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# Laboratory Validation of Sequential Optimization of Adaptive Receivers in Downlink Laser Communications

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## ABSTRACT

Adaptive atmospheric compensation in laser communication systems can be iteratively addressed minimizing the loop bandwidth requirements. Here we evaluate in the laboratory a speckle-based iterative technique within the framework of a communication scenario. Experimental results show significant coupling efficiency gain with a reduced number of iterations. Evaluation of the technique with an integrated 80 Gbps QPSK system shows an error probability of  $10^{-5}$  for highly turbulent atmospheric channels.

**Keywords:** Free-space optics, Adaptive optics, Iterative, Convex

## 1. INTRODUCTION

Earth observation satellites create massive amounts of information that must be downloaded to earth ground stations in the short time of a satellite pass. Today, much of the collected data must be dropped due to limited storage and lack of transmission bandwidth. Substantial operational and economic benefits may result from the possibility of solving this bandwidth limitation. The use of laser links can provide enough bandwidth, but it faces natural-imposed constraints mainly associated with the atmospheric turbulence. High data throughputs above 10 Gbps require a stable and efficient single-mode fiber coupling to integrate optical amplifiers and coherent receivers, allowing the implementation of advanced modulation formats.<sup>1,2</sup> However, the cumulative effect of the turbulence over longer optical paths induces sharp amplitude fluctuations and phase distortions on the beam wave-front. This affects the beam focusing leading to speckled intensity and deterioration of the bit error probability.<sup>3</sup> Consequently, adaptive wave-front compensation systems become relevant.

The standard turbulence compensation systems, based on adaptive optics, can overcome atmospheric limitations by adaptive tracking and correction of atmospherically induced aberrations. However, under strong-turbulence conditions the effectiveness of traditional adaptive optics systems is severely compromised.<sup>4</sup> In such scenarios, sensor-less techniques offer higher efficiency, robustness, hardware simplicity, and easiness of implementation at a reduced cost.<sup>5</sup> The drawback of the stochastic-based approaches is the high number of iterations required to perform the correction, exceeding the temporal coherence of the field and thus falling behind the field evolution.<sup>6</sup>

We have proposed and demonstrated in the laboratory a speckle-based iterative method for strong turbulence compensation that reduces the correction time.<sup>7,8</sup> In this paper, we briefly describe the method, the laboratory experiment, and results within the framework of a QPSK communication system.

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## 2. METHOD AND LABORATORY EXPERIMENT

This technique is based on the standard sensor-less system design, but it additionally uses a short-exposure focal intensity image  $I$  to accelerate the correction. Figure 1 summarizes the main steps of the technique, which combines basic principles of Fourier optics, image processing, and quadratic signal optimization to correct the distorted phase-front  $\varphi$  with an estimated  $\hat{\varphi}$ . This approach directly updates the phases  $\theta$  of the  $M$  most intense focal-plane speckles of peak amplitude  $b$ , each one modeled as a pupil plane wave of the type  $b \exp(j\mathbf{k} \cdot \mathbf{r} + \theta)$ , maximizing the power coupled  $\eta$  into a single-mode fiber. Each optimum phase shift  $\hat{\theta}_{\text{opt}}$  is estimated following a parabolic optimization process where three scalar phase variations  $\theta_{1-3}$  are applied to the plane wave, shaping the mirror and concurrently measuring the coupled power in the fiber  $\eta_{1-3}$ .<sup>9</sup> This process is repeated for each subsequent plane wave, keeping each previously optimized one fixed. As a result, the compensation of a distorted phase wave-front is done sequentially with a total number of iterations equal to  $3(M-1) + 1$ , which is directly proportional to the number of main intensity speckles. Throughout this process, the argument  $\hat{\varphi}$  of the plane wave summation approximates the wave-front distortion.<sup>7,8</sup>

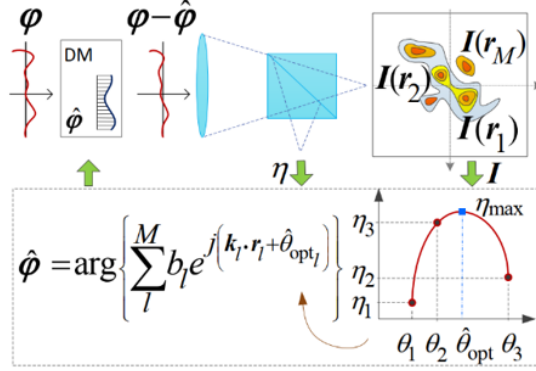


Figure 1. Main steps of the speckle-based iterative adaptive optics technique. Each main focal speckle is modeled as a pupil plane wave. The relative phase shift of each plane wave is estimated via the parabolic optimization of the coupled power. The argument  $\hat{\varphi}$  of the plane wave summation is used to shape the deformable mirror (DM) and compensate for the distorted phase-front.

