

**ICSO 2016**

**International Conference on Space Optics**

Biarritz, France

18–21 October 2016

*Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik*



***Adaptive optics testbed for pre- and post-compensation of earth-to-geo optical communication: downlink results***

*N. Leonhard*

*R. Berlich*

*S. Minardi*

*A. Barth*

*et al.*



icso proceedings



## ADAPTIVE OPTICS TESTBED FOR PRE- AND POST-COMPENSATION OF EARTH-TO-GEO OPTICAL COMMUNICATION – DOWNLINK RESULTS

N. Leonhard<sup>1</sup>, R. Berlich<sup>1,2</sup>, S. Minardi<sup>2</sup>, A. Barth<sup>3</sup>, C. Reinlein<sup>1</sup>

<sup>1</sup>Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Straße 7, 07745 Jena, Germany

<sup>2</sup>Institute of Applied Physics, Friedrich-Schiller-University Jena, Albert-Einstein-Straße 15, 07745 Jena, Germany

<sup>3</sup>Control Engineering Group, Technische Universität Ilmenau, P.O. Box 10 05 65, D-98684, Ilmenau, Germany

### I. INTRODUCTION

Optical communication between optical ground stations (OGS) and geostationary (GEO) satellites is a promising technology for future high-speed data transfer between Earth and space. However, such optical communication links suffer from distortions caused by atmospheric turbulence. To explore adaptive optics mitigation of this effect both in the uplink and the downlink beam, we have developed an adaptive optics testbed. In an earlier publication [1], we reported on the results of uplink compensation. In this contribution, we wish to elaborate more on the efficiency of downlink compensation. Further, we will highlight the differences between uplink and downlink compensation.

The baseline scenario of our setup is shown in Fig.1. A GEO satellite sends a downlink beam to the OGS. Close to the OGS, the beam is distorted by optical turbulence. At the OGS, an adaptive optics system measures the wavefront distortions to post-compensate the downlink beam. Since uplink and downlink pass through the adaptive optics system simultaneously - only in reversed order - the uplink is additionally pre-distorted. The pre-distorted uplink beam exits the OGS and is distorted by the atmosphere. After passing through the atmosphere, it should have a plane wavefront and, therefore, the satellite should receive a homogeneous bright laser signal.

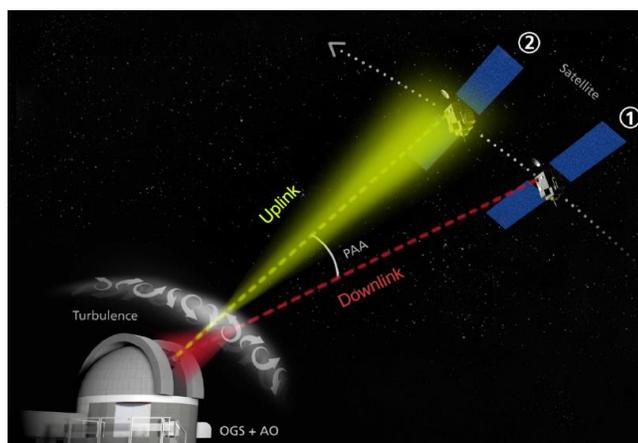


Fig. 1. Baseline scenario of our adaptive optics testbed, taken from [1]

### II. EXPERIMENTAL SETUP

#### A. Description of the setup

In the beginning of our project, we analyzed the baseline scenario and then designed a scaled-down version as our testbed assuming but not restricting ourselves to communication between Alphasat and ESA's OGS on Mount Teide, Tenerife. One important task was the analysis as well as the scaling of the local turbulence conditions which we based on night-time measurements carried out on Tenerife and reported in [2]. In particular, we recalculated the Fried parameter for the wavelength of 1064 nm and zenith angle of 56°. We will only report on our measurements with a Fried parameter of  $(14,3 \pm 1,8)$  cm for the given wavelength and zenith angle which is equivalent to that given in [2] minus one standard deviation (i.e. turbulence stronger than average).

In the following, we will give a short description of our system shown in Fig. 2; more details can be found in [1]. The downlink laser beam is collimated such that a plane wave enters the system similar to the downlink beam in the baseline scenario. After passing through the artificial turbulence introduced by the aberration emulator - a wet-etched glass plate, the downlink beam enters the system at the entrance pupil. Several

telescopes reimage the entrance pupil to the tip/tilt mirror, the deformable mirror and the Shack-Hartmann wavefront sensor. While the tip/tilt mirror is a commercial component, the 40-actuator deformable mirror was designed and manufactured in-house. To achieve a real-time system, we designed all components to allow for a high control loop frequency. In particular, we adapted our custom FPGA-assisted read-out of the wavefront sensor [3] to the newly acquired InGaAs camera. From the Shack-Hartmann spots calculated by the FPGA, control signals are derived for the tip/tilt and deformable mirror.

The uplink laser beam passes the adaptive system in reversed order. It is first collimated, deflected by the deformable mirror, reimaged to both the tip/tilt mirror and the entrance pupil. The uplink beam then passes the aberration emulator and a long-focus lens produces a far-field image of the uplink beam on a camera.

