

A Predictive Real-Time Adaptive Optics Control System for Single-Mode Fiber Coupling in a Free-Space Optical Communication Downlink Channel

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Abstract: Free-Space Optical Communication (FSOC) between ground and space is increasingly emerging as an attractive alternative to conventional Radio Frequency (RF) communication. The low divergence and line-of-sight nature of laser light, combined with the ability to implement Quantum Key Distribution (QKD) schemes, enables high-security data transmission. Furthermore, the high bandwidth and low power consumption of FSOC make it a compelling technology to address the growing demand for high-volume data transmission. However, for FSOC to become a fully mature and commercially viable technology, several challenges must still be overcome — the foremost being the limited stability and performance of the optical channel due to atmospheric turbulence. A primary approach to address this limitation is the integration of an Adaptive Optics (AO) system at the Optical Ground Station (OGS).

In the context of a project funded by the European Space Agency (ESA) under the ARTES 4.0 SPL Optical Communication – Scylight programme — the Generic Adaptive Optics Module (GAOM) — we developed and tested an AO system incorporating a Real-Time Controller (RTC) to mitigate turbulence effects and reduce Single-Mode Fiber (SMF) coupling losses. The GAOM system subsequently served as the baseline for a second ESA-funded project under the same programme: the Optimal pRedictive Adaptive optics Control Loop Engine (ORACLE). ORACLE aims to develop an RTC capable of predicting the temporal evolution of atmospheric turbulence, thereby compensating for the unavoidable latency introduced by the hardware in the control loop.

In this work, we report the performance of the real-time AO control system as measured during the GAOM project validation activities, with particular focus on the 10 km free-space optical link tests of wavefront correction carried out at the LASERCOM laboratory telescope at the Officina Stellare premises in Sarcedo, Italy. We then describe the design and architecture of the new predictive controller being developed within the ORACLE project and conclude with simulation results demonstrating the expected performance improvement achievable with the new controller.

Introduction

The rapid growth in global data traffic is driving the development of communication technologies capable of providing significantly higher transmission capacities than those achievable with conventional Radio Frequency (RF) systems. Free-Space Optical Communication (FSOC) has emerged as a promising solution for both terrestrial and space communication links, offering several advantages including large available bandwidth, low power consumption, reduced size and mass of optical terminals, and the intrinsic security provided by the narrow divergence of laser beams [1][2]. Furthermore, the use of optical carriers enables the implementation of Quantum Key Distribution (QKD) [3][4][5], making FSOC an attractive technology for secure communication between ground stations, airborne platforms, and satellites.

Despite these advantages, the performance of ground-to-space and space-to-ground optical links is strongly affected by atmospheric turbulence. Random fluctuations of the refractive index along the propagation path introduce wavefront distortions that degrade the quality of the received optical beam, leading to beam spreading, beam wander, scintillation, and reduced coupling efficiency into Single-Mode Fibers (SMFs). These effects become particularly critical in high-data-rate optical communication systems, where efficient fiber coupling is required to maximize the received optical power and ensure reliable operation.

Adaptive Optics (AO) has become the primary technique for mitigating the impact of atmospheric turbulence in optical communication systems [6]. By measuring the incoming wavefront distortions using a Wavefront Sensor (WFS) and compensating them in real time with deformable optical elements, an AO system can substantially improve the optical beam quality and increase the coupling efficiency into an SMF. Recent advances in high-speed wavefront sensors, deformable mirrors, and Real-Time Controllers (RTCs) have enabled AO systems capable of operating at kilohertz correction rates, making them suitable for the rapidly evolving atmospheric conditions encountered in long-distance optical links [7].

The performance of an AO system, however, is fundamentally limited by the latency of the control loop. The finite acquisition, processing, and actuation times introduce a delay between the measurement of the incoming wavefront and the application of the corresponding correction. During this interval, atmospheric turbulence continues to evolve, resulting in temporal errors that become increasingly significant under strong turbulence conditions or high wind velocities. Reducing the impact of this latency is therefore one of the main challenges in the development of next-generation AO systems.

