

Demonstration of a monostatic sodium laser guide star adaptive optics system

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ABSTRACT

CaNaPy is a sodium laser guide star (LGS) adaptive optics (AO) facility installed in the ESA Optical Ground Station 1-m telescope at the Observatorio del Teide, Tenerife. CaNaPy aims to demonstrate advanced LGS AO technologies such as high-power guide star lasers, uplink pre-compensation, LGS AO with pyramid wavefront sensor, tilt retrieval from LGS, and LGS AO in daytime. CaNaPy features a unique monostatic design, in which the transmitted high-power laser beam shares the same full telescope aperture for receiving the signal from the LGS. This challenging design is required for uplink pre-compensation and tilt retrieval, where the atmospheric turbulence volume sensed by the wavefront sensor must be similar to -or ideally match- that experienced by the propagating laser beam. CaNaPy also serves as a backbone for the project ALASCA, providing LGS adaptive optics for improved ground-to-satellite optical feeder links. In recent campaigns at the ESA OGS, we successfully demonstrated monostatic propagation and detection of the LGS at a maximum laser power of 55 W using the full 1-m telescope aperture. The LGS spot was imaged on a focal plane camera with narrow field of view. Suppression of high-power laser and Rayleigh backscattering was efficiently achieved with precise synchronisation of a shutter mechanism. A photometric evaluation of the LGS signal and scattering was performed using a photomultiplier tube in photon-counting mode, which also allows characterisation of the sodium layer density profile with high resolution. With the LGS on-axis, a natural star was tracked and employed to close the AO loop with a Shack-Hartmann wavefront sensor, resulting in, to best of our knowledge, the first demonstration of sodium laser guide star pre-compensation. The effect of uplink pre-compensation could be assessed with the LGS image on the focal plane camera, effectively reducing the LGS spot size. These are key milestones towards advanced LGS AO assisted ground-to-satellite optical feeder links demonstrators.

Keywords: CaNaPy, laser guide star, adaptive optics, monostatic, uplink precompensation

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1. INTRODUCTION

Sodium laser guide stars are artificial beacons created in the sodium layer between 85 km and 100 km altitude, using a high-power laser resonant to the D2 transition of sodium atoms at the vacuum wavelength of 589.1591 nm. With an adaptive optics system, a single or multiple LGSs can be used as reference sources to measure and compensate, in real time, the wavefront aberrations introduced by the atmospheric turbulence during astronomical observation from the ground, resulting in increased spatial resolution images approaching the diffraction of the optical system. The great advantage of LGS is that they can be generated in any boresight pointing direction, significantly relaxing the requirements (brightness and availability) of a natural guide star, and effectively expanding the sky coverage of AO-assisted observations. The operational conditions in remote places, such as the European Southern Observatory's (ESO) Paranal site in the Atacama Desert, demand the use of a reliable LGS system, which was the driver for the development of Raman Fiber Amplifier technology at ESO¹ (European Patent No 2081264B1), further matured into a high TRL laser system by industry. The outcome of this joint technological venture was a commercially available LGS source,² with several of them in regular operation at Paranal Observatory and elsewhere for over 10 years.³

Despite the success in regular LGS AO operations, the method presents some limitations. In particular, the sensitivity of a Shack-Hartmann wavefront sensor to the measured wavefront slopes decreases as the angular size of the laser beacon increases. Moreover, atmospheric turbulence during the uplink propagation imposes a trade-off on the optimal laser beam (and projector) diameter: while a larger beam reduces diffraction-induced divergence, speckle formation in the sodium layer becomes significant as the beam size exceeds the spatial coherence length (Fried parameter) under the prevailing turbulence conditions. For example, under good seeing conditions, an optimal beam diameter of about 0.3 m $1/e^2$ results in observed LGS spot in the range of 0.8 to 1.5 arcsec FWHM.⁴ Projecting the beam with a larger aperture does not, by itself, provide a benefit in term of reducing the spot size and improving AO sensitivity, unless the uplink beam is pre-compensated for atmospheric turbulence.

