Uplink Wavefront Corrector System: On-sky performance validation

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ABSTRACT

The Uplink Wavefront Corrector System (UWCS) has been conceived by following the premises from simulation outcomes as a pathfinder instrument to demonstrate Adaptive Optics uplink correction in both applications: Free-Space Optical Communications and generation of Laser Guide Stars. Preliminary designs and expected performance have been analysed via simulations in previous studies. A Rayleigh LGS is propagated to the sky while the atmospheric wavefront it suffers, is measured by a Shack-Hartmann with 12 x 12 sub-apertures in synchronized operation with the laser pulses. The laser upwards propagation path is then pre-compensated by a 97-actuator deformable mirror. By attaching a score camera to the finder telescope next to the main aperture, the demonstration outcome is assessed in terms of beam power concentration and spot size reduction. Present paper describes on-sky performance validations of an AO system designed to pre-compensate a Laser Guide Star launched through the Optical Ground Station telescope at Teide Observatory (Tenerife, Spain).

Keywords: Uplink correction, LGS, Pulsed Lasers, On-sky Validation

1. INTRODUCTION

The atmosphere is a very dynamic system, whose temperature changes produce fluctuations in the atmospheric refraction index. These fluctuations cause the well-known atmospheric turbulence, which results in distortions in the light propagation as it travels through the atmosphere, i.e. the upwards propagated path of a laser beam (uplink). Both applications, the generation of Laser Guide Stars and Earth-to-Satellite Free Space Optical Communications suffer from the atmosphere influence on their laser uplinks.

A Free-Space Optical communication (FSOC) system consists of a line-of-sight technology which transmits a modulated laser beam through the medium for broadband communications, performed from satellite to satellite, from satellite to aircraft/drone, from ground to ground, or from satellite to ground and vice versa.[1] In the scenario where Earth-to-Satellite FSOCs are performed, the transmitter is placed on the Earth surface; as the laser travels through the atmosphere, its beam width will not exceed the inertial range of the atmosphere. As a consequence, the uplink in Earth-to-Satellite FSOC will show effects mostly related to large angular displacements: beam wander and fluctuations in the angle-of-arrival.[2]

Adaptive Optics (AO) systems measure and correct the aberrations the light suffers during its propagation through a turbulent medium. The light of a reference object on the sky is used to properly sense the turbulence. Laser Guide Stars (LGSs) are artificial references for the adaptive optics systems, which are used to cope with the lack of natural stars up on the area of interest. They are produced by laser beams projected to the atmosphere to create focused spots of light in the upper part of the atmosphere (Rayleigh LGS) or in the Sodium layer at 90km above the Earth surface (Na-LGS). The atmosphere turbulence will also affect the LGS uplink, which will

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present certain distortions producing larger and fainter artificial stars at the corresponding altitude.

The Uplink Wavefront Corrector System (UWCS)[34] has been designed as a proof-of-concept instrument to be tested in the 1-meter telescope of the Optical Ground Station (OGS) at Teide Observatory (Tenerife, Spain). Its main objective is the demonstration of the advantages of applying Adaptive Optics techniques to Earth-Satellites optical communications (uplink), or the so-called upwards propagation path of a laser beam, and furthermore, to Laser Guide Star generation in conventional AO systems, by creating more focused and hence, brighter spots in the Na layer or in the upper parts of the atmosphere. This goal is achieved by the uplink atmospheric pre-compensation of the laser beam. The UWCS consists of an Adaptive Optics system which introduces on-purpose added aberrations onto the laser by creating certain shapes in a deformable mirror, which will counteract the effects of the atmospheric turbulence when travelling through it.

2. UWCS OPTICAL BENCH

The Uplink Wavefront Corrector System is an AO proof-of-concept instrument, whose main goal is the reduction of the atmospheric turbulence effects in the lasers upwards propagation path. It is based on the measurement of the uplink wavefront along its propagation direction.

The UWCS consists of a 532-nanometre laser, acting as both, Rayleigh Laser Guide Star and laser to be pre-compensated, a 12x12 sub-aperture Shack-Hartmann as wavefront sensor, a 97-actuator deformable mirror, and a calibration system for prior tasks to the on-sky operation. Table 1 gathers the most relevant technical details of the UWCS subsystems.

