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CANARY

Phase B: The LGS upgrade to the tomographic MOAO pathfinder

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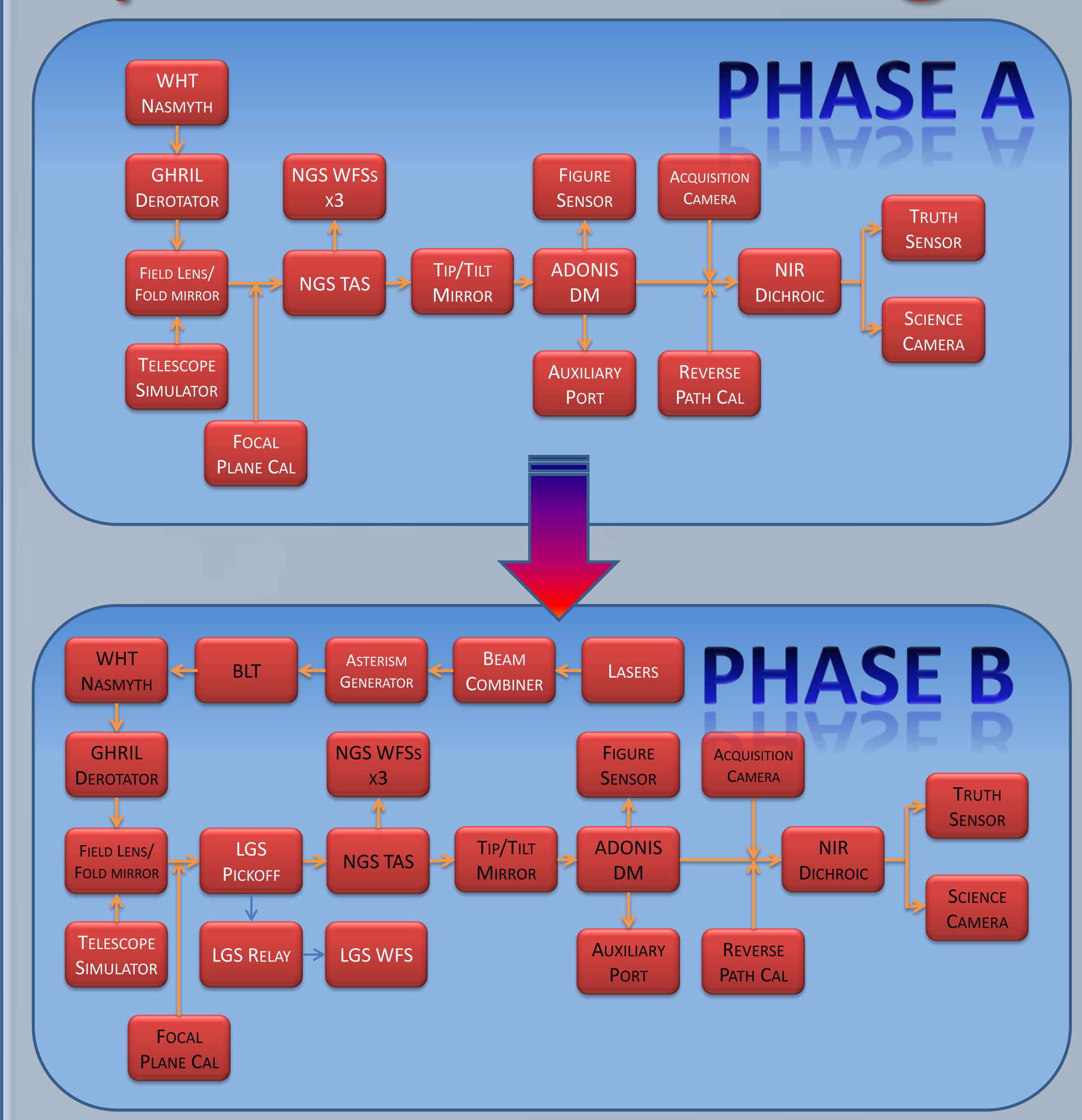
CANARY has been designed to demonstrate full tomographic LGS MOAO in a configuration as close as possible to that of the proposed EAGLE instrument for the E-ELT. A phased approach to the instrument development has been adopted to reduce the overall risk and developmental complexity with the initial Phase A system performing NGS MOAO only using three off-axis NGS WFS. The Phase B system will add four off-axis open-loop LGS WFSs to this system allowing combined LGS/NGS tomography to be performed, thereby taking CANARY one step closer to an EAGLE-like configuration. The upgrade to include LGS within CANARY requires several new and upgrades subsystems, including a multiple LGS launch system, LGS WFSs and a new LGS calibration unit. Here we present the requirements, design, and subsystem performance for the Phase B system, as well as simulations of the on-sky AO performance of CANARY.

