

ATLAS: An Experimental Platform for Optical Communications Through Atmospheric Turbulence

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ABSTRACT

Free-space optical communications require efficient mitigation of atmospheric turbulence to maximize received optical power and fiber-coupling efficiency. This paper presents ATLAS, a 1550 nm experimental platform dedicated to the evaluation of adaptive optics (AO) technologies for optical communications under realistic propagation conditions. The platform combines a programmable turbulence generator based on a Digital Micromirror Device (DMD), capable of reproducing both phase distortions and scintillation effects, with a high-speed AO system. The AO bench integrates a deformable mirror (DM), a Shack-Hartmann wavefront sensor, a tip-tilt mirror, a tip-tilt sensor. A dual-loop (2SISO) control architecture enables independent correction of tip-tilt and higher-order aberrations at loop frequencies up to 9.5 kHz. Dedicated calibration and optimization procedures, including non-common-path aberration compensation, allow repeatable assessment of AO and fiber-coupling performance.

The platform is first used to characterize the temporal performance of the AO system through the measurement of Error Transfer Functions (ETFs) and rejection bandwidths under controlled conditions. To overcome deformable mirror bandwidth limitations, we evaluate a DM-Shaper control strategy that accounts for mirror dynamics. Experimental results demonstrate substantial gains in temporal performance and high-speed AO correction.

Finally, experimental results with turbulence applied using the emulator are presented using a 97-actuator deformable mirror. The measured performance demonstrates the benefits of high-speed AO correction and DM shaping for turbulence mitigation and fiber-coupling enhancement. Beyond adaptive optics characterization, the platform can also be used for end-to-end communication testing by inserting a modulated optical transmission chain before the turbulence emulator and assessing demodulation performance after fiber injection through metrics such as bit-error rate (BER). These capabilities establish ATLAS as a versatile platform for the development and validation of future optical ground stations.

Keywords: free-space optics communication, adaptive optics, experimental bench, atmospheric turbulence emulation, deformable mirror, optical ground stations

1. INTRODUCTION

Free-space optical (FSO) communications are a promising solution for future satellite networks owing to their large available bandwidth and immunity to radio-frequency spectrum congestion. However, atmospheric turbulence remains a major limitation for ground-to-space and space-to-ground optical links. Wavefront distortions, scintillation, and beam wander degrade both the received optical power and the coupling efficiency into single-mode fibers, directly impacting communication performance. Adaptive optics (AO) is widely recognized as a key technology for mitigating these effects. This challenge has motivated the development of advanced optical communication demonstrators ranging from high-capacity deep-space links, including recent demonstrations of 100 Gbit/s optical transmission in lunar communication scenarios [3], to operational optical ground stations such as FrOGS for GEO and LEO laser communication experiments [4,5]. In parallel, realistic laboratory testbeds have become essential for the validation of AO architectures and communication subsystems under representative atmospheric conditions. Notable examples include the ONERA PICOLO turbulence emulator, developed for the assessment of adaptive optics systems in ground-to-satellite optical links and subsequently extended to the characterization of strong-turbulence propagation effects and scintillation [1,2]. Discussions with the NOKIA Lab team and the growing need for flexible AO validation platforms motivated the development of complementary experimental capabilities at Bertin Alpao. To this end, Bertin Alpao has

developed ATLAS (Atmospheric Turbulence LAsER link Simulator), a 1550 nm experimental platform combining programmable turbulence and scintillation generation, high-speed adaptive optics, and fiber-coupling measurements. The platform is designed to reproduce realistic propagation conditions representative of satellite optical links while providing the flexibility required to investigate advanced control approaches and communication-system performance. In particular, ATLAS serves as a testbed for advanced deformable-mirror control strategies such as the DM Shaper approach, recently shown to significantly improve adaptive optics performance by extending the effective correction bandwidth [6]. The remainder of the paper presents the ATLAS platform, its adaptive optics commissioning results, the validation of turbulence and scintillation emulation, and fiber-coupling measurements.

2. THE ATLAS EXPERIMENTAL TESTBED

The ATLAS facility combines three main subsystems: a programmable turbulence generator, a high-speed adaptive optics bench, and a fiber-coupling focal plane.

The turbulence generation module relies on a complex-field modulation approach capable of reproducing both phase and amplitude aberrations representative of atmospheric propagation. The system can emulate turbulence strengths up to $D/r_0 < 25$ and scintillation levels up to a scintillation index of 0.5. Compared with conventional rotating phase-screen approaches, the proposed architecture provides significantly greater flexibility. Arbitrary phase and amplitude screens can be uploaded and replayed, enabling the reproduction of measured turbulence data acquired on optical ground stations, synthetic phase screens generated from a given optical turbulence profile, or scenarios representative of specific satellite links such as LEO downlinks. This versatility makes the platform well suited for investigating a wide range of propagation conditions within a controlled and repeatable laboratory environment. Atmospheric phase and amplitude aberrations are generated using a dedicated software package, WARP, developed by Bertin Alpao and subsequently reproduced by the turbulence emulator.