Another important limitation of LGS AO is the tilt indetermination problem, which arises from the double pass geometry (uplink + downlink) which cancels out the effect of tilt in the wavefront propagation.⁵ Therefore, LGS wavefront sensors are, to first order, unable to measure and compensate for atmospheric tilt. For this reason, LGS AO systems generally incorporate an additional, slower tip/tilt and focus wavefront sensor that

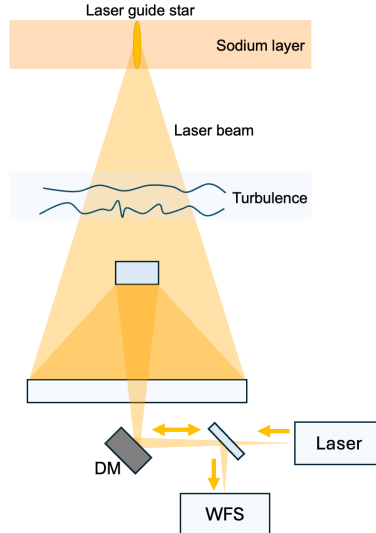


Figure 1. Scheme of the monostatic system to create a sodium laser guide star and detect the LGS return flux through the same optical path in the wavefront sensor (WFS). The small arrows indicate the direction of propagation. A deformable mirror (DM) is placed in the common path (uplink+downlink) to pre-compensate the laser beam. In CaNaPy, the full 1-m aperture is used to project the laser and to collect the photons from the LGS, the natural star and the satellite beacon for ALASCA.

uses a natural guide star in or near the science field to provide the required low-order wavefront correction. One approach proposed to measure tilt with an LGS is the propagation delay method.⁶ In this method a small differential tilt signal in the LGS accumulated during the finite propagation time between laser emission and photon return arrival (<1 ms), is measured and integrated to recover (and compensate for) the atmospheric tilt. In both cases - uplink pre-compensation and propagation-delay measurement - the same volume of the atmosphere must be sampled by the uplink and downlink path, highlighting the need of a monostatic optical system.

Existing sodium LGS systems in operation employ a bistatic architecture, with the laser launched either from a projector located laterally with respect to the main aperture (side launch) or from a projector located typically behind the secondary mirror structure (central launch), while the receiver LGS signal is collected through a separate optical path. To advance the technology towards higher-sensitivity LGS wavefront sensing and tilt-corrected LGS AO, the CaNaPy facility,⁷ featuring a unique monostatic architecture, was developed and installed at the ESA OGS 1-m telescope in the Observatorio del Teide, Tenerife. A conceptual design of the monostatic system at OGS is depicted in Fig. 1. The facility entered full operations in July 2026, and the results from various field tests are reported in this conference. In particular, we report on the laser beacon detection performance and the first results from LGS uplink pre-compensation adaptive optics, demonstrating the potential for future applications in astronomy^{8,9} and LGS-AO assisted satellite optical communications.^{10–15}

2. CANAPY

2.1 General description

An overview of the CaNaPy optomechanical system, together with the host ESA's OGS telescope, is shown in Fig. 2. A full description of the system has been reported by Janout et al.¹⁶ The main optical components of the CaNaPy laser path are a high-power 63 W sodium laser source equipped with a 100 W Raman Fiber Amplifier from MPB Communications,¹⁷ Second-Harmonic-Generation and a chirping unit from TOPTICA Projects,¹⁸ an amplitude electro-optical modulator, and beam shaping optics using axicons.¹⁹ The adaptive optics subsystems comprises a 10×10 Shack-Hartmann wavefront sensor in R-band for NGS AO, with a field scoring camera, and a Pyramid wavefront sensor equipped with narrow-band sodium filters for LGS AO, and also with a field-scoring camera. An ALPAO 97-15 deformable mirror (DM) is shared for the uplink laser and the downlink paths. The system further includes polarization control optics, two rotating mechanical shutters, and several

