Towards MOAO on the ELT: the CANARY program

E. Gendron[1a], T. Morris[2], F. Vidal[1], A. Basden[2], M. Brangier[1], Z. Hubert[1], R. Myers[2], G. Rousset[1], F. Chemla[1], A. Longmore[3], T. Butterley[2], N. Dipper[2], C. Dunlop[2], D. Geng[2], D. Gratadour[1], D. Henry[3], P. Laporte[1], N. Looker[2], O. Martin[1], D. Perret[1], A. Sevin[1], G. Talbot[2], and E. Younger[2]

[1] Observatoire de Paris – CNRS – Université Paris Diderot, 5 place Jules Janssen, 92190 Meudon, France
[2] Centre for Advanced Instrumentation, Durham University, South Road, Durham, DH1 3LE, UK
[3] UKATC, Royal Observatory Edinburgh, Blackford Hill, Edinburgh, EH9 3HJ, UK

Abstract. From the very early concept presented in 2001 to the first on-sky Multi-Object Adaptive Optics (MOAO) prototype system, exactly 10 years have elapsed. End of 2010, the pathfinder instrument called CANARY obtained the first open-loop, tomographically MOAO compensated images on the WHT. What were the challenges and what was demonstrated? What will be the future steps for a real astronomical MOAO system to be installed on an extremely large telescope (ELT)? We present the Canary program and discuss how these achievements contribute to improve the technical readiness of the MOAO instruments for ELT.

1 Introduction

In 2001, a new adaptive optics (AO) and instrument concept was presented at the conference *"Beyond conventional adaptive optics"* held in Venice. The targeted science was the study of distant forming galaxies and the goal was to simultaneously observe the near-IR integral field spectra of a few tens of these tiny objects sparsely distributed across the 20 arcmn field of view of the VLT. The instrument, named FALCON [15], proposed to encapsulate AO systems into the integral field units (IFU) of a fiber-fed multi-object spectrograph. Those corrective elements, nicknamed as *"corrective buttons"*, were populating the focal plane, together with others, *"wavefront sensing buttons"*. Corrective mirrors were driven in open-loop from a tomographic blend of all the wavefront sensor (WFS) measurements.

Around 2003, the acronym MOAO (multi-object adaptive optics) appears first in [10]: this concept becomes part of the TMT instrumentation plan. From FALCON, MOAO keeps the concepts of tomography and open-loop regime. However, the implementation is revisited as in IRMOS/TiPi [12] or later on in EAGLE [28]: the numerous potential pickoff scenarios (fibre bundles, MOEMS, beam steering systems, reconfigurable optical probes, tiles, etc) that allow to pick up light from laser (LGS) and natural guide stars (NGS), or from science objects, produce a variety of trade-offs and designs that are evaluated one against the others. The strong potential of MEMS deformable mirrors (DM) was spotted immediately by D. Gavel at LAO [12], but their limited stroke make a second DM, denoted as a woofer, necessary to handle some of the stroke range.

The same reflexion occurs in Europe, in the conceptual design studies for the instruments of the European extremely large telescope (E-ELT). The instrument MOMFIS [8] (France) shares some similarities with IRMOS at the TMT. In the UK, MOMSI [23] resembles to MOMFIS, but with a different concept using pickoff arms. In 2007, the various MOS consortia in Europe merge together in the EAGLE project [9]. At that time, MOAO is not mature enough, as many technical issues still need to be evaluated in real operating conditions and that on-sky demonstrators are required before being able to actually launch design phases of MOAO-based instruments. The Observatoire de Paris, the University of Durham, the UK Astronomy

[a] eric.gendron@obspm.fr

Technology Centre (UKATC) and the Isaac Newton Group (ING) then decided to create the CANARY consortium, for developing an on-sky MOAO pathfinder for EAGLE [21]. From 2001, the Observatoire de Paris had pursued several studies in the field of open-loop control of DM [16] and tomography [25] using the multipurpose AO bench called SESAME. The University of Durham and ING had proposed to use the William Herschel Telescope (WHT) as an on-sky testbed [20] for testing the next-generation AO LGS technologies to mitigate risk of ELT LGS AO systems.