The adaptive optics bench consists of a deformable mirror (DM), a Shack-Hartmann wavefront sensor (WFS), a tip-tilt mirror (TTM), and a tip-tilt sensor (TTS). The architecture is designed to accommodate several ALPAO deformable mirrors, including the DM97, DM192, and DM308, with minimal modifications to the optical layout. The results presented in this paper were obtained with a DM97 operating at loop frequencies up to 9.5 kHz. Such operating conditions are representative of the adaptive optics systems currently deployed on optical ground stations, including the French Optical Ground Station (FROGS). A key feature of the platform is its flexibility in terms of control architectures. The system can operate using the high-order correction loop alone (DM/WFS), the tip-tilt loop alone (TTM/TTS), or both loops simultaneously through a decoupled 2SISO architecture. The optical layout also supports more advanced configurations, such as woofer-tweeter architectures involving multiple deformable mirrors. ATLAS therefore provides a versatile environment for the evaluation of advanced control strategies and high-speed adaptive optics concepts.

At the science focal plane, the corrected beam is injected into a single-mode fiber. The coupled optical power provides a physically meaningful performance metric directly related to free-space optical communication systems. This subsystem enables the assessment of adaptive optics performance beyond conventional wavefront-sensor metrics by quantifying the impact of turbulence correction, control strategies, and non-common-path aberration compensation on fiber-coupling efficiency. As a result, ATLAS offers an end-to-end framework for studying the relationship between atmospheric turbulence, wavefront control, and communication system performance.



Figure 1: Picture of the ATLAS experimental testbed

3. EMULATING PHASE AND AMPLITUDE ABERRATIONS

Atmospheric turbulence is generated using the DMD, which reproduces complex fields computed with WARP under the frozen-flow hypothesis. In the present work, turbulence is modelled as a single atmospheric layer whose temporal evolution is entirely determined by the wind speed and the turbulence generation rate. The sampling frequency used in WARP is identical to the DMD update frequency, ensuring faithful playback of the generated phase screens. Because the DMD is a discrete-time device, it cannot reproduce a truly continuous evolution of the atmosphere. To minimize temporal discretization effects, it is operated at its maximum stable refresh rate of 10 kHz, substantially higher than the Shack-Hartmann WFS sampling frequency. As a consequence, several phase-screen updates occur during a single WFS exposure, providing a close approximation of continuous atmospheric evolution. WARP therefore generates turbulence sequences at 10 kHz. A total of 55,000 turbulence realizations are precomputed, stored in the FPGA memory, and replayed cyclically during the experiments.

Characterization results show that the phase accuracy reproduces the expected Kolmogorov spectrum to within 10%. Representative examples are presented below. A coupling between phase and intensity aberrations is observed when the phase aberrations become too large, particularly at high spatial frequencies corresponding to large turbulence strengths (typically $D/r_0 > 25$).

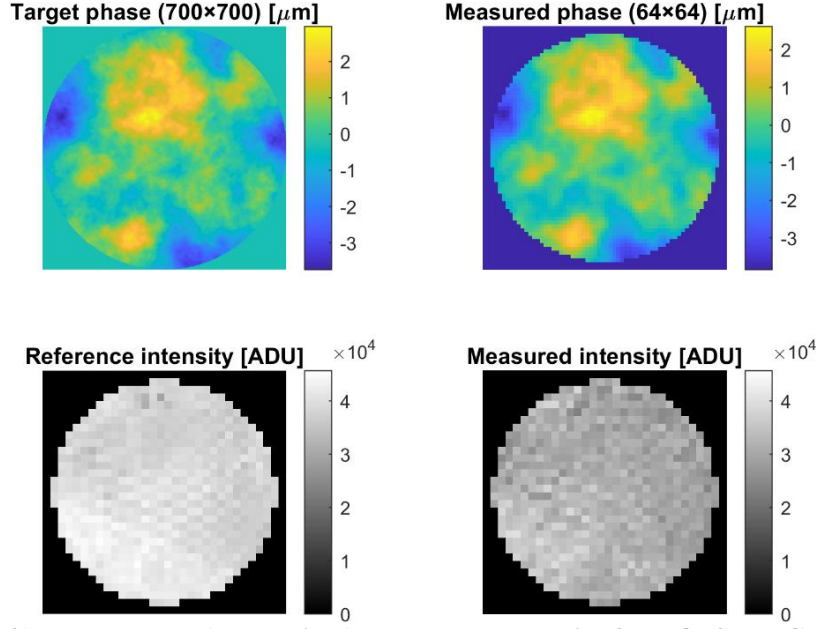


Figure 2: (Upper left) Target phase. (Upper right) Measured phase with full ROI SH-InGaAs fast using 64x64 subapertures. (Lower left) Shack-Hartmann intensity (sum for each subaperture) when no phase aberration is applied on the turbulence emulator. (Lower right) Shack-Hartmann intensity when the target phase is applied.

4. AO COMMISSIONING

As part of the adaptive optics commissioning campaign, the temporal performance of the control loop was characterized both with and without the DM-Shaper enhancement. By explicitly accounting for the dynamic behavior of the deformable mirror, the DM Shaper is expected to extend the effective correction bandwidth and improve disturbance rejection at higher frequencies. The objective is to quantify the bandwidth extension and disturbance rejection improvements enabled by compensating for the deformable mirror dynamics. These measurements were first performed by injecting calibrated perturbations directly onto the deformable mirror while operating the AO loop in closed loop. Error Transfer Functions (ETFs) were measured with a conventional integrator controller and the DM Shaper configuration.