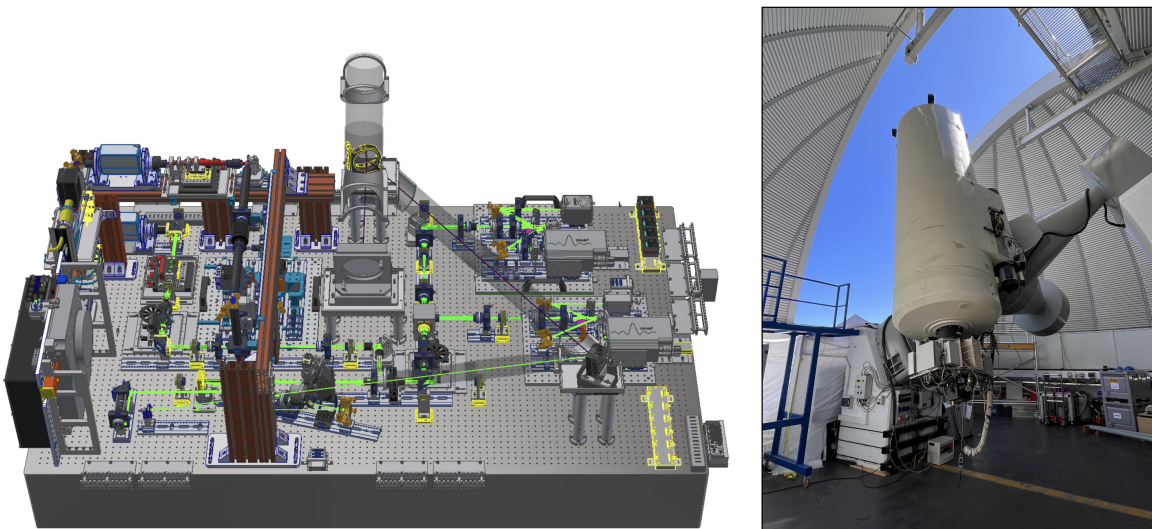


Figure 2. (Left) CaNaPy with all subsystems and electro-optical components distributed over an optical bench of $1.5 \text{ m} \times 2.4 \text{ m}$. The optical components of ALASCA are also presented. (Right) The bench is located at the Coudé focus of the 1-m OGS telescope, behind the southern pier.

fast piezoelectric actuators. The adaptive optics system is controlled in real time using the Advanced Real Time Instrument Control (ARTIC),²⁰ together with a custom Interface Module (IM) electronics developed by Microgate. The IM provides high-speed data transfer and synchronization between the real-time controller and AO devices, including the wavefront-sensor cameras, DM controller, and piezoelectric actuators.

2.2 Monostatic propagation

In CaNaPy, a high-power laser beam is injected in the common path (uplink + downlink) through a polarising beam splitter (PBS). A pair of rotating waveplates in the path converts the beam polarisation from vertical to circular, maximising the LGS return flux.²¹ Optically pumped sodium atoms re-emit photons with circular polarisation but opposite handedness, acting as an ideal mirror. Upon propagating back into the waveplates in the reverse direction, their polarisation is converted from circular to horizontal. The LGS return photons are then transmitted through the PBS towards the wavefront sensors, thereby separating the uplink laser path from the receiver downlink path. However, the photon flux from strong laser scattering within the common-path optics, together with atmospheric Rayleigh backscattering, far exceed the LGS flux to the detector and would saturate the WFS.

Monostatic propagation is achieved by synchronised time-division duplexing (TDD) of the optical path. The uplink laser is intensity-modulated (pulse mode), while a mechanical shutter blocks the downlink path during the pulse propagation, preventing intense backscattered light from reaching the wavefront sensor. During the interval between pulses, the shutter opens to enable downlink detection. This temporal separation of the uplink and downlink allows the same optical path to be alternately used for high-power laser transmission and low-light detection of the LGS return photons, enabling monostatic operation without saturating or damaging the wavefront sensors. A timing scheme is shown in Fig. 3. A second shutter is also used in the uplink path to block any residual laser light between pulses.