During the same period (2007-2010) others MOAO-related projects have been developed around the world. The *ViLLaGEs* team at Lick Observatory aims at demonstrating on-sky the functioning of high-actuator count MEMS devices, using open-loop wavefront sensing and control [11]. Successful on-sky open-loop results were obtained in April 2008, with Strehl ratios (SR) of 0.12 in I band on the 1 meter Nickel telescope at Lick Observatory. The 'go-to' error is of the order of 30 nm rms [11], much lower than the other terms of the wavefront error. The University of Victoria developed VOLT [2], an on-sky open loop on-axis AO system using an 8x8 voice-coil actuator DM from ALPAO. Their goal was to identify and analyze the sources of open loop error in order to mitigate the risk for future MOAO systems. First images were obtained in May 2008 and showed substantial improvement in image quality albeit a bad (2.5") seeing. The examination of the sources of error from the telemetry data shows a 'go-to' error as low as 10 nm rms. Tohoku University is starting in 2010 lab developments in MOAO [1], in particular large stroke MEMS DMs with large number of actuators, and tomographic algorithms. Recently, the University of Victoria in collaboration with the HIA and Subaru telescope have undertaken RAVEN [3], an MOAO pathfinder which not only goals in demonstrating the on-sky feasibility of MOAO, but also aims to deliver science results from two science pickoff arms that will patrol a 2 arcminute diameter field of regard. RAVEN will boost the sky coverage performance thanks to an on-axis sodium laser beacon. It should be delivered early 2014.

2 The CANARY project

The goal of CANARY consists in operating on-sky a single channel of a MOAO instrument with a control based on a tomographic combination of LGS and NGS measurements and a woofer-tweeter structure in order to reproduce the EAGLE configuration [22]. The woofer works in closed loop both on NGS and LGS beacons and simulates the closed-loop control of the M4 adaptive mirror of the E-ELT, while the tweeter is a higher order MEMS DM operating in open-loop thanks to the same measurements. The plan was to demonstrate the feasibility of MOAO before the starting of the EAGLE preliminary design phase in a fast-track project. It was divided into phases called CANARY-A, -B and -C, each of increasing complexity [21].

Phase CANARY-A consists in demonstrating the first step: open-loop and tomography on NGS. It uses the future woofer DM as the open-loop DM. In order to evolve to the next stage, the bench is composed by optical modules that can be added, swapped or moved around, with a logic that permits a smooth transformation towards complexity. Phase CANARY-B (in 2012) adds new modules to the -A bench: a new laser projection system integrated to the telescope and the 4 LGS WFS with a steering mirror for spot stabilization (see [18]). They also come with a bunch of software evolutions, both in the control software and in the tomographic analysis. An evolution to the CANARY strategy is also to include in phase -B some scientific goals, on a best effort basis. In Phase CANARY-C1 (in 2013), the WFS modules (both NGS and LGS) just move to a closed-loop position *after* the woofer. Tomography is then achieved in closed-loop. With CANARY-C2, the tweeter module is then added at the end to get the full picture.

2.1 Description of the bench during Phase A

The bench is installed on a flat optical table at the Nasmyth focus (GRILH) of the WHT. A field derotator using a K-mirror, delivers a stable field of view of 2.5 arcmn in diameter, corresponding to 33 mm at the f/10.84 focus of the telescope. The star that mimics the corrected science target lays at the center of this field, so that the central 10×10 arcsec beam goes straight to the corrective optics. At the periphery of this field in the focal plane, three WFS are placed on the off-axis guiding stars. They do not see any effect from the corrective optics, they work with no feedback from any optical element, just in open-loop. The corrective channel is made of a 2 symmetric off-axis parabolae relay of magnification 1:1, with the DM in the pupil plane (66.5mm diameter). It is a low order 8×8 piezostack array DM from CILAS, manufactured in 1990, previously used at ESO in the ADONIS instrument [6]. It is made in a very hard piezoelectric material and exhibits an hysteresis as low as 2% [16]. Creeping effect is substantial but has not shown to be a showstopper. The tip-tilt mirror is a copy of that used in the VLT instrument SPHERE [19]. Its position is servo-controlled by internal sensors so that it has virtually no go-to error.

The three off-axis NGS WFS are of Shack-Hartmann type, each with 7×7 sub-apertures. They use Andor iXon^{EM}860 EMCCD cameras read on-sky at a rate of 150 Hz. They have 24μm pixel size, featuring 128×128 active pixels, and we use 16x16 pixels of 0.26 arcsec in each sub-aperture for a total field of view of nearly 5 arcsec, i.e. large enough to accommodate for the open-loop requirements. The measured readout noise ranges between 0.3 and 0.7 electron/pixel thanks to the EM gain. However, this gain induces also fluctuations of the gain factor, that is equivalent to divide the quantum efficiency by a factor of 2. The three NGS WFSs can be positioned anywhere within the 2.5 arcmin field of view, with a minimum distance of 20 arcsec (4.4 mm) between two of them. An anti-collision system, with a software and a hardware level of security, avoids damaging the heads of the pick-off prisms.