System level design

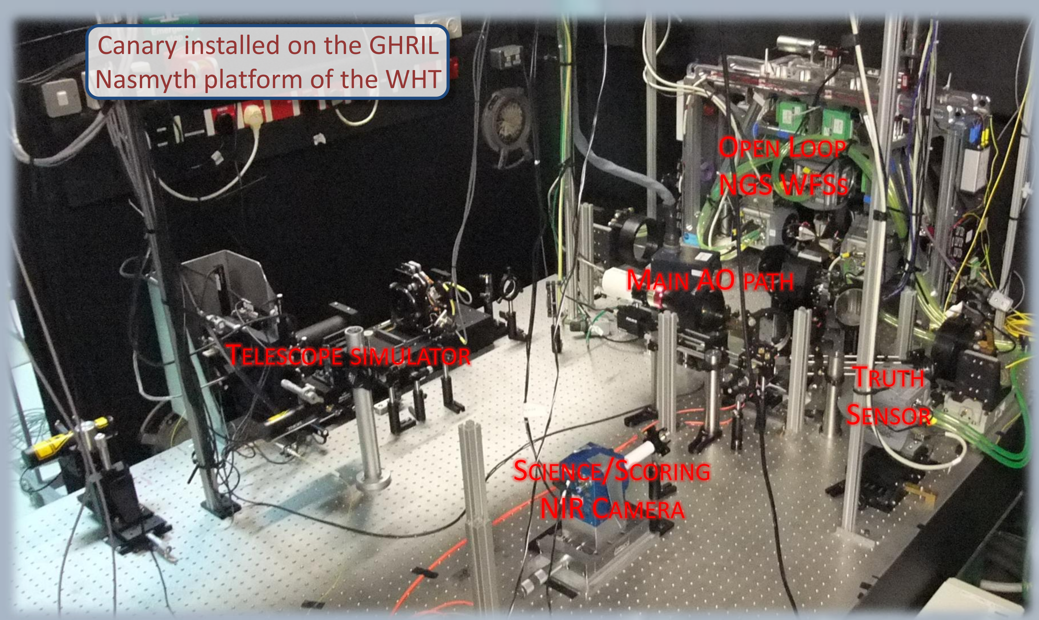


Phase A (Tomographic NGS-based MOAO) and Phase B (Tomographic NGS or LGS based MOAO) modular layouts for CANARY. Subsystems shown in black in the Phase B layout are modules that remain unchanged from their existing Phase A implementation or are existing parts of WHT infrastructure.

The Phase A system used three off-axis NGS WFSs to correct the on-axis beam using a 54-actuator deformable mirror (DM) controlled in *open-loop*. The corrected wavefront is observed by a 4th WFS and a NIR imaging camera for characterising higher order calibration errors.

CANARY also included a full telescope simulator capable of recreating any 4 star NGS asterism and includes two etched glass phase screens for turbulence emulation. This was permanently installed with the instrument and was fundamental to the on-sky results obtained with CANARY.

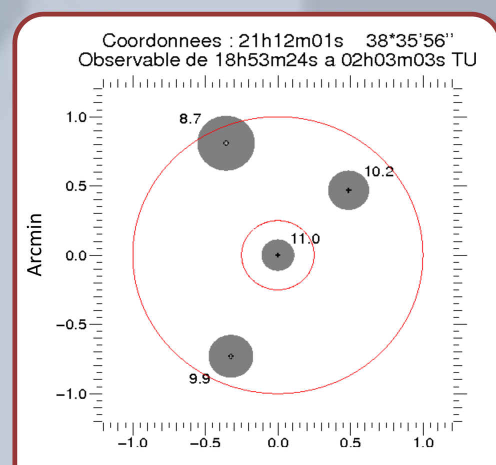
The modular design of CANARY allows all of the Phase A subsystems to be reused in later development phases without modification. The Phase B layout and new subsystems are shown to the left, and can be separated into three main areas; the laser launch system, the laser guide star WFS and the Telescope Simulator.