The validation of the method in a communication scenario is performed in a laboratory testbed. The schematic of the setup is shown in Fig. 2. To emulate a laser downlink from a LEO satellite, one must consider that the laser is exposed to the turbulence in the last 20 km of the atmosphere, and the beam wave-front can be modeled as a plane wave. Here, a laser source is collimated to generate a free-space laser beam propagating towards the detector. The trajectory of the laser beam is represented with the arrows. The beam size is modified throughout the system using a set of three optical relay systems (R1-3). After the first relay (R1), the beam passes through an H-polarizer previous being reflected in a spatial light modulator (SLM), which is used to imprint the phase-only distortions in the wave-front. The SLM offers flexibility to imprint the desired set of phase-screens for different turbulent conditions. It also gives the possibility to repeat experiments and verify the performance with identical field states. After the SLM, the distorted beam is guided to a tip-tilt mirror (TTM) to correct the phase-front tilt. After the TTM, the beam is newly compressed with the relay (R3) to a diameter of 3.7 mm and split. One beam is focused on an infrared camera (CAM 1) with a 500 mm lens (L3) to obtain approximately  $28 \times 28$  pixels per speckle. This camera is used for the optimization process. The second beam is reflected in a membrane-based DM. Note that the CAM 1 is located before the DM to follow the speckle evolution throughout the correction. The beam reflected in the DM is split and focused on a single-mode fiber (SMF) and a second infrared camera (CAM 2). This camera is used to verify the evolution of the focal speckle pattern during the correction process, where a lens (L2) of 500 mm is selected to assure enough speckle resolution ( $18 \times 18$  pixels). For the SMF, a lens (L1) of 19 mm allows a maximum coupling efficiency of 60% when the wave-front is assumed with minimum aberration. The signal for the optimization process is measured with an avalanche photodetector (APD). The coupled power can be attenuated with a single-mode variable optical attenuator (VOA). The output electrical signal from the photodetector is acquired with a data acquisition system (DAQ).

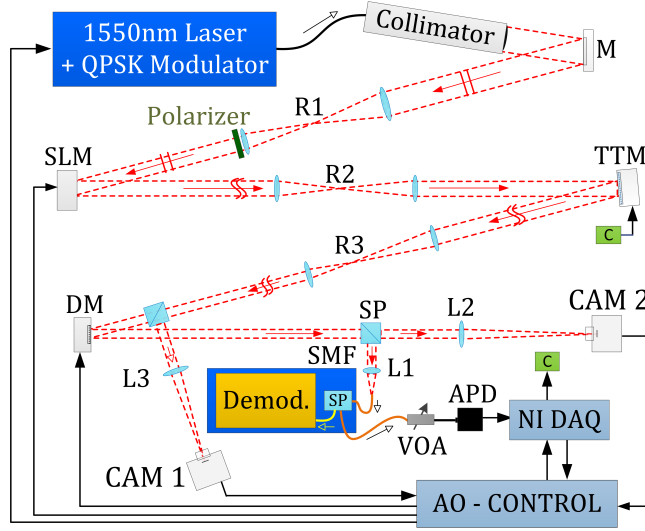


Figure 2. AO setup with the integrated coherent transmission system.

This setup is integrated with a coherent transceiver that modulates the laser carrier in Quadrature Phase Shift Keying (QPSK).<sup>2</sup> The modulation is performed at 40 Gbauds (80 Gbps). The coupled signal in the SMF is split, sending 90% of the signal to the QPSK demodulator, and 10% to the APD detector.

### 3. RESULTS

The performance of the AO technique in a communication scenario is experimentally tested using 200 uncorrelated fields in a non-real time regime. Each uncorrelated field is generated with the single-screen phase method<sup>10,11</sup> for the scenario  $D/r_0 = 6$ , which is representative of a satellite downlink at elevations near 10 with an aperture  $D = 40$  cm.<sup>12</sup> In our experiment, we use not less than 600 polynomials for an accurate statistical generation of each phase front.

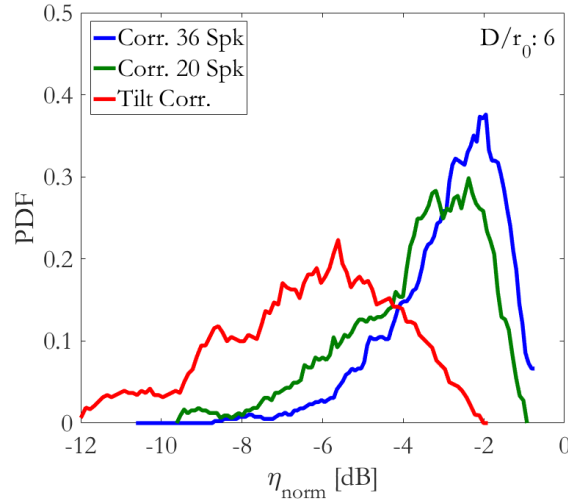


Figure 3. Experimental PDF of the coupling penalty for the scenarios  $D/r_0 = 6$ . Comparison between the correction with 36 speckles (106 iterations) and 20 speckles (58 iterations).