Real-time control for CANARY is provided by the Durham AO Real-time Controller (DARC) [5]. This is a high performance, flexible CPU based system, which is open source. For CANARY, using moderate hardware, a latency smaller than 700 μs is achieved, defined between readout of last WFS pixel and setting of last DM actuator. The flexibility afforded by DARC allows many different algorithms to be selected on-the-fly, or even developed without stopping the real-time system. Algorithms tested on-sky at phase A include command laws for open and closed loop operation, figure sensor operation, GPU powered wavefront reconstruction, and a variety of centroïding algorithms (namely brightest pixel selection providing an adaptive window on a per-subaperture basis [4], correlation, weighted centre of gravity centroïding, all of them possibly used in conjunction with an adaptive windowing (spot tracking) allowing sub-apertures to be sub-windowed to reduce the effect of readout noise). At Phase B, additional algorithms will be available for test, such as slope linearisation, matched filter centroïding, LQG control, and conjugate gradient reconstruction. A powerful telemetry system allows pixel and slope data to be recorded at full rate, while simultaneously viewing real-time displays of the data. DARC proved to be highly stable and reliable during operation, essential for any on-sky experiment.

CANARY is equipped with various diagnosis tools, placed downstream the DM. A dichroic plate separates the visible light (below 0.9 μm), from the IR one (1 μm – 2.5 μm). On the visible channel we have installed a *Truth Sensor* (TS), which is an on-axis copy of the off-axis NGS WFS. The TS allows us to close the loop on the DM, as in the very classical scheme, for performance comparison with the open loop approach. It is therefore interfaced with the real-time computer just as the others WFS and its data are processed, acquired and stored synchronously with the off-axis WFS data. The other diagnosis tool, on the IR channel, is a near-IR camera Xeva-1.7-320 from Xenics, featuring 320×256 pixels with a measured read-out noise of 200 e^- rms per pixel. The camera has a single filter: H band. However, the quantum efficiency (QE) of the camera drops rapidly after 1.6 μm, while the atmospheric transmission has a strong cutoff at short wavelengths at 1.45μm : for this reason the central wavelength is $\lambda_c = 1.53\mu m$, with a passband of $\Delta\lambda = 0.16\mu m$.

The bench is equipped with a telescope simulator, able to recreate the 2.5 arcmn field of view of the WHT. Four motorized sources can be placed anywhere in this field. The optical simulation of the atmospheric turbulence is operated thanks to 2 rotating phase screens made by SILIOS company (France) of 100 mm in diameter. The disks can be conjugated to any altitude between -1 to 10 km. The total seeing generated is equivalent to approximately 1 arcsec on a 4.2m telescope. This telescope simulator is permanently sitting on the CANARY bench and allows to test the system at any time, even when installed at the Nasmyth focus. The telescope simulator provides critical alignment and calibration functionality, as well as allowing complete characterization of the system when under testing in the laboratory. In the telescope focal plane, a translation stage can insert a variety or sources, pinhole, retroreflector. The calibration sources allow us to close the loop with the TS, check and optimize the image quality in the IR path, and derive best reference positions for the spots on the TS. With the pinhole, they are also used for optical alignment. At the transported focus after the DM, we also have a source lightening back into the system through the DM and feeding the light into one of the open-loop WFS thanks to the retroreflector system. This allows us to measure interaction matrices (poke matrix) between the DM and the open-loop WFS that would normally not *see* the DM.

It is usually accepted that the interaction matrices can be measured by poking each actuator individually. We determined that this way of doing is sensitive to local bench turbulence (low, but still existing). We used instead a Fourier approach. We activate all actuators simultaneously with a sine wave at a given temporal frequency for each, and proceed to a frequency analysis of the measured temporal signal : a specific frequency will show only the contribution of the concerned actuator. This way of doing explores all possible voltages within a given range and a wide variety of possible voltage combinations between adjacent actuators. Although this has no impact when the DM is perfectly linear, it can make the difference with real hardware by fitting the average behavior of the DM across the concerned range.

2.2 Tomography algorithm : the Learn & Apply

CANARY has to demonstrate the effectiveness of tomography on-sky, and the key point here is the tomographic reconstructor. Looking at other systems, the ESO MCAO demonstrator 'MAD' produces experimental on-sky interaction matrices [17] with the altitude-conjugated DMs, and proceed to a global least-square inversion of it. CANARY cannot copy this method since we have no altitude DM (our reconstructor would just reduce to a GLAO instead). The alternative consists in modeling these matrices instead of measuring them. However, the model must be accurate enough, because while a model error vanishes in closed-loop thanks to the successive iterations of the loop, in open-loop any error directly translates into pure wavefront error. We have developped the method called *Learn & Apply* [25,26] to work around this issue. A sequence of turbulence is acquired by all the WFS simultaneously and the tomographic reconstructor is searched for from these data. We search the matrix that retrieves best (in a least-square sense) the TS measurements from the off-axis ones. It is straightforward to demonstrate that this reconstructor converges towards the minimum mean square error (MMSE) reconstructor for a sufficiently long sequence of turbulence. The method involves the computation of covariance matrices and their fit by a model that includes the system characteristics, the atmospheric profile (with some priors about the phase structure function). The system characteristics include the geometry of the WFS but also some parameters to account for their possible misregistrations. This way of doing ensures that the underlying model will fit best to the actual tomographic configuration.