Table 1. UWCS subsystems technical details

Rayleigh LGS	Coherent Verdi CW 18W 532nm SCITEC Instruments Optical Chopper
Shack Hartmann WFS	Firstlight OCAM2k camera 12x12 microlenses array
Deformable Mirror	CILAS SAM97 97 actuators in 11x11 grid
Calibration system	JSDU He-Ne Laser 21mW 632.8nm

The UWCS optical bench was installed and integrated at the Coudé focus of the OGS telescope at Teide Observatory. The set-up is shown in Figure 1: in red the calibration system optical path; in green solid line, the laser launch optical path, and in green dashed line, the path followed by the return light from the sky to the WFS.

The Rayleigh LGS was designed to be launched through the whole telescope aperture, working in shared-path operation with the wavefront sensor: both laser launch and photon return follow a common optical path to a certain extent. Therefore, not only the LGS system needs an optical chopper to create the Rayleigh artificial star, but also the WFS system; an optical chopper placed right before the WFS avoids the sensor saturation when the laser is propagating and allows the direct measurement of the Rayleigh return at the desired atmospheric height. Both choppers, LGS and WFS, shall work within a tight synchronisation scheme, in order for the WFS to acquire the light coming from the focused spot at 20-kilometre height above the ground, instead of the out-of-focus return from the Rayleigh column at any other altitude.

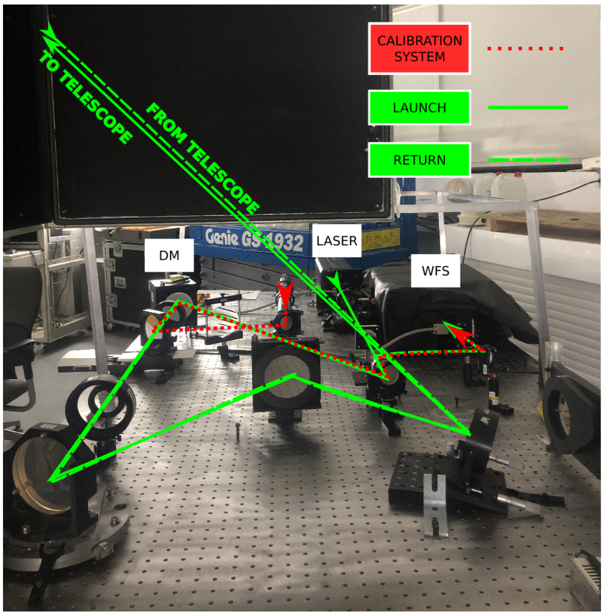


Figure 1. The light from the Verdi laser follows the solid line through the optical elements, the deformable mirror and the folded mirrors which inject the laser beam to the telescope tube; on the return path (dashed line), the light coming from the sky follows the exact same optical path until the 50/50 beam splitter which divides the beam and leads it to the WFS. In red, the calibration system described later in this chapter.

As the laser is propagated through the entire aperture, the telescope secondary mirror that obscures the primary, would introduce significant central vignetting losses. With the aim of avoiding the clipping losses, several laser profiles were simulated, concluding that ring-shaped laser beams perform better when launching them through the whole telescope aperture. Hence, the laser (either FSOC or LGS laser) needed to be properly shaped before exiting from the AO system to the telescope input. An axicon-scheme was devised for efficient coupling of the laser to the obscured launching telescope. The laser ring was propagated throughout the optical set-up to the telescope tube and ultimately, to the sky. Figure 2 presents the axicon launch system and the ring generation on the OGS dome.

3. AO CLOSED-LOOP OPERATION

The Durham Adaptive Optics Real-Time Controller (DARC)[5] was selected as the RTC for the UWCS; DARC is a real-time control system (RTCS) for AO that was initially developed to be used with the CANARY on-sky multi-object AO technology demonstrator, due to a demand for DARC to be used with other instruments, an improved version of DARC was released to the public using an open source GNU General Public License.