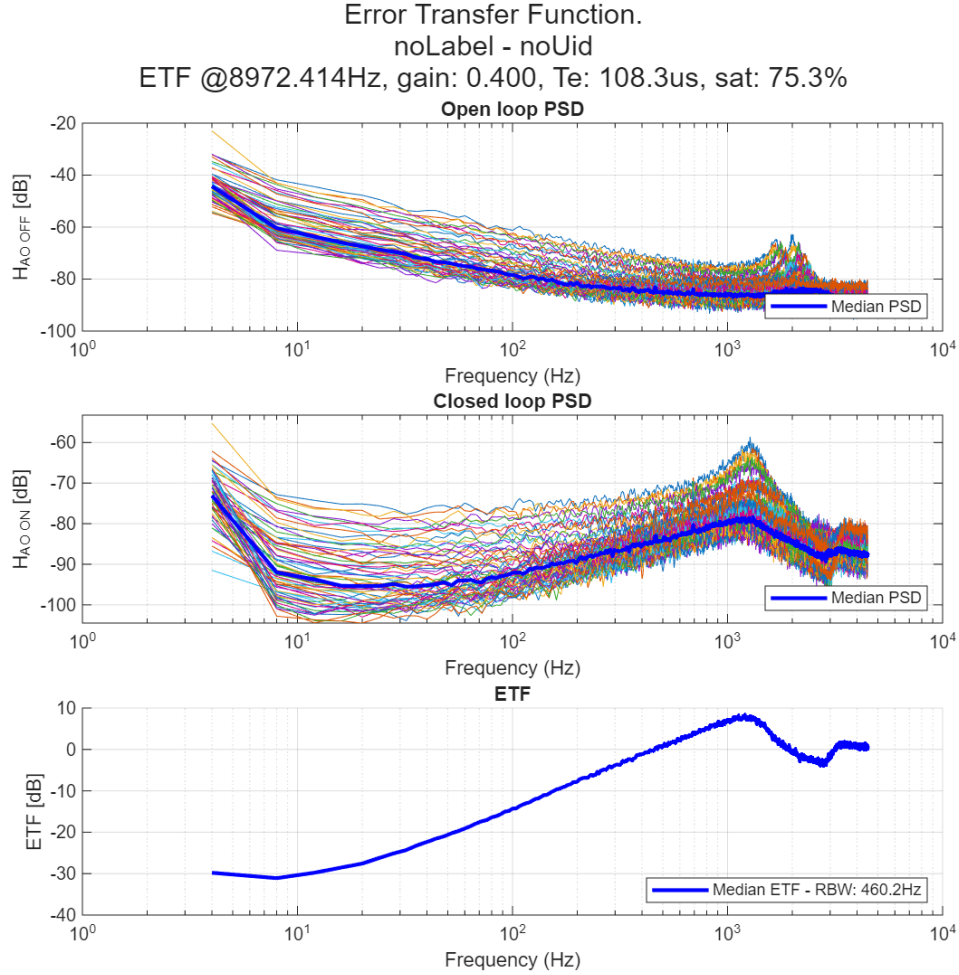


Figure 3: Error Transfer Function results for the DM97-15 operating at 8.975 kHz

Loop frequency [Hz]	RBW 0 dB [Hz]
3975	308
4750	344
5987	384
8972	460

Table 1: Rejection bandwidth at 0 dB using the high-speed DM97-15

5. FIBER INJECTION RESULTS

TODO

6. CONCLUSION

A high-speed adaptive optics platform operating at 1550 nm has been developed for the experimental evaluation of free-space optical communication links under realistic atmospheric conditions. The bench combines programmable turbulence and scintillation generation, kHz-rate adaptive optics correction, and fiber-coupling measurements. Experimental results demonstrated its ability to characterize AO temporal performance through Error Transfer Function measurements and to evaluate advanced correction approaches such as DM shaping.

Beyond adaptive optics characterization, the platform can also be used to assess the end-to-end performance of optical communication systems. Telecommunication signals can be modulated prior to propagation through the turbulence

emulator and demodulated after fiber injection, enabling the measurement of communication metrics such as bit-error rate (BER) under controlled atmospheric conditions.

The versatility of the bench makes it a valuable tool for the validation of future optical communication systems. Future work will focus on extending the range of emulated propagation scenarios. While the present work validated representative downlink conditions, further investigations will address LEO downlink and GEO uplink links, the latter remaining particularly challenging to reproduce realistically on the current setup.

Another major objective is the evaluation of predictive control strategies, including Linear Quadratic Gaussian (LQG) and reinforcement learning-based controllers [7]. These approaches are expected to reduce temporal errors under high apparent wind speeds while also mitigating mechanical vibrations, thereby improving adaptive optics performance, fiber-coupling efficiency, and ultimately communication performance for future optical ground stations.

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