Predictive control has recently emerged as a promising approach to overcome these limitations [8][9]. Rather than correcting the wavefront measured by the WFS, predictive algorithms estimate its future evolution by exploiting the temporal correlation of atmospheric turbulence and apply a correction corresponding to the expected wavefront at the instant the deformable mirrors are updated. By compensating for the control-loop delay, predictive control has the potential to significantly improve AO performance without requiring faster hardware, making it an attractive solution for future high-performance FSOC systems.

Within this context, the European Space Agency (ESA), under the ARTES 4.0 Strategic Programme Line (SPL) Optical Communication – Scylight programme, funded the Generic Adaptive Optics Module (GAOM) project, aimed at the development and experimental validation of a high-speed AO system for free-space optical communications. The GAOM system incorporates a Linux-based Real-Time Controller (RTC), a Woofer-Tweeter deformable mirror architecture, and a high-speed Shack-Hartmann Wavefront Sensor (SH-WFS) to compensate for atmospheric turbulence and improve SMF coupling efficiency. The successful validation of the GAOM platform established the basis for the subsequent Optimal pRedictive Adaptive optics Control Loop Engine (ORACLE) project, whose objective is the development of a predictive RTC capable of compensating for the unavoidable latency of the AO control loop.

In this paper, we first present the architecture and measured performance of the GAOM real-time AO control system, with particular emphasis on the experimental validation carried out over a 10 km free-space optical link at the LASERCOM laboratory telescope located at the Officina Stellare premises in Sarcedo, Italy. We then introduce the architecture of the predictive controller developed within the ORACLE project and discuss simulation results demonstrating the performance improvements expected from predictive AO control compared with the conventional real-time controller.

Overview of the GAOM system

GAOM is an AO bench based on a Woofer-Tweeter architecture employing a single high-speed Shack-Hartmann Wavefront Sensor (SH-WFS), operating at frame rates of up to 2 kHz, to provide feedback to all the deformable optical elements of the system, namely a Fast-Steering Mirror (FSM), a Woofer Deformable Mirror (DMW), and a Tweeter Deformable Mirror (DMT). The FSM is used for Tip-Tilt correction and provides a dynamic range of approximately $\pm 1.5^\circ$, with a response time below 800 μs . The DMW is dedicated to the correction of low-order aberrations and consists of a Deformable Mirror (DM) with 97 actuators and a single-actuator response time of less than 400 μs . The DMT is used exclusively for the correction of high-order aberrations and is implemented as a DM with 492 actuators, featuring a single-actuator settling time below 75 μs . The system is controlled by a Linux-based Real Time Controller (RTC), developed in-house, which manages all AO components. The RTC supports frame rates of up to 4 kHz while maintaining an AO loop jitter below 18 μs . The AO system is designed to improve coupling efficiency into a Single-Mode Fiber (SMF).

The optical and mechanical layouts of the GAOM AO bench are shown in the two images of Figure 1. The system is composed of the following six blocks:

- The telescope interface collimator, which is used to provide the system with a collimated beam and an image of the telescope pupil.
- The PAT block, whose primary role is to provide pointing feedback to the telescope mount by carrying out the pointing, acquisition and tracking of the satellite.
- The AO correction block, containing pupil-reimaging optics and the AO phase modulators.
- The AO sensor block, with a SH-WFS as feedback to the closed-loop AO controller for actuating the adaptive optics.
- The fiber coupling block, where the classical and QKD are spectrally demultiplexed and coupled into the SMFs of the communication terminals.
- The Self-Test Fiber Interface (STFI) block, which is GAOM's self-testing calibration source module.

The optical beam collected by the telescope enters the AO breadboard through an aperture on the Rx breadboard and is directed towards the collimator by a folding mirror positioned after the telescope focal plane. The resulting collimated beam is then reflected to the FSM (supporting beam diameters up to 31 mm) and subsequently relayed to the tweeter DM followed by the woofer DM, before being delivered to the SH-WFS and SMF coupling stations. A small fraction of the incoming Rx beam is diverted to the PAT camera by a dichroic mirror located upstream of the FSM.