2.3 Asterisms

The asterisms selected for CANARY are made of 3 off-axis stars surrounding a 4th central one. They have been selected by parsing the Tycho 2 catalogue. A list has been produced, and sorted by a relevance criteria that ensures the stars are arranged in a triangle as equilateral as possible, with the fourth one as close as possible to the center of gravity. A final list of 54 asterisms visible at La Palma site, was selected (see Fig. 1). An analysis showed that most of these asterisms belong to young open clusters and that these stars are rather blue ones.

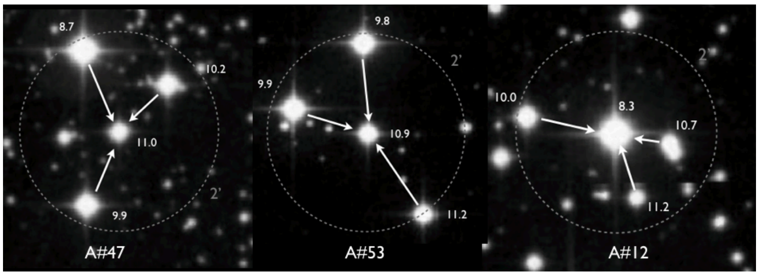

Fig. 1. The 3 asterisms observed with CANARY in September 2010. The circle is 1' radius. The star V magnitudes are in the range 9-11.

3 Results and performance

CANARY obtained the first MOAO-compensated on-sky images in September 2010 (see [13]). We alternated the observations between the SCAO (single-conjugate AO, stands for AO in closed loop on the TS), open-loop GLAO and MOAO modes as the turbulence profile evolved and as we changed asterisms. Telemetry data sequences (i.e. synchronous slopes from all WFS) were acquired together with the IR images. Only 3 asterisms were observed during each night (Fig. 1). The first images we saw on the display convinced ourselves that the MOAO performed nearly as well as SCAO. Fig. 2 is an example of the uncorrected PSF at $1.53 \mu m$, corrected by open-loop GLAO, SCAO and MOAO. The SR are 0.04 (seeing), 0.09 (GLAO), 0.27 (SCAO) and 0.25 (MOAO). The MOAO image, compensated thanks to 3 off-axis stars distant from nearly 1 arcmin, is nearly at the same level of correction than the SCAO image.

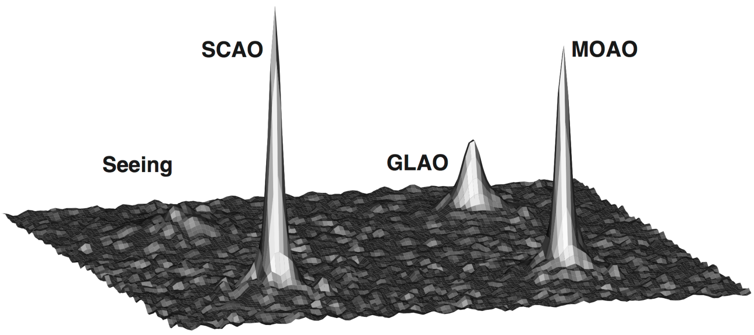

Fig. 2. Typical set of IR images ($1.53 \mu m$) compensated by open-loop GLAO, SCAO, MOAO and uncorrected, represented in a 3D. The SR are 0.04 (seeing), 0.09 (GLAO), 0.27 (SCAO) and 0.25 (MOAO).

With the open-loop engaged, the residual wave-front error was assessed by the TS. A detailed analysis of the data has been performed, and is fully described in [27]. The total residual wavefront error has been split into the major error terms, and compared to a numerical simulation. Of course the parameters of this latter have been adjusted to the on-sky conditions. The atmospheric parameters have all been aligned on what was measured (r_0, C_n^2, v, ...). The value of r_0 and the $C_n^2(h)$ profile were determined from open-loop off-axis measurements. The simulated average wind speed was tuned (to 6 m/s) in order to cope with the measured bandwidth error. The simulated flux level was adjusted to reproduce the same noise variance as that measured on-sky on the different WFS. Table 1 shows the error terms for several MOAO cases, showing the couple of values on-sky / simulated when relevant, and only a single number when the simulated value has been adjusted to be equal to the on-sky one. The important point is to notice that tomography terms match remarkably well. This makes us confident in establishing the error budget for future ELT instruments. We were suspecting other possible sources of errors here, in particular in the open-loop measurements of the WFS such as non-linearities or errors correlated with the turbulence. It seems that none error has shown up, since the numbers agree with a very good accuracy. It must be said that we have been using the brightest pixel selection centroïding algorithm which provides an instantaneously adaptive threshold together with an adaptive windowing (spot tracking) which allows the spot to always be centered in the centroïding window, thus reducing biases.