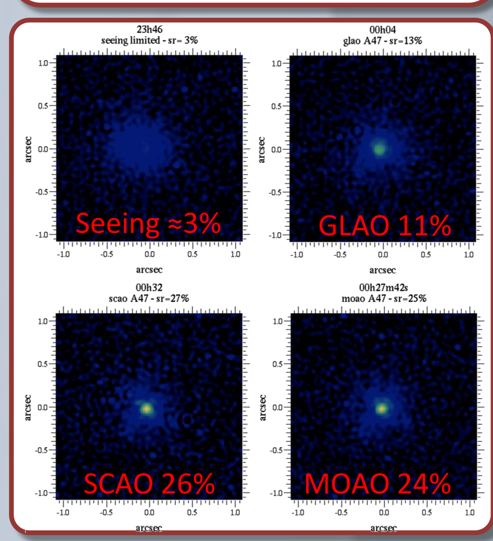
CANARY Phase A had a total of 19 wavefront and pupil reference sources to allow investigation of a variety of alternative calibration and alignment techniques. This 'belt and braces' approach to system calibration allowed us to investigate and compare a wide variety of calibration and alignment techniques that could be applied to future ELT AO systems.

Phase A results

CANARY was commissioned at the WHT for a total of 8 nights between September and November 2010. Due to unusually bad weather for the time of year, only 1 night of useful data was obtained.



Example asterism shown with R-band magnitudes.



System parameter	Value
Number of NGS	3 + 1 on-axis
NGS off-axis distance	25" to 65"
Magnitude range (R-band)	8.3 to 11.2
RTCS update rate	150 – 300Hz
Number of subapertures	36 (7x7)
Pixels per subaperture	<16x16
Science wavelength	1490nm

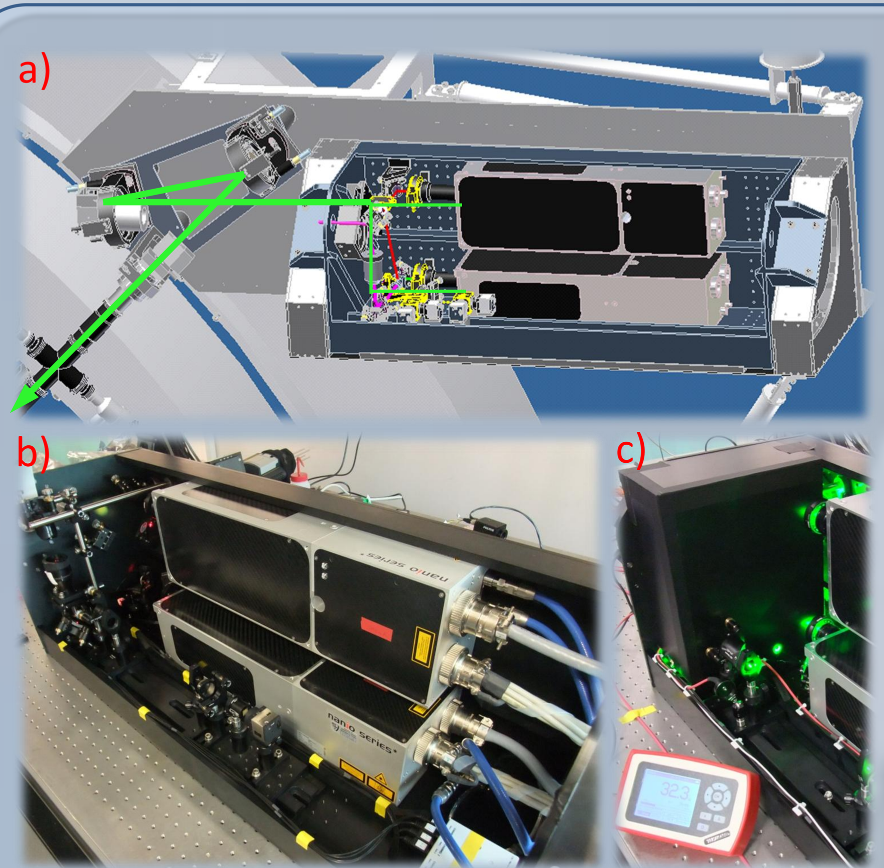
An example of CANARY on-sky performance @ 1.49µm obtained with the shown asterism is provided to the left

The correction to apply to the on-axis DM for both the MOAO and GLAO (also running in open-loop) corrected PSFs was determined using a fully tomographic open-loop reconstructor determined using the *Learn and Apply* technique (Vidal *et al**). The SCAO loop was closed on the fainter central star.

More detailed information on the Phase A performance will be presented in the talk by Eric Gendron on Monday at 16h50 and in the poster by Fabrice Vidal.