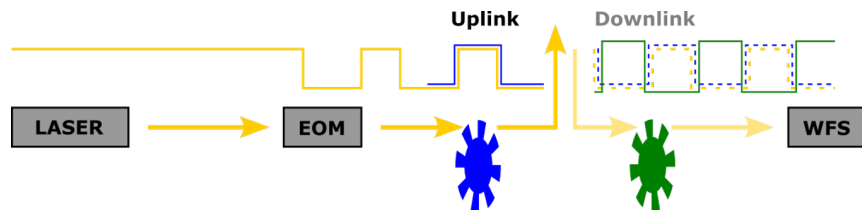


Figure 3. Schematic illustration of pulse shaping and timing concept in CaNaPy. The electro-optic modulator (EOM) generates a square pulse, which always passes through the opening of the uplink shutter. The downlink shutter only opens when the uplink is securely closed.

2.3 Simulations

The modelling of the CaNaPy return has been presented by Fruck et al.²² and is here summarised. The model includes the instrument, a simplified model of the light propagation and overlap, Rayleigh scattering and a realistic sodium density profile. After specifying a certain set of timing parameters, a light curve at the receiver is predicted. The Rayleigh-scattering model uses the formalism from Bucholtz 1995²³ and assumes the US Standard Atmosphere²⁴ for calculating molecular densities.

For the total sodium return flux at the telescope aperture N_{Na} we use calculations and actual measurements by Holzlöhner et. al. 2010/2016.^{21,25}

$$N_{Na} = S_{ce} P \cdot \frac{C_{Na} X T_{atm}^{2X}}{L^2} \cdot \pi(D/2)^2 = \frac{S_{ce} P C_{Na} T_{atm}^{2X} \pi(D/2)^2}{H^2 X} \quad (1)$$

The symbols are explained in Table 1. The shape of the sodium layer in the simulation has later been directly taken from contemporaneous measurements, normalised to a flux calculated as laid out above. The overlap/collection efficiency uses a simplified geometric model with physical field-stop radius a , full field stop

Table 1. Symbols used in Eq.1

Symbol	Value	Description
X	$1/\sin \alpha$	airmass at pointing elevation α
S_{ce}	250	specific cross-section efficiency ($\text{photons s}^{-1} \text{W}^{-1} (\text{atom m}^{-2})^{-1}$)
P	55.0	laser power (W)
C_{Na}	$3.0 \times 10^{13} \text{ m}^{-2}$	zenith sodium column density
T_{atm}	0.8	one-way atmospheric transmission at zenith
H	$90 \times 10^3 \text{ m}$	zenith height of sodium layer
D	1.0	telescope aperture diameter (m)

diameter angle Ω_{fs} , and diffraction-limited blur radius r_{diff} at the focal plane (with effective focal length F) as input:

$$a = F \tan\left(\frac{1}{2} \Omega_{\text{fs}}\right), \quad r_{\text{diff}} = \frac{1.22 \lambda}{2D} F. \quad (2)$$

The spot radius with the optical system focused at a distance d_{foc} with respect to the object's distance d is

$$r_{\text{blur}} = D F \left| \frac{1}{d_{\text{foc}}} - \frac{1}{d} \right|, \quad (3)$$

and the total spot size is

$$r_{\text{total}} = \sqrt{r_{\text{blur}}^2 + r_{\text{diff}}^2}. \quad (4)$$

The collection efficiency is then:

$$\eta_1(h) = \begin{cases} 1 & r_{\text{total}} \leq a \\ \left(\frac{a}{r_{\text{total}}}\right)^2 & r_{\text{total}} > a \end{cases}. \quad (5)$$

A simplified linear model is used for the edge transition of the mechanical shutter through the beam, which is considered negligible for the uplink, but relevant for the downlink due to the larger LGS spot size.

A simulated received light curve is shown in Fig. 4. Note that the plot is logarithmic on the Y-scale, meaning that Rayleigh scattering (blue curve) still plays a major role in the integral signal, despite dying off relatively quickly. The timing in this configuration is optimised for maximal efficiency on the sodium return (orange curve), covering nearly the entire return signal generated by the uplink pulse and broadened by the spatial extent of the sodium layer.