The UWCS Control System was also installed at the dome, next to the south pillar of the telescope as the CameraLink cables for the WFS frame grabber have a maximum length of 10m. It consists of the electronics cabinet with the DM control modules, the NI PXI to send the corresponding actuation to the mirror electronics, and the RTC computer, which contains the DARC controller.

Initially, the UWCS design was thought to use the Rayleigh return from the launched Laser Guide Star as the reference source for the wavefront sensing and therefore, the close loop operation. However, due to the mechanical nature of the optical choppers (WFS and LGS) and the limited chopping speed, neither the laser beam nor the return light from the Rayleigh backscattering were chopped abruptly in time, but in several microseconds,

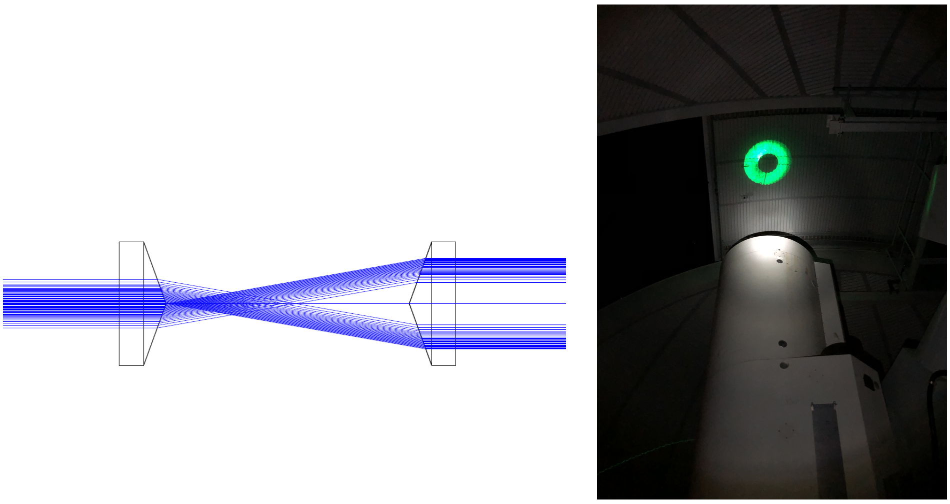


Figure 2. Zemax layout of the positive and the negative axicon in the LGS launch system and the ring-shaped generation with the axicon at the OGS dome.

causing delays in the reception which were translated into a reduction in the received backscattered return. Additionally to the chopping malfunctioning, some residual light was entering the wavefront sensor when operating the laser at maximum power. After carefully analysing the UWCS set-up, the cause was found out to be a fluorescence light coming from the beam splitter, which lasted around 3ms, further impairing the system performance.

Based on the insignificant Rayleigh return captured by the camera without the microlenses array and the unexpected fluorescence, the decision of using a Natural Guide Star instead to close the AO loop, had to be made in order to guarantee the experiment success. The AO control loop was closed with Arcturus as Natural Guide Star at 300 Hz.

4. RESULTS

The OGS has a 20 cm finder telescope, attached and aligned to the main telescope. This finder telescope was used to get a large field-of-view image to ease the localization and spot size analysis of the LGS launched through the 1 meter telescope focus. An ANDOR iXon3 888 with 1024x1024 pixels was attached to it as scoring camera. The wavefront correction in the laser uplink was evaluated by analysing the detected light in the ANDOR. Figure 3 shows two long exposure frames (integration time 500 ms) from the ANDOR camera, before and after closing the loop, demonstrating the successful pre-compensation of the LGS upwards propagated path, whose plume gets brighter at its focus position when closing the AO loop.

The ANDOR images of the laser beam were analysed by selecting a region of the plume and within it, 5 columns in the image to study the intensity profile shape (Figure 4).

The beam profiles along the selected lines in the laser plume are represented in Figure 5(a); the top graph corresponds to the least focused positions in the LGS plume (first red line on the left in Figure 4), and the bottom graph to the most focused one (last red line on the left in Figure 4). The analysis was repeated for a case in which the AO loop was closed without the prior DM flattening (Figure 5(b)), with the purpose of studying the effect of ignoring the best flat configuration of the deformable mirror.