The other term specific to MOAO that an on-sky demonstrator had to look closely, is the go-to error : it is demonstrated to be very small (in particular when compared to tomography or fitting error), only 12 to 15% of the total rms compensated value. However from previous lab measurements a value of 3 to 6% was expected. The reason is that the go-to error is evaluated as the difference between the total error measured by the TS, and the quadratic sum of all the other error terms : it contains everything which is unidentified : go-to error, and possibly more (drifts of bench aberrations, local unseen turbulence, etc...).

Finally, only one term has been identified, that was not included in the initial simulations of CANARY: the quasi-static field aberrations. These aberrations is a static term which is assessed by the TS when the open MOAO loop is engaged. It comes from the fact that the telescope and the optical path (derotator, optical path in front of each WFS) have some field-dependent aberrations. Those aberrations need to be identified and treated separately from the tomographic loop. The way to measure them is to average the turbulence over a long period. Unfortunately, turbulence is very difficult to average with time and the aberrations may evolve during the observing time, so that the determination of these quasi static terms come with an error, of the order of 70 to 100 nm rms. On the ELT, those static field aberrations will also not be static, but likely to evolve slightly because of the residual errors in the active optics of the telescope. This will bring a problem in all tomographic techniques and thus will have to be solved for the E-ELT instruments.

Table 1. Detail of the error terms computed from the WFS data. The tomography term is compared to numerical simulation, with the same $C_n^2(h)$ profile as that found in the data.

r_0 (cm)	16.3	10.0	13.0
error term	nm rms	nm rms	nm rms
tomography	156 / 161	219 / 220	188 / 201
open loop	55 / 22	140 / 33	116 / 26
noise	48	56	97
aliasing	96	135	86
bandwidth	115	142	128
fitting	138	206	165
NCPA	115 / 0	115 / 0	115 / 0
field static aberr.	77 / 0	106 / 0	72 / 0
total	297	419	357
expected SR ($e^{-\sigma^2}$)	22.6 %	5.2 %	11.7 %
measured SR on IR image	20.1 %	10.3 %	16.4 %

We also tried to compare the wavefront error results obtained from the TS measurements with the IR image quality (see Table 1). A number of errors on the SR have to be underlined. Firstly due to the background level to be subtracted, we estimate the uncertainty on the SR to be of the order of ±0.02, which means ±70 nm rms. Secondly the total exposure time of the IR images was 30 seconds, obtained by averaging 100 individual images of 0.3 s each. The instantaneous frame-to-frame rms fluctuation of SR is measured to be about 1/3rd of its value. For an average SR of 21%, this leads to an instantaneous fluctuation of ±7% that would average down to 0.7% after 100 frames. Although small, these 0.7% correspond to an uncertainty of 45 nm rms, comparable to the smallest error terms we want to determine. Thirdly, the absolute value of SR depends on the knowledge of the average effective wavelength and the pixel size, that has revealed -after deeper analysis- not to be known better than ±2% contrarily to what initially thought. This may bias the results at a level of ≈ 50 nm rms. Much worse, the IR images and the WFS data were not taken over the very same period of time, they were taken one after the other. Some statistics have shown that the rms fluctuation of r_0 (computed over 8 seconds) over 10 seconds of time is ±2 cm : these non-stationary fluctuations prevent an accurate comparison, they correspond to fluctuations of the order of 150 to 200 nm rms on the total wavefront error.

The conclusion of this error budget is that no major source of error could be identified. In particular the go-to error has been demonstrated to be kept at a negligible level, and the tomography error behaves just as expected by the simulations. However, it cannot be excluded that small errors do exist, but they are sufficiently small to disappear behind the error bars of the determination of other errors. The determination of small error terms, such as the go-to error for example, requires a very high accuracy on the determination of large error terms, when they all sum up quadratically. Moreover, the accurate comparison of the *a posteriori* derived error budget with the IR images requires an extreme care in the image processing and calibration of parameters, together with a precise synchronization of the acquisition of wavefront data and images.

4 Next phases

The next phase of CANARY will consist in adding the 4 Rayleigh laser beacons, as explained in [18]. The actual challenge for the CANARY team is to increase the complexity of the experiment with 4 additional WFS and a laser launch system, while increasing the level of reliability and accuracy of the calibrations, and converting into automatic procedures what has been learnt from phase-A (for instance on line estimation of the error budget). We aim to increase the efficiency, alternating rapidly observations in different modes (SCAO, MOAO, GLAO by scripting), so that drifts in observing conditions can be cancelled out. For tomography, there is not more unknown related to a spherical wave crossing turbulent layers than there is in the plane wave case. An effort has been done to adapt the *Learn & Apply* method to this case, and we are confident that computation of the terms of phase correlations should behave as expected. The real unknowns are more about the ability of performing an accurate, unbiased open-loop wave-front sensing on elongated beacons in a real experimental environment. Of course, we envision playing with the range gate of the Rayleigh beacons to simulate the handicap of elongated sources.