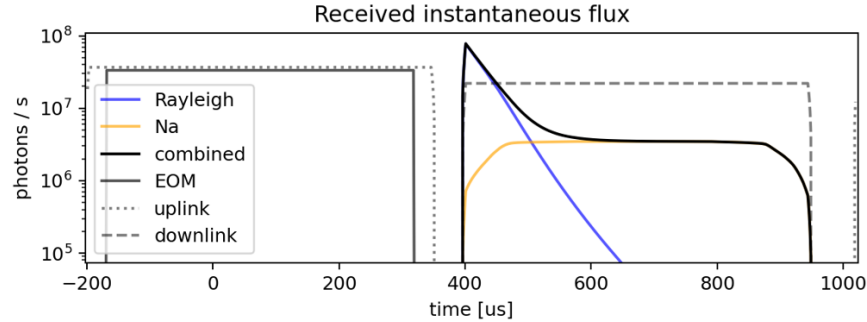


Figure 4. Simulated time profile of the return signal (right curve), which is a combination of Rayleigh scattered light (blue) and light from the sodium layer (orange).

3. ON-SKY RESULTS

3.1 LGS imaging and photometry

During a campaign in April 02-12, 2026, first observations of an LGS in monostatic configuration were recorded using the scoring camera from Emergent Vision Technologies, model HB-1800-S-M, in the downlink path inside of the Pyramid WFS module. An example of this detection is shown in Fig. 5, obtained with the laser source set at 55 W output power and a pulse rate near 800 Hz. The on-axis laser guide star is surrounded by residual Rayleigh backscattering distributed over the field limited by a stop of 15 arcsec. The size of the LGS in this example could be estimated as ≈ 2 arcsec FWHM.

To understand the time-evolution of the return flux with high accuracy and for TDD synchronisation optimisation, we introduced an optical branch with a photomultiplier tube (PMT) just outside of the PyWFS module in the downlink path, which collects all return photons within a field of view of 11 arcsec.²² Using the scoring camera or the PMT, alternated measurements with high-spatial or high-temporal resolution can be obtained. In Fig. 6 the averaged PMT signal over one cycle is shown. During the first half-cycle, the pulse propagates and the square signal is the result of straylight on the bench that leaks into the PMT. After a short transition period, the downlink signal appears on the second half-cycle, which is the period when the downlink shutter opens. A time series with the laser detuned is first acquired (green curve), detecting only backscattered photons (laser background). Then, a second acquisition is performed with the laser on-resonance, showing increased flux during the downlink opening due to photons from the LGS (blue curve). A simulated curve is also included. A photometric analysis of these data shows that a signal to background of 1.51 can be achieved exceeding the theoretical estimate of 0.57. During the downlink shutter opening time of 550 μ s, the estimated number of photons from the LGS is 1534 photons and from Rayleigh backscattering is 1013 photons on the detector. The downlink throughput to the LGS detectors was estimated as 0.36, and the laser uplink throughput was estimated as 0.50. Since Rayleigh-backscattered photons are distributed across the entire field, as shown in Fig. 5, the laser background can be further suppressed by reducing the field of view, provided that the field stop does not vignette the LGS spot.