When closing the loop with the optimal parameters and after initialising and calibrating the system properly, an increase of 22% in the laser intensity is achieved at the most focused position; and the beam profile becomes

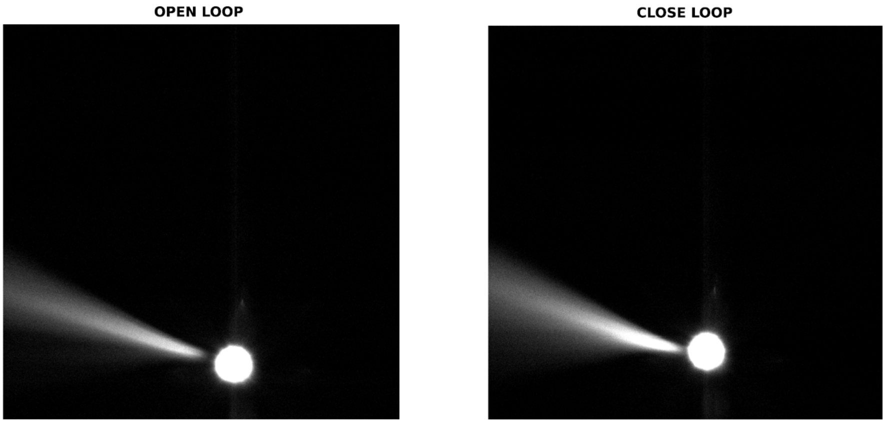


Figure 3. Scoring camera images of the laser plume before and after closing the AO loop with Arcturus as NGS, also in the image. Notice the increase in brightness when the laser wavefront is being pre-compensated.

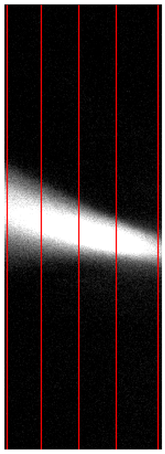
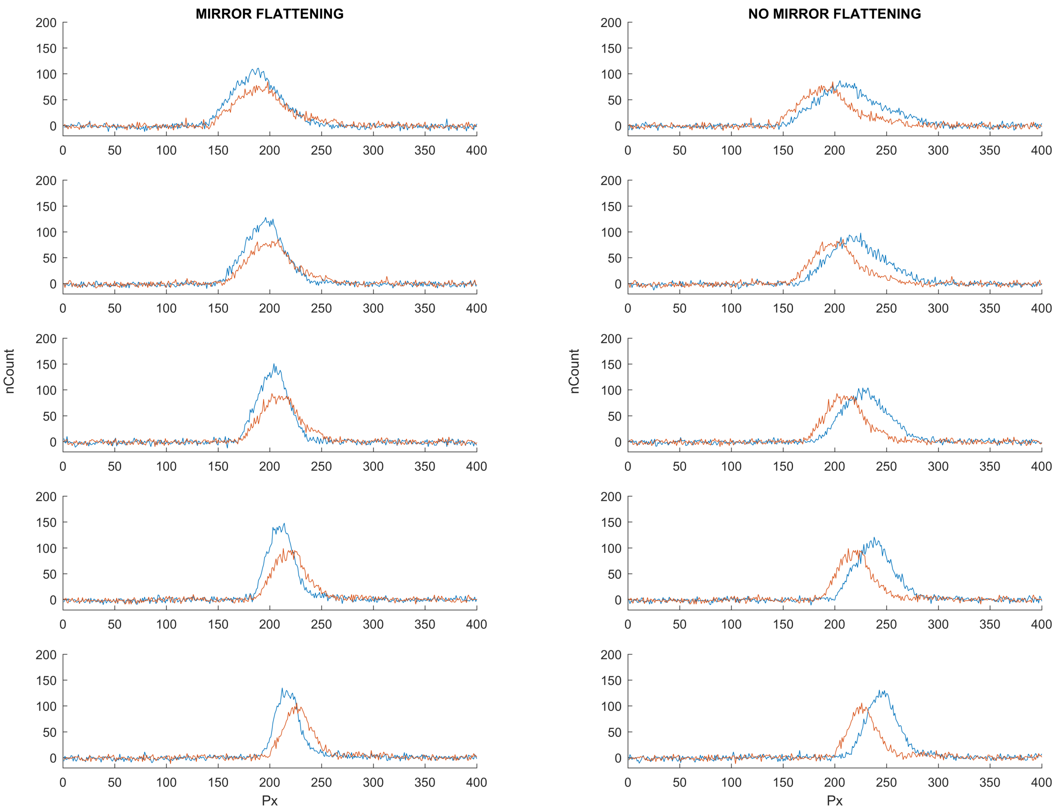


