optical layout is shown in Fig. 1. The main AO path uses an f/11 off-axis parabolic relay to reimage the WHT pupil onto the DM. This relay has a magnification ratio of 1:1 and provides an unvignetted FOV of greater than 2.5 arcmin to allow the NGS WFSs to be relocated to behind the DM for phases B and C. The remaining optical modules (acquisition camera, DM figure sensor, diagnostics package) all require an input f/11 beam, also allowing easy reconfiguration between CANARY phases without requiring a major redesign.

The CANARY Real-Time Control System (RTCS) uses a hybird FPGA-CPU architecture running on standard commercial PCs. Pixel processing is handled within a dedicated FPGA pipeline (developed for the HOT experiment[8]), while the reconstruction and DM control is performed within CPU. Tests on the RTCS have shown that phases A and B can be run at 300-400Hz using a single-threaded reconstructor, although latency and jitter still require characterisation. At phase C, the reconstructor will be parallelised to handle the higher order LGS WFSs and DM.

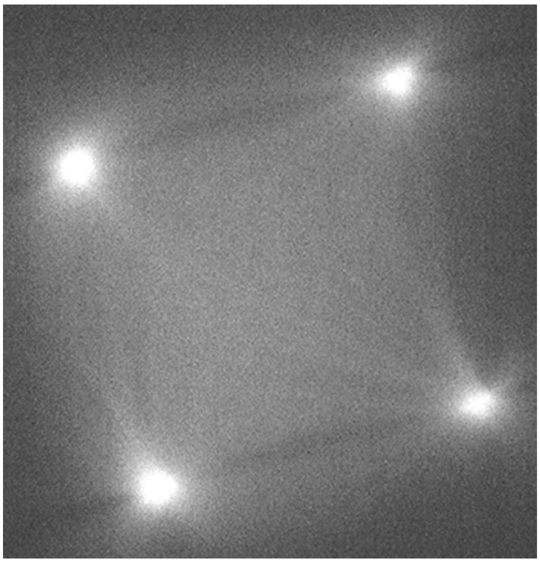

Fig. 2. Image of CANARY phase B/C LGS asterism taken at the WHT Nasmyth focus. A non-range gated image of the Rayleigh LGS imaged at an altitude of approximately 6.7 km. The LGS asterism is approximately 40 arcsec in diameter, the uncertainty on this diameter being caused by the defocused LGS plume biasing the centroid towards the centre of the image.

2.2 Phase B/C Design

The phase B and C designs both use multiple Rayleigh LGS for performing wavefront tomography. The key upgrades for the phase B design relate to the LGS launch system and LGS WFS. The 4-LGS asterism is created by inserting a diffractive optical element (DOE) into the existing GLAS laser launch system[5]. The DOE is mounted in a rotation stage to compensate for field derotation at the WHT Nasmyth platform. The CANARY LGS launch system was tested on-sky in May 2009 in order to feed back into the phase B LGS WFS design. An image of the 4-LGS asteism that was created using this technique is shown in Fig. 2. The apparent angular diameter of the asterism is approximately 40 arcsec with 80% of the laser light being directed into the frst diffracted order of the DOE. All four LGS will be reimaged onto a single 128x128 pixel detector[6]. At Phase B, this allows 8x8 pixels per Shack-Hartmann subaperture. At Phase C, alternative WFSing methods that are more pixel efficient are being investigated.

2.3 System diagnostics

CANARY will include a comprehensive diagnostics package and data logging system that will allow measurement of all relevant system, telescope and atmospheric parameters. The principal performance monitor will be the Truth Sensor (TS). The TS is a closed-loop WFS that observes the MOAO corrected on-axis target star. Optically, the TS is a copy of the open-loop WFSs while the data from the TS is synchronised with them via the RTCS. The TS can also be used to run CANARY in a closed-loop fashion as a performance comparison with the open-loop tomographic WFSs.

A NIR (J and H-bands only) Science Verification Camara (SVC) will also look at the AO corrected on-axis star and determine the system Strehl Ratio (SR). Although scienctific performance has not been a principle design driver throughout the CANARY design, the requirements on throughput to the TS mean that at phase C a demonstration science programme will be attempted. Although during the current early phase of the CANARY project our focus must be on demonstrating MOAO, the possibility of coupling a visible-light IFU (such as OASIS[7], already at the WHT) to the AO corrected CANARY focus will be investigated.