However, the Sodium laser beacons of the E-ELT will inevitably come with all variability-related issues of the Sodium layer, plus the extreme elongation due to the ELT diameter. As an on-sky demonstrator, CANARY should directly tackle these problems and is seeking for a collaboration with ESO who developed a transportable Sodium laser system [7]. The laser could be launched from 30 to 40 meters away from the WHT in order to get the maximum spot extension (typ. 15-20 arcsec). This would allow us to study the fast fluctuations of the Sodium layer structure with a full aperture analysis and to demonstrate in-situ that we are able to cope with the random defocus fluctuations and that centroïding algorithms adapted to extended beacons (correlation, matched filter, etc) are effective at minimizing biases and non linearity effects to obtain suitable wave-front measurements. We envision to replace the green dichroic for the Rayleigh beam by a 589 nm dichroic and install a wide-field sodium WFS in replacement of the Rayleigh WFSs by 2014. This highly desirable Sodium step has to be confirmed, depending on the availability of a Sodium laser launch system at that time.

As a technical testbed, CANARY is well suited for implementing and testing new exploratory concepts, parallel to MOAO developments. The present temporal controller which we use in conjunction with the *Learn & Apply* is a sliding average. In 2011, the L2TI and ONERA join the CANARY team in order to upgrade this part, and will implement LQG optimal command laws [24]. They will also take advantage of the form of this controller to implement and test vibration tracking algorithms. It is important to use and test these algorithms in a real uncontrolled environment, since it is already known they will play a major role in the future ELT. Some other WFS will be tested on CANARY too, in particular pyramid and YAW [14]. Those WFS can both provide a very high number of measurements in the pupil plane, particularly suitable for an ELT. As they have not extensively been used on sky on laser beacons, a technical demonstrator such as CANARY offers a great opportunity to be able to test those under real observing conditions.

5 Beyond CANARY capabilities ?

MOAO needs to pick targets (guide stars, scientific sources) across the patrol field of view, and relies on a *target acquisition system* (or TAS, following the EAGLE designation). The TAS is constrained both by strong positioning specifications of the field (stability, reproducibility, etc), and by severe pupil alignment specs. The actuator frame of the open-loop MOAO DMs, the actuator frame of M4 of the E-ELT and the sampling grid of the WFS (LGS and NGS) need all to be registered through the TAS with respect to each other to an accuracy of a fraction of a sub-aperture, i.e. to an accuracy of the order of $1/500^{th}$ of the pupil diameter (25" in a f/17 beam, or 5 mm on the surface of M4). The level of accuracy required suggests that the pupil registration of these independent, open-loop sub-systems may need to be actively controlled. CANARY does not share with EAGLE the problem of pupil registration, first because in CANARY the pupil centering requirements are broader by a factor of 10 (i.e. by the ratio between the telescope sizes) compared to the E-ELT, secondly because with only 1 MOAO channel instead of 20 the optical alignment can be perfected by hand until being exactly in spec, and thirdly because the CANARY TAS has been simplified (on purpose) up to a point where no pupil shift is possible, just because there is no moving part : the WFS just translate as a whole with no modification of the optics system.

Unfortunately, in the optical design of the E-ELT, the adaptive mirror M4 is conjugated to an altitude of 400 m, it is noticeably tilted in the telescope optical design, and rotates in the pupil plane with respect to the asterism. This results in a slow but permanent evolution of the coefficients of the tomographic reconstruction. While the rotation angle of M4 is perfectly predictable, the center of rotation is more questionable since it depends on the rotation axis of the telescope elevation axis, and the field de-rotation of the instrument itself. This makes M4 anything but a reference. We proposed in EAGLE [22] a calibration scheme for the accurate registration of pupils, using lights sources in the telescope. Each MOAO channel (science or WFS channel) would be equipped with a high resolution pupil viewing camera, conjugated to the open-loop DM in the science channels, and to the microlens array in the WFS ones. We proposed to place point-like light sources in the telescope at M4, around the reflective surface (common LEDs would be ideally suited here). As the point-sources at M4 shine over the whole field of view, they permit to measure in a snapshot the pupil shifts in all the MOAO channels simultaneously. Adding a calibration source at the E-ELT intermediate focus and some wave-front sensing capabilities to this pupil viewing camera (e.g. curvature sensing by acquiring out-of-focus pupil images or else) would permit to calibrate *in-situ* the influence functions of the MOAO DMs, and to calibrate how they register with everything else including M4 actuator frame. These functionalities are managed by the *calibration and alignment sensor (CAS)* in EAGLE. It is not surprising that a global calibration of a MOAO instrument involves a participation of the telescope. Alternative methods consist in retrieving the actuator positions of M4 from the WFS residuals during on-sky close-loop operation. However, the performance of these methods still need to be demonstrated at low flux levels, they require observing time and heavy computational processes to run in parallel of observations, and that need to be optimized. And they don't solve the registration problem of open-loop DMs, that still need to rely on a CAS –or equivalent– to 'see' the actuators of M4. These experimental studies will open to CANARY a wide field of investigations during phase-C.

