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First star images corrected by multi-object adaptive optics

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The CANARY pathfinder at the William Herschel Telescope demonstrated on-sky an innovative technique that allows turbulence compensation of multiple very faint targets in a wide field of view.

To understand the evolution of the early Universe, it is necessary to observe a very large number of galaxies at high redshift and obtain information about their physics and evolution. Moreover, first-light objects must be detected and characterized. For such observations, the first key tool will be the optical European Extremely Large Telescope (E-ELT). This instrument, currently under design, will have a primary mirror diameter on the order of 40m. Because it is ground-based, this telescope will suffer from image quality degradation caused by atmospheric turbulence. To overcome the problem, adaptive optics (AO) technology is required for real-time compensation of spatial and temporal fluctuations in the wavefront. AO uses deformable mirrors (DMs) to cancel these aberrations. It has been under development for the last 20 years and is used on all 10m-class telescopes.

To date, AO has been applied only over fairly limited fields of view. New concepts are needed to fulfill the requirements for wide-field observation, such as ground-layer[1] or multi-conjugate AO.[2] The second key tool for performing the required observations is a multi-object integral field unit (IFU) near-IR spectrograph installed on the E-ELT. A conceptual design for such an instrument was recently studied[3] by a consortium of laboratories in France and the UK. This instrument, called EAGLE, will be able to analyze 20 spatially resolved galaxies at a time in a very large field of view (10′), each one of which will be separately corrected for atmospheric distortions. It relies on an innovative distributed AO concept[4] called multi-object AO (MOAO). Therefore, the instrument development plan targets a pathfinder, CANARY,[5] with the goal of demonstrating the on-sky feasibility of MOAO.

MOAO aims to simultaneously compensate turbulence for many very faint small astronomical objects (1–2″ each) spread over a wide field (5–10′) in a multiplex configuration. Instead of whole-field AO correction, as in multi-conjugate AO, in MOAO one dedicated DM per object is implemented in the optical train feeding an IFU. Moreover, the objects will be too faint to allow measurement of atmospheric distortions. Consequently, a few sufficiently bright natural guide stars (NGSs) must be found within the field for this purpose. Laser guide stars (LGSs) may also be generated when the number of suitable NGSs in the field is inadequate.[4] Wavefront measurements made across the field are simultaneously processed to reconstruct the 3D turbulence volume using a tomographic approach.[6] The correction is then computed by projecting the 3D turbulence in the direction of each object.[6] Thus, the main concern in MOAO is conducting open-loop compensation for each object, i.e., operating without feedback to the wavefront sensors (WFSs) using the NGSs and LGSs.

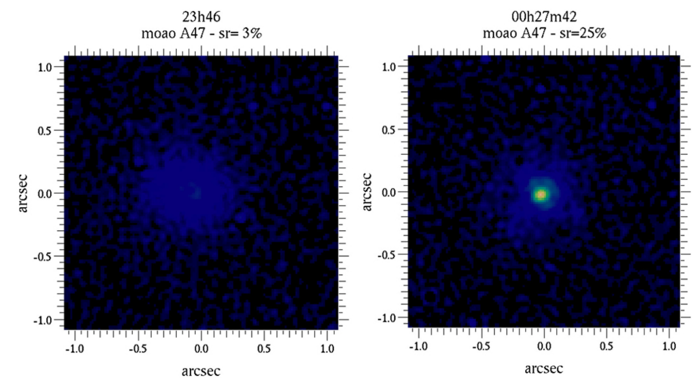

***Figure 1.** Left: Uncompensated image, Strehl ratio (SR) $\simeq$ 3%. Right: Multi-object adaptive optics (MOAO) compensated image, SR $\simeq$ 25%. H band, $r_0 \simeq$ 15cm.*

CANARY's goal is to demonstrate on-sky the capability of driving one DM in an open loop by tomography using a few off-axis guide stars (three NGSs in the first phase and four Rayleigh LGSs and a few NGSs in the second phase). It is designed to be set up at the Nasmyth focus of the 4.2m William Herschel Telescope (WHT) at Roque de los Muchachos, Canary Islands, Spain.[5] The first results[7] were obtained using three

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off-axis NGSs for the measurements and one open-loop DM for compensation of an additional on-axis star serving as the science object. CANARY must therefore use star asterisms formed by four NGSs. We selected asterisms with a typical distance between the central on-axis star and the three off-axis ones ranging from 15 to 65″, while using only stars brighter than $m_v = 12$ and setting the WFS frame rate to 150Hz. CANARY is equipped with three Shack-Hartmann WFSs, which can acquire the off-axis NGSs, and with one similar WFS set on the central on-axis star. The central star beam feeds both this WFS and an H-band IR camera via relay optics, including a piezostack 52-actuator DM (conjugate to the pupil) and a high-speed tip-tilt mirror.

Here, we briefly present the results obtained on 27 September 2010 and published elsewhere.[7] MOAO correction was achieved the first time it was attempted on-sky. Furthermore, it operated at the expected performance level. Figure 1 shows the image of a test star without (left) and with (right) the correction system. The performance achieved with MOAO, including off-axis wavefront measurements, tomography, and open-loop control of the DM, is very similar to that obtained with the conventional adaptive optics mode, i.e., on-axis measurements and closed-loop control. In the best performance achieved, the Strehl ratio (*SR*) was around 25% in the H band, whereas it was only a few percent without correction at a Fried parameter $r_0(0.5\mu\text{m})$ of around 15cm.

Ground-layer AO correction was also tested, and the resulting performance was significantly worse under the same conditions ($SR \simeq 10\%$). The first MOAO wavefront error budget was analyzed using both IR images and the on-axis WFS measurements. The MOAO loop error, including temporal, noise, and tomographic errors, was around 230nm for $r_0(0.5\mu\text{m})$ around 12cm. The fitting error, which is associated with the number of actuators, was around 170nm, and the uncorrected bench static aberrations were around 150nm. Thus, $SR \simeq 22\%$ in the H band.

In summary, the challenging technique of MOAO has been successfully demonstrated on-sky for the first time by the CANARY pathfinder installed at the WHT in the Canary Islands. A preliminary analysis of the first on-sky results in September 2010 shows that MOAO performs nearly as well as conventional on-axis closed-loop AO under the same conditions.[7] An in-depth analysis of the recorded data will be published in a forthcoming paper. The next step in the CANARY program will be to perform an on-sky test of MOAO using four Rayleigh LGSs in addition to NGSs.

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