The FSM, tweeter DM, woofer DM, and SH-WFS are positioned at planes optically conjugated to the telescope entrance pupil. To maintain these conjugate planes, a series of optical relays (L1/L2, L3/L4, and L5/L6) is implemented between successive AO components. The magnification of each relay is selected to match the clear apertures of the FSM, DMs, and SH-WFS.

Following the final optical relay (L6/L7), a dichroic mirror (BS3) reflects a portion of the collimated beam at the Rx wavelength towards the measurement cameras (SH-WFS). The transmitted beam is then directed to a second dichroic mirror (BS5), which separates it between the Rx and QKD A/B channels (SMF port for ~ 1550 nm signals) and the QKD C fiber coupling ports (SMF port for ~ 800 nm signal).

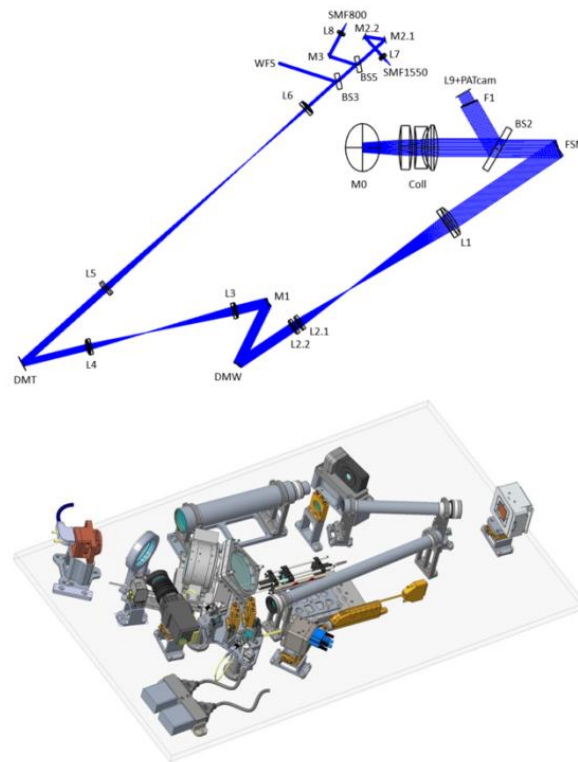


Figure 1 The optical layout of GAOM's Rx AO bench is presented in the upper image, while the mechanical layout is reported in the lower image. Image taken from [10][1].

Free-space optical link tests

An experimental setup was specifically developed to evaluate the reception of an optical signal over a propagation path representative of a satellite communication link, with the aim of supporting the GAOM verification and validation activities. For this purpose, an unobstructed optical path was identified between Malga Foraoro (municipality of Caltrano, 1340 m altitude) and the Officina Stellare headquarters in Sarcedo. The optical link, superimposed on a topographic map of the area together with its altitude profile, is shown in Figure 2.

The experimental setup consists of two main parts:

- the transmitting terminal, which emits the laser beam used to simulate the optical signal transmitted by the satellite;
- the receiving terminal, an Optical Ground Station (OGS) telescope prototype used to collect the signal emitted by the transmitter.

The GAOM AO bench was installed inside the receiving terminal. More specifically, it was mounted and aligned on one of the two Nasmyth ports of the Officina Stellare 700 mm-class telescope, featuring a 41% central obstruction, through a joint effort between Dynamic Optics and Officina Stellare.