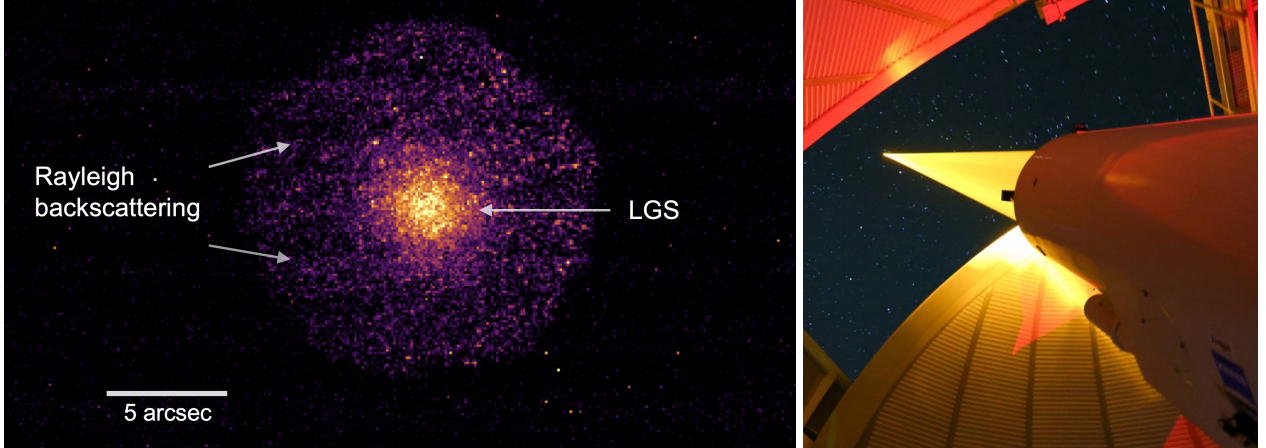


Figure 5. (Left) Example of a monostatic LGS observed with the scoring camera of the PyWFS module, after timing optimisation. In this raw image, the sodium LGS appears centred surrounded by residual Rayleigh backscattering within a field view of approximately 15 arcsec in diameter. Outside the field stop no light reaches the detector. (Right) Photo of the laser beam projected through the full 1-m aperture of the ESA OGS telescope. Image credit: ESO/Christian Fruck.

3.2 LGS uplink pre-compensation

Following TDD synchronisation optimisation and minimisation of the laser background, an LGS uplink pre-compensation experiment was performed. In this experiment, a bright natural guide star (magnitude < 2) was used for the Shack–Hartmann wavefront sensor. The laser was propagated at maximum output power, with both the NGS and LGS kept on axis. A dichroic element blocked the LGS light from reaching the Shack–Hartmann wavefront sensor (SH-WFS), reflecting it towards the PyWFS. While NGS AO correction was applied to the

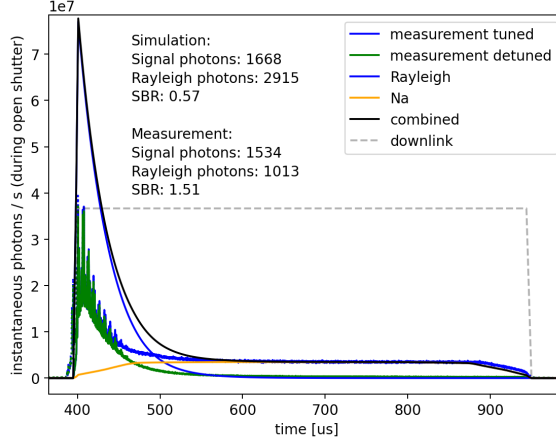


Figure 6. Simulation and measured LGS return and Rayleigh backscattering using a PMT, collected over a field of view of 11 arcsec during the opening of the downlink shutter.