Figure 4. Selected region of the plume; the light distribution along the red lines has been selected for further analysis.

narrower with a 25% decrease in the FWHM (Figure 6(a)); whereas, without performing the DM flattening (Figure 6(b)), the light gain is around 20%, but the FWHM only diminishes by a 9%. This result indicates that the FWHM in open loop is mostly due to the atmospheric aberrations, as the DM flattening only becomes noticeable when applying the wavefront correction, in which case, the optimum performance of the AO system is achieved when the deformable mirror has been previously flattened.

5. CONCLUSIONS

The UWCS was successfully integrated in the OGS telescope. The Rayleigh Laser Guide Star was propagated using the whole primary mirror, avoiding the clipping losses the secondary mirror would have introduced, by using a novel approach in laser launch: the axicon system.
Due to the limitations associated to the mechanical nature of the optical choppers and an unexpected fluorescence coming from the beam splitter, it was not possible to use the Rayleigh return from the LGS as the reference for the wavefront sensor. However, the Adaptive Optics loop was successfully closed with a Natural Guide Star, demonstrating the uplink pre-compensation of the laser beam.



(a) (b)

Figure 5. From top to bottom light distribution corresponding to the selected lines in the laser plume (red lines from left to right in Figure 4); in red, open-loop operation, in blue, close-loop operation. (a) DM flattening performed prior AO operation and (b) Without performing prior DM flattening.

ACKNOWLEDGMENTS

The authors would like to thank the Instituto de Astrofísica de Canarias (IAC) and the European Space Agency (ESA) for co-funding this research.

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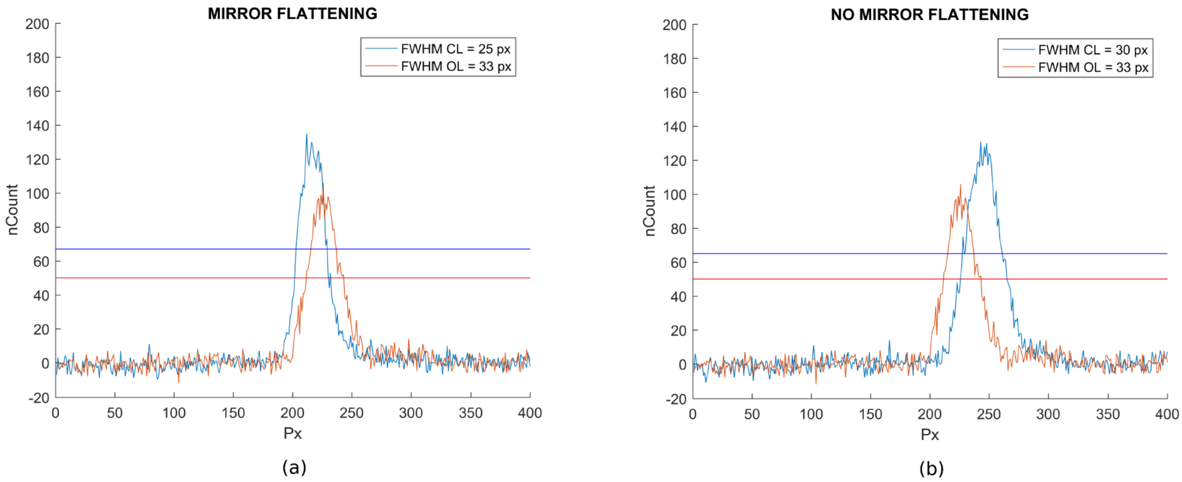

Figure 6. Laser intensity distribution corresponding to the most focused point the laser plume (last red line in Figure 4); in red open-loop operation, in blue, close-loop operation with (a) and without (b) performing the DM flattening