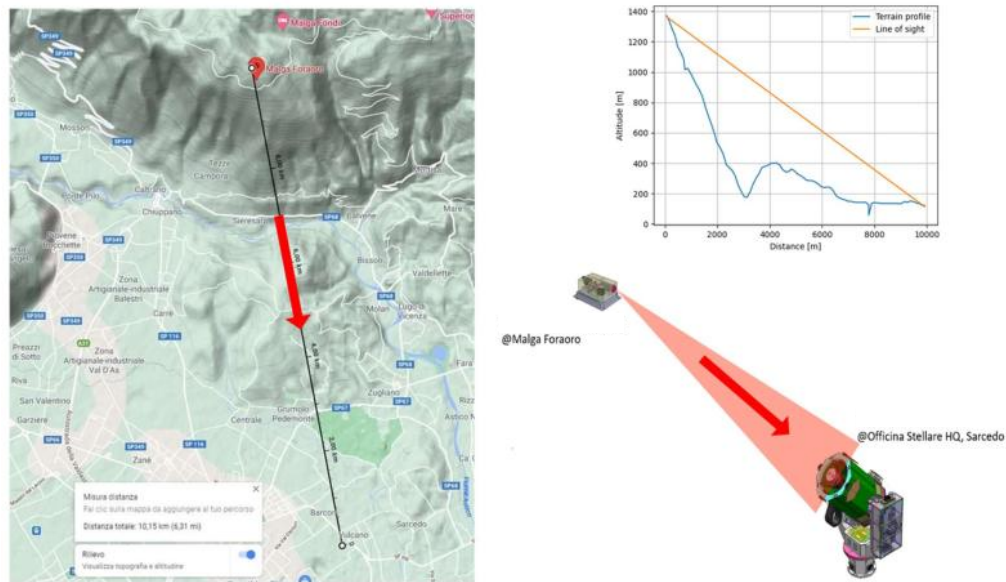


Figure 2 Left: map of the link between Malga Foraoro and Sarcedo. Right, up: terrain profile (blue); optical link (red). Right, down: representative diagram of the test setup with receiving and transmitting terminals. Laser beam is directed from Malga Foraoro towards Sarcedo.

The performance of the AO system was evaluated by measuring, with a power meter, the optical power transmitted through the Single-Mode Fiber (SMF), corresponding to the light emitted by the transmitter, collected by the receiving telescope, and coupled into the fiber. Measurements were performed with the AO loop both open and closed in order to quantify the improvement provided by the AO system. More specifically, each measurement session was divided into two consecutive phases: the first with the AO correction disabled and the second with the AO loop closed.

Figure 3 shows the wavefront Root Mean Square (RMS) error measured by the SH-WFS during one of the measurement sessions. The blue curve represents the total RMS, while the orange and yellow curves correspond to the Tip and Tilt components, respectively. The purple curve shows the high-order RMS, computed after removing the Tip-Tilt contribution from the measured wavefront. As expected, the dominant contribution to the wavefront

error arises from Tip-Tilt aberrations. Closing the AO loop reduces the mean wavefront RMS error from 913 nm to 191 nm.

Table 1 summarizes the performance of the AO bench across the different measurement sessions. In particular, it reports the mean SMF coupling efficiency, expressed in dB, measured with the AO loop closed, together with the corresponding value of (D/r_0) estimated with the AO loop open.

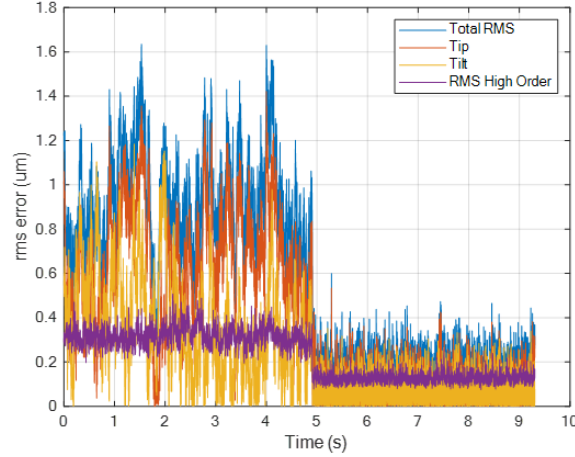


Figure 3 Time series of the wavefront RMS error measured by the SH-WFS during one of the measurement sessions. We have respectively with blue the total RMS, with orange the Tip, with yellow the Tilt and with purple the RMS high order, which is the RMS of the wavefront after tip-tilt subtraction. The first half of the time series is with the AO loop open while the second half is with the AO loop closed.