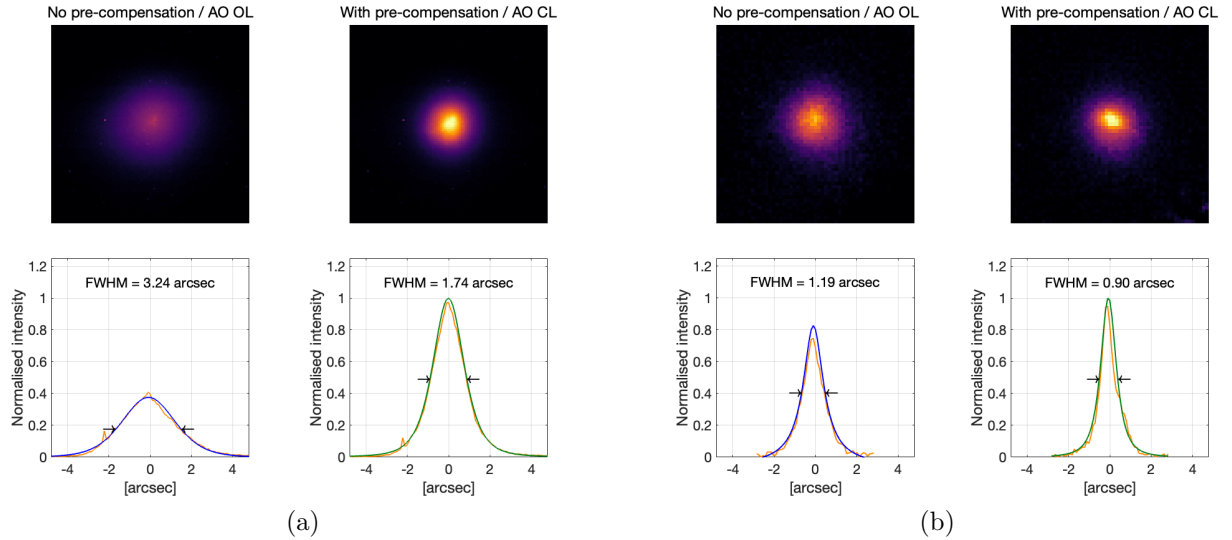


Figure 7. Example results of the first reported LGS pre-compensation experiment, performed under seeing conditions of (a) 2–3 arcsec and (b) 1–1.5 arcsec. The top images show the long-exposure LGS spots in open loop (left) and in closed loop with an on-axis NGS (right). A Moffat fit is applied to each profile to estimate the FWHM spot size, which is indicated by the arrows.

DM in the common path, the LGS was simultaneously monitored with the scoring camera inside the PyWFS module. LGS images were also recorded in open loop with the SH-WFS, as close as possible to the corresponding AO closed-loop measurements, to provide a reference and estimate the reduction in LGS size achieved through uplink correction.

Uplink correction data were recorded during two separate test campaigns, in April and July 2026. Very different atmospheric conditions were encountered during these two campaigns, with estimated strong seeing of 2–3 arcsec in April and typical seeing of approximately 1 arcsec in July. Examples of the experiment are shown in Fig. 7. In all recording series, a reduction in LGS size was obtained with uplink correction. The LGS spot size was estimated by fitting a Moffat function to the long-exposure image and calculating the corresponding FWHM. Under strong-seeing conditions, the LGS spot FWHM was reduced from 3.24 arcsec to 1.74 arcsec. Under good-seeing conditions, a reduction in spot FWHM from 1.19 arcsec to 0.90 arcsec was observed.

4. CONCLUSION

We have demonstrated, to the best of our knowledge, the first sodium LGS uplink pre-compensation in a monostatic system using CaNaPy at the ESA’s 1-m OGS telescope. The monostatic configuration was enabled through synchronised time-division duplexing of the optical path, achieved by intensity-modulating the laser source and periodically blocking the downlink path to suppress strong backscattering and straylight. The measured signal-to-background ratio over an 11 arcsec field of view was 1.51. This ratio can be further improved by reducing the field of view up to the size of the LGS and optimising the timing and shutter-opening periods. In the monostatic configuration, uplink pre-compensation of the LGS beam was achieved in closed loop operation, using a natural guide star as the reference for the Shack-Hartmann wavefront sensor, resulting in an effective reduction of the observed LGS spot size under strong and good seeing conditions. Further exploration and optimisation of LGS uplink pre-compensation are planned for upcoming campaigns and will be reported in dedicated publications. These demonstrations represent an important milestone toward further advances enabled by CaNaPy at the ESA-OGS, including higher sensitivity LGS adaptive optics with a Pyramid wavefront sensor, LGS tilt retrieval based on propagation-delay measurements, LGS AO assisted optical feeder-link experiments via ALASCA, sensing of segmented mirrors discontinuities with LGS, remote LGS optical magnetometry, enhanced return flux through chirped LGS excitation, and investigation of daytime LGS adaptive optics, some of them described in companion papers presented at this conference.

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