* Vidal, F., Gendron, E. & Rousset, G., JOSA A, 27, A253 (2010)

Laser Guide Stars

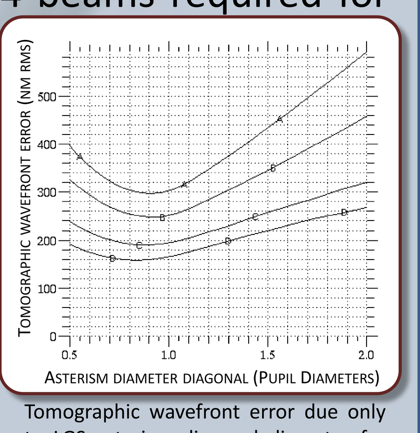


CANARY laser launch system a) installed at the top end ring of the WHT, showing the beam path (in green) to the beam launch telescope situated behind the WHT secondary, b) during AIT in Durham and c) with a power meter measuring output of the combined beam

A new laser launch system will be installed at the top-ring of the WHT at the beginning of October. Two pulsed 16W 532nm lasers are combined both spatially and temporally and then sent through the existing WHT beam launch optics to create the Phase B LGS. An etched-glass diffractive optical element is used to separate the combined beam into the 4 beams required for the Phase B asterism.

CANARY is a single channel MOAO system therefore the performance can be optimised for the on-axis direction only allowing use of the optimal 'LTAO-like' asterism. The optimum asterism diameter has been calculated to be between 0.85 and 0.95 of the pupil diameter for any given altitude (see graph).

The launch system throughput has been measured and the combined beam outputs 30W. The 2-layer DOE places ~64% of the light into the 1st diffracted order. With this efficiency a 400m LGS @ 15km should provide 450 photons/subaperture/frame at 300Hz assuming standard atmospheric conditions.



Tomographic wavefront error due only to LGS asterism diagonal diameter for asterisms at a distance of 8km(A), 10km(B), 15km(C) & 20km(D).

Telescope Simulator

The Telescope Simulator is the principal means of both system alignment and off-sky performance characterisation. At Phase B, the Telescope Simulator is being upgraded to include new LGS reference sources and a wedge plate that will allow the measurement of LGS WFS-DM interaction matrices.

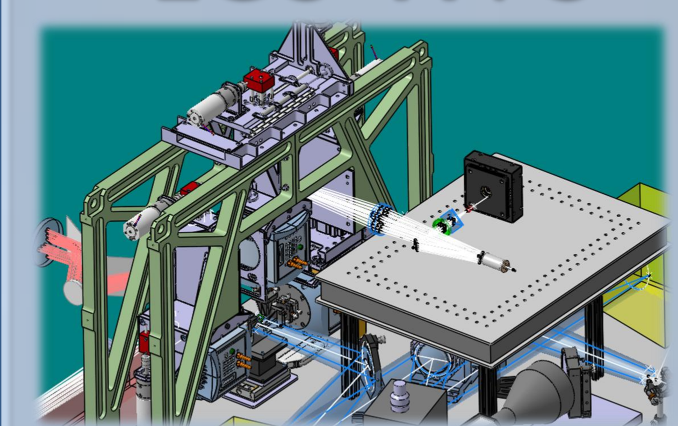
The LGS WFS reference sources are fibre-coupled green LEDs that are placed in a separate LGS arm that is fed into the optical train using a plate beam-splitter. The LGS source altitude can be changed over a range of 11-21km, and the asterism diameter changed by replacing the machined plate in which the sources are held.

One of the procedures of the system calibration at Phase A compared the influence of the DM on the open-loop NGS WFSs to the interaction matrix of the closed-loop Truth Sensor. To achieve this, a reverse path calibration source was included within the system. This source cannot be used at Phase B because the LGS path cannot observe the DM directly and the NGS and LGS sources are not in the same plane. A tilted wedge plate will therefore be placed in the plane conjugate to the telescope pupil. When this plate is rotated, all NGS and LGS WFSs in the system will observe the same angular tip and tilt. By comparing the WFS spot motion for identical subapertures on different WFSs, the link between LGS WFS spot motion and DM influence functions can be established.

LGS source path during assembly and testing at the UKATC. The system will be ultimately mounted vertically in the Telescope Simulator.

LGS WFS

The LGS WFS will observe the four off-axis LGS created by the laser launch system. All the LGS are imaged using a single detector with integrated electronic shutter that allows us to temporally range gate the outgoing laser pulses. A 7x7 subaperture Shack-Hartmann pattern from each LGS is imaged onto a 64x64 pixel quadrant of the detector, providing 8x8 pixels per subaperture.