Table 1 Summary of the results of the measurement sessions performed with 10 km free space optical link.

Date	Time	Ambient temperature [°C]	CE [dB]	D/r0
11/07/2025	20:45	22.8	-8.9	6.6
11/07/2025	21:41	23.5	-8.2	6.5
14/07/2025	23:01	24.2	-10.4	7.5
14/07/2025	23:19	23.8	-10.4	12.7
15/07/2025	21:43	28.4	-8.0	5.9
15/07/2025	22:12	27.7	-7.9	7.4
15/07/2025	22:50	27.2	-8.4	6.2
15/07/2025	23:02	27.1	-8.7	7.4
15/07/2025	23:29	26.4	-7.9	8

Predictive controller architecture

In an Adaptive Optics system, the Wavefront Sensor (WFS) measures the phase aberration introduced by atmospheric turbulence, and a DM is then shaped to impose an equal-and-opposite phase correction. In practice, however, neither the WFS measurement nor the DM update is instantaneous, but it requires some operational time. As a result, by the time the DM is commanded, the atmospheric turbulence has already evolved, leaving a residual mismatch between the measured wavefront and the correction applied. To mitigate this two-step delay, the proposed idea is to introduce a predictive controller that works in parallel with the conventional feedback loop. Rather than relying solely on the chosen feedback law, whether a Proportional-Integral (PI) loop or, alternatively, a Linear Quadratic Regulator (LQR), the predictive controller generates a feedforward term that anticipates how turbulence will evolve over the next steps. By adding this feedforward contribution to the selected feedback output, the final DM command compensates for the dynamic lag. In other words, the actuator signal now consists of two parts: the feedback component (proportional–integral if using PI, or state-feedback if using LQR) and a predictive feedforward component that offsets the two-step delay.

Specifically, the quantity anticipated by the predictor is the Pseudo-Open-Loop Slope (POLS) vector $s(k)$. When the DM is flat, $s(k)$ equals the raw WFS slope measurement $e_{WFS}(k)$. When the DM is active, the incoming

wavefront's slopes are reconstructed by combining the residual slopes $e_{WFS}(k)$ with the previous DM command $c(k-1)$ mapped into slope space via the influence matrix B :

$$s(k) = e_{WFS}(k) + B c(k-1)$$

POLS are chosen because they provide the best linear estimate of the true, aberrated wavefront given the data available in a real-world AO system (namely residual slopes and DM commands). In contrast, raw residual slopes alone tend to have low amplitudes and are heavily affected by the DM's own dynamics, which vary across DM models and can drift over time.

In Figure 4 a scheme of the overall closed-loop architecture with the predictor is reported.

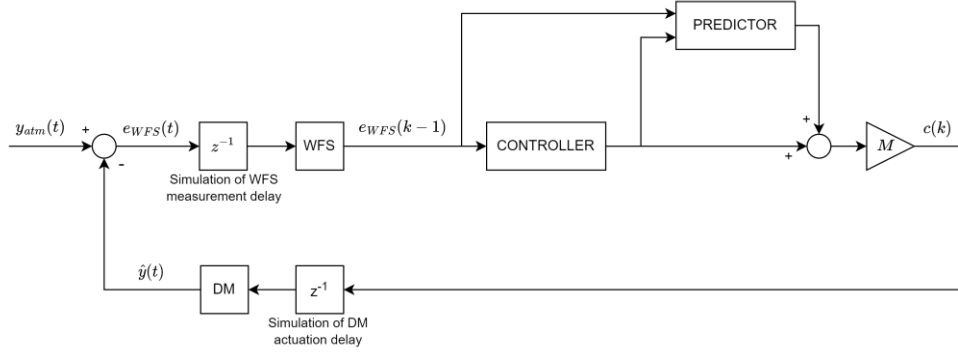


Figure 4 Scheme of the overall closed-loop architecture, showing signals flow from WFS and to DMs, along with the synergy of controller and predictor (arranged in order to provide a feedforward contribution).