A high temporal and spatial frequency Figure Sensor (FS) will be observing the open-loop DM at all times. The FS has three modes of operation. The first is as a simple monitor of mirror shape that will allow measurement of the instantaneous DM open-loop error. The second mode attempts to force the DM to the shape requested by the RTCS. The final mode uses a robust H-infinity controller that should allow the higher temporal sampling of the FS control loop to reduce temporal errors within the system[9].

At phases B and C, the restricted altitude of the four LGS mean that some turbulence may be above the LGS altitude. In order to measure this we propose to have several turbulence monitors, capable of mapping both low and high-altitude turbulence. The WFSs within CANARY can be used as a multi-baseline SLODAR[10] system, but we will also have an external SLODAR and MASS-DIMM[11] turbulence profilers that will be configured to measure the full atmoshperic turbulence profile.

2.4 Alignment and Calibration

Alignment and calibration within an open-loop AO system is one of the critical issues that can affect AO performance. Simulations of system performance have shown that a pupil shear of $1/70^{th}$ pupil diameter will cause a significant reduction in system performance. During system calibration and measurement of the DM-WFS interaction matrix, the alignment of the DM to each of the WFSs must be determined. The DM-WFS alignment must then be retained regardless of changes to WFS pickoff location. This alignment can be measured using the several pupil alignment tools that are contained within the CANARY telescope simulator.

The telescope simulator can be used to recreate the focal plane of the WHT for CANARY and will be present during laboratory testing and on-sky. The telescope simulator contains several reference sources and will recreate any possible NGS/LGS geometry that will be encountered on-sky. Two rotating turbulent phase plates within the simulator can be reconjugated to any altitude between 0 and 10 km to probe the effects of tomographic WFSing during laboratory testing. During the testing phase the telescope simulator will be used to develop and perfect the alignment and calibration tasks that will be performed when installed at the WHT.

3 System Performance

Independent Monte-Carlo simulations of CANARY performance at phase A have been performed using YAO (developed by F. Rigaut) and DASP[12]. A breakdown of CANARY performance under typical operating conditions expected at the WHT is shown in Table 1. The residual wavefront error after correction corresponds to an H-band SR of between 0.19 and 0.31 for m_R=12 NGS. This variation demonstrates the importance of reconstructor choice and optimisation for tomographic AO performance.

The asterism diameter also has a large impact on tomographic AO performance. A 30 arcsecond asterism diameter can be used to achieve reasonable AO correction (as indicated in Table 1), but suitable 4-star m_R asterism of such a small diameter are limited. 1-2 suitable targets will be observable from the WHT throughout the months of June-October.

The 8x8 actuator DM has been used on the SESAME[13] AO test bench under identical open and closed-loop AO configurations. After calibration for actuator linearity an open-loop DM error of 4% was measured. This percentage value means that there would be a 40 nm RMS error on a requested DM figure shape of 1000 nm RMS. This value will be monitored within CANARY using the closed-loop figure sensor described in Sect. 2.3.

4 Conclusion

An overview of the CANARY design and design philosophy has been presented, focusing on some of the major subsystems within CANARY. The CANARY project will be able to answer many of the

Table 1. CANARY Phase A performance breakdown

Source of Error	Wavefront Error (nm rms)
WFS open-loop estimation	63
WFS noise (quantum + readout)	40 (m_R=10)
	80 (m_R=12)
	190 (m_R=14)
Tomographic reconstruction (30 arcsecond radius)	260 (GLAO least-square)
	220 (tomographic least square)
	170 (L&A MMSE)
DM fitting	140
DM open-loop error	48
Tip-tilt open-loop error	26
Temporal and aliasing	113
Residual high-order from optics	50
TOTAL	mR=12: 285-340

problems relating to the on-sky operation of an MOAO system, and will have the instruments to be able to characterise MOAO performance.

The CANARY project will be on-sky from 2010-2012, after which point it will have demonstrated open-loop AO correction using LGS tomography in a configuration similar to that currently proposed as the baseline for the EAGLE instrument on the E-ELT. We also aim to have performed some demonstration scienctific observations in this final phase of the experiment. After 2012, the modular nature and ease of reconfiguration of CANARY will allow demonstration of other AO techniques and technologies and therefore could be used as a testbench system for on-sky verification of these future concepts.

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