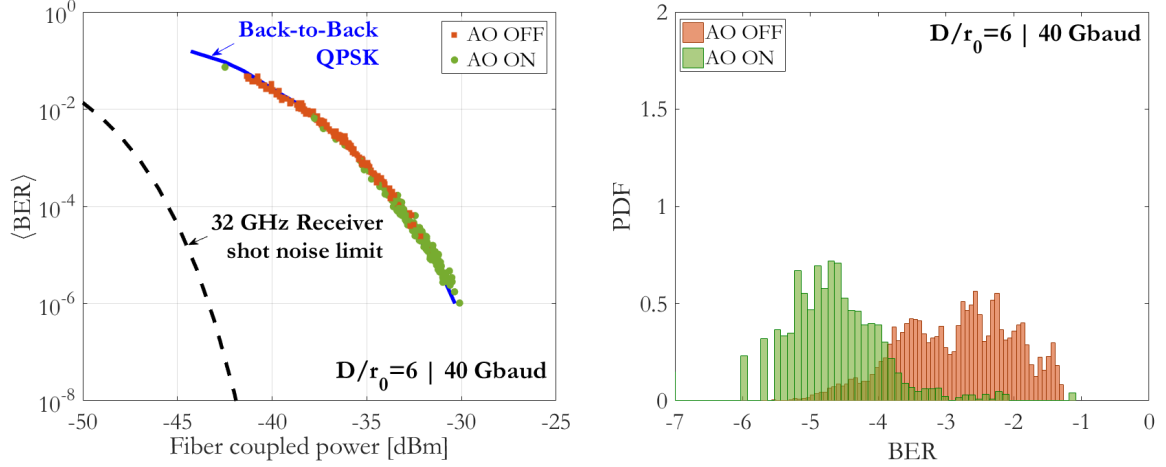


Figure 4. Receiver sensitivity measurement for a 40 Gbaud QPSK data transmission corrected by the AO system. PDF of the BER when the AO system is set on/off. The dashed curve represents the shot-noise limited ideal performance. The blue curve represents the back-to-back reference of the receiver.

Figure 3 shows the improvement in the variance of the normalized coupled signal in the fiber  $\eta_{\text{norm}}$  when the fields are corrected with  $M = 36$  (106 iterations) and  $M = 20$  (58 iterations) speckles. Here, the reduction in the number of iterations results in a slight increase of the signal variance, still maintaining a significant improvement with respect to the case where only the tilt is compensated.

To quantify the improvement in the communication channel, with each applied field the coupled signal is measured before and after the correction of 20 speckles (58 iterations). Concurrently, the mean Bit Error Ratio (BER) of the received data is measured. For each distorted field, 50 data sequences with  $10^6$  bits each are generated by a PRBS7 (pseudorandom bit sequence of size  $2^7-1$ ). Each data sequence is modulated in the laser carrier in QPSK at 40 Gbaud. In the receiver side, the signal is sampled with an oscilloscope at 80 GSample/s. Then, the sampled signal is saved for post-processing. The procedure is repeated after each field distortion is corrected with the algorithm. The post-processed 50 data sequences per field result in a mean BER value, one for the corrected state with the AO system activated (AO ON) and one for the uncorrected state (AO OFF). Both are plotted in Fig 4 and contrasted against the 40 Gbaud back-to-back reference curve and the ideal shot-noise limited curve (dashed black). The PDF of the BER, when the AO system is set on/off, is also shown in Fig 4.

The results show a better BER when the AO correction is performed, which confirms the increment in the SMF coupled power. The correction of the speckle results in an improvement in the quality of the beam, which increases the coupled power and reduces its variance, improving the BER by three orders of magnitude. Signal enhancement is achieved reducing the errors in the data transmission, as shown in the histograms.

#### 4. CONCLUSIONS

We have experimentally evaluated the speckle-based adaptive optics method in a communication scenario. A coherent QPSK system operating at 80 Gbps was integrated into the AO system, and BER tests were performed for turbulent scenarios.

The results show that the technique corrects distorted fields typical from scenarios of low-elevation satellite downlinks,<sup>12</sup> increasing the coupled power, reducing its variance, and leading to BER of  $10^{-5}$ . This BER is enough for FEC systems to deliver error-free data communications. Such performance is achieved with less than 60 iterations per corrected field, representing a 40% reduction in the bandwidth utilization of standard stochastic iterative methods.

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