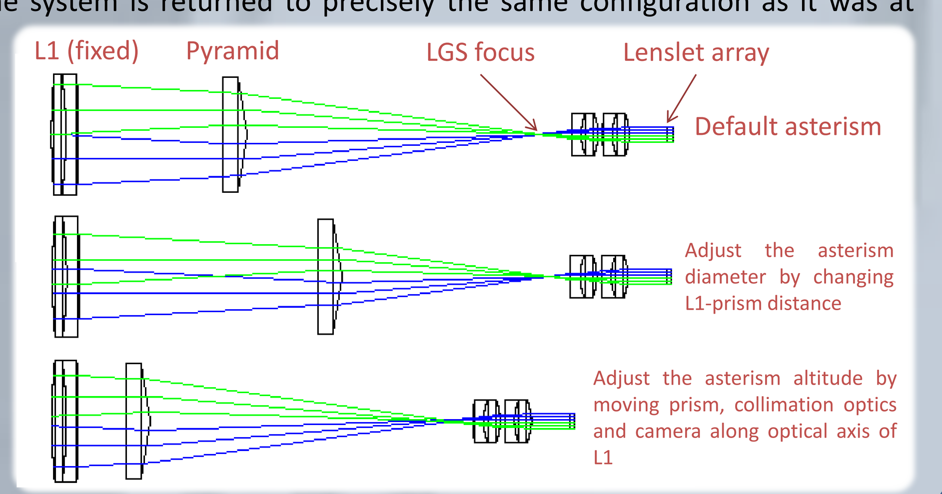
CAD model of LGS WFS layout showing auxiliary LGS WFS bench situated above main AO path. The LGS light is picked off dichroically before the NGS WFSs and fed through the TAS (Target Acquisition System) shown in green.

Because the number of on-sky nights at Phase A was limited, the decision was made to fit the LGS WFS around the existing Phase A layout. To achieve backwards compatibility, the LGS WFS has to be mounted on a bench above the existing AO path. The LGS light is picked off by a 532nm Rugate notch filter before the focal plane and the light directed through the existing NGS WFS support structure. By removing the LGS dichroic, the system is returned to precisely the same configuration as it was at Phase A.

The flexibility of investigating alternative LGS asterism diameters and altitudes is key to characterising and understanding the tomographic performance of the LGS system. This is particularly important on a 'small' diameter telescope as the WHT where the Rayleigh LGS pupils separate at a relatively low altitude, thereby limiting the tomography to 3-4km above the telescope.

To fit the four LGS WFS patterns on to a single CCD and allow us to observe a wide range of LGS asterisms, a pyramidal prism is used to correct for both the off-axis angle of the LGS.

The LGS WFS also contains a tip-tilt mirror for the correction of LGS launch jitter.



Performance and status

In addition to the tomographic and closed-loop modes available at Phase A, Phase B will also be able to perform open-loop MOAO/LTAO, open-loop LGS GLAO, with either single and multiple tip/tilt/focus NGS reference stars. CANARY is also capable of using all open-loop NGS and LGS WFSs simultaneously.

The principal terms in the Phase B error budget are tomographic error (due to the low altitude pupil separation of a 4.2m telescope), followed by DM fitting error, and then static bench errors. This final error is dominated by high order terms within the AO path, presumably on the DM, but this is being investigated.

We are also implementing LQG control within the real time control system in addition to the Learn and Apply tomographic calibration.

Phase B wavefront error (WFE) budget (in nm RMS) for two tomographic configurations using 4 off-axis LGS @ 15km in addition to the NGS configuration indicated in columns 2 and 3. The final error term has been derived by adding simulated Phase B performance under median CANARY atmospheric parameters (r0 = 12cm, 45:15:30:10 % turbulence split @ 0:2.5:4:13.5km) to the Phase A measured performance of non-simulated error terms. The resulting H-band Strehl is indicated.

Error Term	3 off-axis high order NGS	1 on-axis tip/tilt NGS	Status
Static residual errors	160nm	160nm	Calculated
DM open-loop error	48nm	48nm	Calculated
TT open-loop error	26nm	26nm	Calculated
LGS pulse synchronisation error	10nm	10nm	Calculated
Simulated performance	300nm (SR=27%)	277nm (SR=33%)	Simulated
TOTAL ERROR	**344nm (SR=18%)**	**324nm (SR=22%)**	

CANARY is currently installed at the Observatoire de Paris in its phase A configuration. Phase B hardware integration begins at the end of October. The real time control system (DARC – see Basden *et al**) has been interfaced to the Phase B hardware and tested, and the User Interface software has been upgraded to handle LGS calibration and streamline the data acquisition process.

The Laser Launch system is currently in transit to the WHT in La Palma and will undergo initial commissioning over two nights in November, with a backup run in May. Time for Phase B commissioning has been applied for in June 2012.

* Basden, A., Geng, D., Myers, R., Younger, E., Appl Opt. **49**. 5354-63 (2010)

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