With its 5-mirror optics, the E-ELT will convey a beam of several meters in diameter just across the turbulence of the ground layer: this will result in a turbulence profile distributed over unusual altitudes and that could be handled with difficulty by the algorithms if a special model is not taken into account. In addition, the amount of turbulence may not be stationary over the pupil.

6 Conclusion

CANARY is a single channel MOAO demonstrator setup at the WHT. It obtained the first on-sky MOAO-compensated images in September 2010. The progression of CANARY towards the simulation of EAGLE is done in 3 steps : the first one, successfully passed, uses NGS only. The second one, in 2012, will use Rayleigh LGS. The third one, in 2013 and beyond, will use a woofer-tweeter configuration and will mimic the full MOAO functioning in EAGLE.

With CANARY not only some images were produced, but the identification of the terms of the error budget could be checked and successfully compared to simulations and expectations. The conclusion is encouraging : the open-loop term, although larger than expected, is negligible compared to the other terms, and the tomography term behaves just as expected in the simulations. CANARY shown that some terms were not included in the initial simulated error budget : the static field aberrations. These aberrations are not linked together by any tomographic relation, so that they must be treated separately in the loop. CANARY has proposed a first method to estimate them by averaging turbulence and has shown that the method works, but needs to be improved.

CANARY makes use of a supplementary WFS called 'truth sensor' and that performs several functions. One is of course to assess the wavefront flatness after compensation. But also, the TS plays a fundamental role in calibrating the MOAO channels. We would not recommend to build a MOAO instrument without this functionality. In particular it will play an important role in calibrating the field static/drifting aberrations of the telescope.

Our tomographic reconstruction is based on the *Learn & Apply* method. However, extrapolating the current method to a 40 m telescope leads to a computation load currently out of reach of any 'reasonable' computer. A parallel effort needs to be undertaken to optimize the speed and reduce the computation load. Some points should be facilitated however: with the large number of subapertures in the ELT, the covariance matrices for the estimation of the $C_n^2(h)$ profile should converge much more rapidly than on a 4.2m telescope.

The motion of the telescope adaptive mirror M4 will certainly impact a lot the algorithm of an MOAO instrument, and the way the pupil registration will be calibrated or controlled in the final ELT instrument is not yet known. In any case, CANARY has an important role to play because those problems can be studied anyway, simulating the effects on the optical bench. The bench is installed at the Nasmyth on a flat optical table which makes an access or a modification always easier than for any other compact instrument. Whatever the final implementation of the E-ELT MOAO instrument will be, CANARY has already convinced the community that MOAO is the right way to go.

This work is supported by Agence Nationale de la Recherche (ANR) program 06-BLAN-0191, CNRS / INSU, Observatoire de Paris, and Université Paris Diderot – Paris 7 in France, Science and Technology Facilities Council, University of Durham in UK and European Commission Framework Programme 7 (E-ELT Preparation Infrastructure 2007-1 Grant 211257 and the program OPTICON JRA1).