Preliminary simulation performance of the predictive controller

The simulations were performed in MATLAB using the Object-Oriented Matlab Adaptive Optics (OOMAO) toolbox [11], which was modified to account for scintillation effects and multi-layer atmospheric turbulence following the approach described in [10]. Several control architectures were implemented and compared. In particular, the following controllers were evaluated:

- **I:** Integrator.
- **LQR:** Linear Quadratic Regulator.
- **PI + UNet:** Proportional-Integrator aided by a UNet-based predictor.
- **LQR + UNet:** Linear Quadratic Regulator aided by a UNet-based predictor.
- **UNet:** Pure UNet-based controller.
- **PI + EOFs:** Proportional-Integrator aided by Empirical Orthogonal Functions (EOFs).
- **EOFs:** Pure Empirical Orthogonal Functions-based controller.

The performance of all control architectures was evaluated in terms of SMF coupling efficiency, estimated by computing the overlap integral between the SMF mode and the incoming optical field after wavefront correction by the AO system.

Figure 5 presents the results obtained from one representative simulation. The simulation was carried out under atmospheric turbulence conditions characterized by a Fried parameter (r_0) of 5 cm and a Greenwood frequency of 120 Hz, representative of a typical Low Earth Orbit (LEO) optical communication scenario for the GAOM AO bench. All control architectures were operated at the same sampling frequency of 2 kHz.

Among the control architectures investigated, the PI + UNet approach appears to provide the most promising trade-off between performance and computational efficiency. Although it does not consistently achieve the highest SMF coupling efficiency or availability, it offers a relatively short inference time and is well suited to parallel implementation. Furthermore, its multi-threaded architecture enables improved performance under highly variable

atmospheric conditions. The next step of the ORACLE project will be the validation of this controller using experimental data.

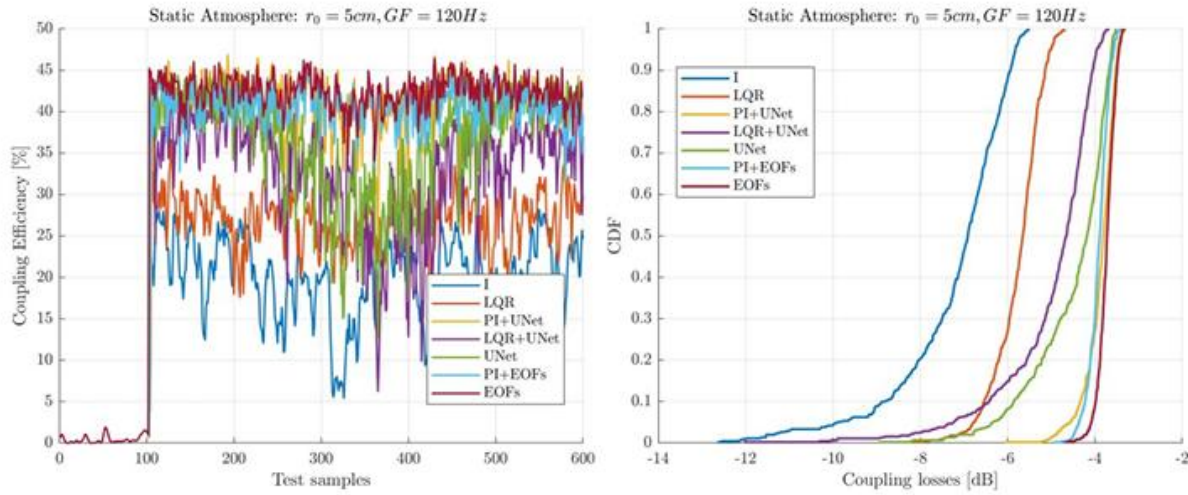


Figure 5 Coupling efficiency obtained with different control architectures in a simulated turbulence scenario with Fried Parameter r_0 equal to 5 cm and a Greenwood Frequency GF of 120 Hz. The plot on the left shows the coupling efficiency during the simulated time series while the plot on the right shows the Cumulative Distribution Function (CDF) of the coupling losses for the same time series.

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