References

1. M. Akiyama, S. Oya, K. Hane, et al. "MOAO activities in Tohoku University", volume 7736 of *Proc. SPIE*, July 2010.
2. D. R. Andersen, M. Fischer, R. Conan, M. Fletcher, and J.-P. Véran. VOLT: the Victoria Open Loop Testbed. volume 7015 of *Proc. SPIE*, July 2008.
3. D. Andersen, C. Blain, C. Bradley, et al. "RAVEN, a Multi-Object Adaptive Optics technology and science demonstrator", in this conference, 2012.
4. A. G. Basden, R. M. Myers, and E. Gendron. Wavefront sensing with a brightest pixel selection algorithm. *M.N.R.A.S* , 419:1628–1636, January 2012.
5. A. Basden, D. Geng, R. Myers, and E. Younger. "Durham adaptive optics real-time controller". *Appl. Opt.*, 49 (32), pp 6354–6363, Nov 2010.
6. J.-L. Beuzit, N. Hubin, E. Gendron, et al. "ADONIS: a user-friendly adaptive optics system for the ESO 3.6-m telescope". volume 2201 of *Proc. SPIE*, pp. 955–961, May 1994.
7. D. Bonaccini, A. Friedenauer, V. Protopopov, et al. "PM fiber lasers at 589nm: a 20W transportable laser system for LGS return flux studies". volume 7736 of *Proc. SPIE*, 77361U, 2010.
8. J.-G. Cuby, J.-P. Kneib, F. Hammer, et al. "The first galaxies: instrument requirements and concept study for OWL". volume 232 of *IAU Symposium*, pages 176–180, 2006.
9. J.-G. Cuby, S. Morris, T. Fusco, et al. "EAGLE: a MOAO fed multi-IFU NIR workhorse for E-ELT". volume 7735 of *Proc. SPIE*, July 2010.
10. R. G. Dekany, M. C. Britton, D. T. Gavel, et al. "Adaptive optics requirements definition for TMT". volume 5490 of *Proc. SPIE*, pp. 879–890, October 2004.
11. D. Gavel, M. Ammons, B. Bauman, et al. "Visible light laser guidestar experimental system (Villages): on-sky tests of new technologies for visible wavelength all-sky coverage adaptive optics systems". volume 7015 of *Proc. SPIE*, pp. 70150G–70150G–11, July 2008.
12. D. Gavel, B. Bauman, R. Dekany, M. Britton, and D. Andersen. "Adaptive optics designs for an infrared multi-object spectrograph on TMT". volume 6272 of *Proc. SPIE*, p. 62720R, July 2006.
13. E. Gendron, F. Vidal, M. Brangier, et al. "MOAO first on-sky demonstration with CANARY", Astron. & Astrophys. 529, L2, 2011
14. E. Gendron, M. Brangier, G. Chenegros et al. "A new sensor for laser tomography on ELTs", In *1st AO4ELT conference - Adaptive Optics for Extremely Large Telescopes*, 2010.
15. F. Hammer, F. Sayède, E. Gendron, et al. "The FALCON Concept: Multi-Object Spectroscopy Combined with MCAO in Near-IR". In J. Bergeron & G. Monnet, editor, *Scientific Drivers for ESO Future VLT/VLTI Instrumentation*, page 139, 2002.
16. A. Kellerer, F. Vidal, E. Gendron, et al. "Deformable mirrors for open-loop adaptive optics". volume 8447 of *Proc. SPIE*, 1-6 July 2012.
17. E. Marchetti, R. Brast, B. Delabre, et al. "MAD on sky results in star oriented mode". volume 7015 of *Proc. SPIE*, pages 70150F–70150F–12, July 2008.
18. T. Morris, Z. Hubert, F. Chemla et al. "CANARY Phase B: the LGS upgrade to the CANARY tomographic MOAO pathfinder", in this conference, 2012.
19. D. Mouillet, J.-L. Beuzit, M. Feldt, et al. "SPHERE: A 'Planet Finder' Instrument for the VLT". In A. Moorwood, editor, *Science with the VLT in the ELT Era*, page 337, 2009.
20. R. M. Myers, D. Bonaccini Calia, N. Devaney, et al. "The European LGS test facility". volume 6691 of *Proc. SPIE*, pages 66910Q–66910Q–8, September 2007.
21. R. Myers, Z. Hubert, T. Morris, et al., "CANARY: the on-sky NGS/LGS MOAO demonstrator for EAGLE", volume 7015 of *Proc. SPIE*, 2008
22. Rousset, G., Fusco, T., Assemat, F. et al., "EAGLE MOAO system conceptual design and related technologies" volume 7736 of *Proc. SPIE*, 77360S-1 (2010)
23. A. P. Russell, G. Monnet, A. Quirrenbach, et al. "Instruments for a European Extremely Large Telescope: the challenges of designing instruments for 30- to 100-m telescopes". volume 5492 of *Proc. SPIE*, pages 1796–1809, September 2004.
24. G. Sivo, C. Kulcsar, H.-F. Raynaud, et al. "MOAO LQG control for CANARY: theory and first laboratory results", in this conference, 2012.
25. F. Vidal, E. Gendron, M. Brangier, et al. "Tomography reconstruction using the Learn and Apply algorithm". In *1st - Adaptive Optics for Extremely Large Telescopes Conf.*, p. 07001–1, 2010.
26. F. Vidal, E. Gendron, and G. Rousset. "Tomography approach for multi-object adaptive optics". *JOSA A*, 27, pp A253–A264, November 2010.
27. F. Vidal, et al., "Detailed analysis of the first MOAO results obtained by CANARY at the WHT", in this conference, 2012.
28. M. Wells, S. Vives, E. Prieto, et al. "Optical solutions for the multi-IFU instrument EAGLE for the European ELT". volume 7014 of *Proc. SPIE*, pages 70141L–70141L–12, August 2008.