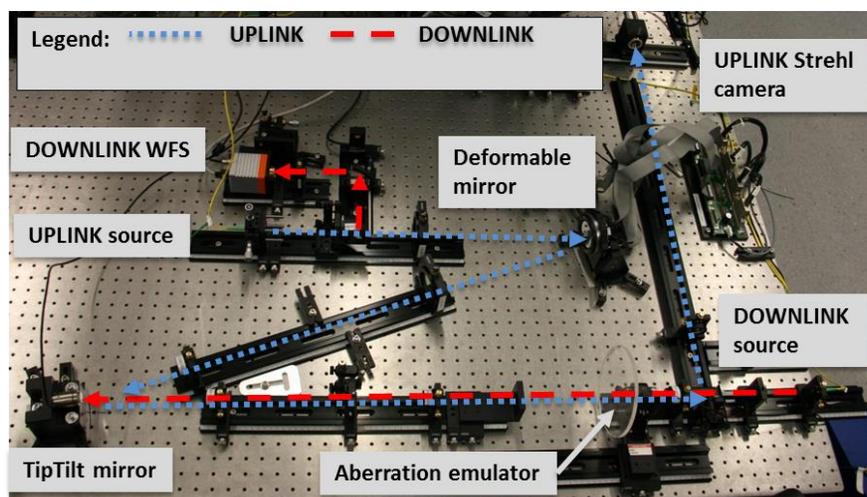


Fig. 2. Photograph of the experimental setup

### B. Evaluation of downlink performance

We used the spots measured with our Shack-Hartmann sensor to evaluate the performance of the downlink compensation. We consider both the Strehl ratio and the beam wander derived from the wavefront. Please note that we also include the beam wander in our definition of the Strehl ratio which is often neglected. An important quantity of our system is the reference wavefront, i.e. the wavefront that the controller tries to achieve by activating the tip/tilt and deformable mirror. Although uplink and downlink beam were very carefully aligned, a plane wavefront of the downlink did not yield an optimal Strehl ratio at the uplink camera. We decided to optimize the reference wavefront of our controller to achieve an optimal *uplink* beam. Thus, the Strehl ratio given in the following determines how well the controller was able to achieve the reference wavefront rather than a plane one.

## III. DOWNLINK COMPENSATION RESULTS

The evolution of the Strehl ratio over time with and without control is shown in Fig. 3. Without control (blue line), the Strehl ratio is always close to zero, sometimes achieving values up to 30%. On average it is as low as  $(6,4 \pm 6,4) \%$ . With control (red line), the overall Strehl ratio is much higher, achieving values above 80% and on average  $(60 \pm 19) \%$ . Still, there are dips in the Strehl ratio where it drops to very low values. We aim to reduce this effect by a further optimization of the control algorithm which was mainly optimized with respect to the uplink beam.

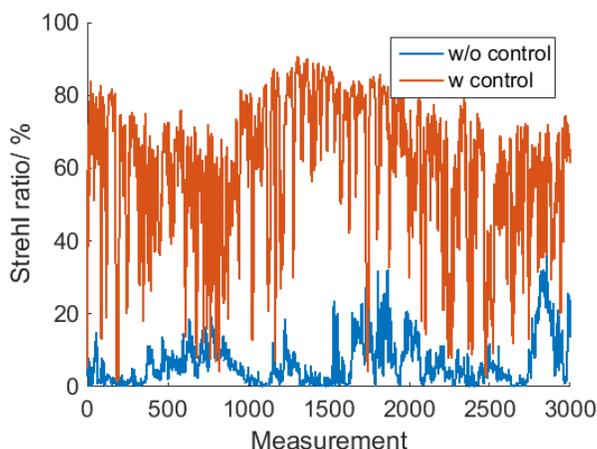


Fig. 3 Strehl ratio of the downlink beam

To evaluate the residual beam wander after correction, we analyzed the position of the beam’s centroid. As in our earlier publication [1], we analyze the cumulative distribution function (CDF) of the beam’s centroid position which is shown in Fig. 4. Basically, the CDF gives the proportion of measurement points with a beam wander smaller than or equal to a certain value. As a reference, we have chosen the half-width-at-half-maximum (HWHM) of the diffraction-limited beam

$$\beta_{HWHM} = 0.51 \frac{\lambda}{D_{Tel}}. \tag{1}$$

Consequently, if tip/tilt were the only aberration present, the CDF at the HWHM corresponds to the number of data points where an intensity of at least half of the maximum intensity is measured by the camera. One can see in Fig. 4 that without control merely 19 % of the data points have a beam wander below the HWHM. In contrast, with control the majority of the data points (90%) have a beam wander below this value. This shows the effectiveness of our tip/tilt control on the downlink beam.

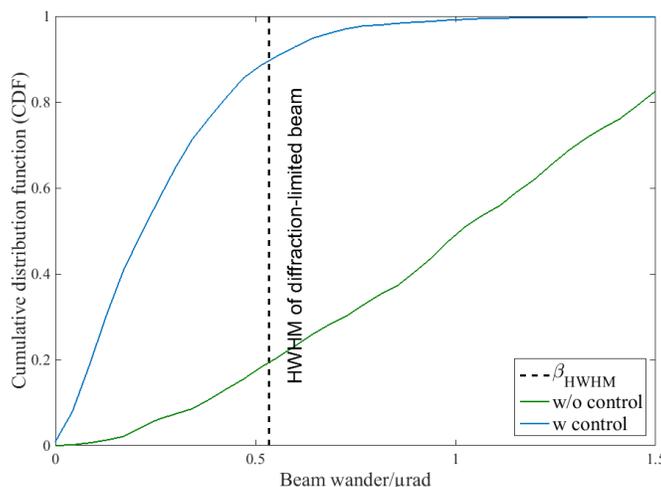
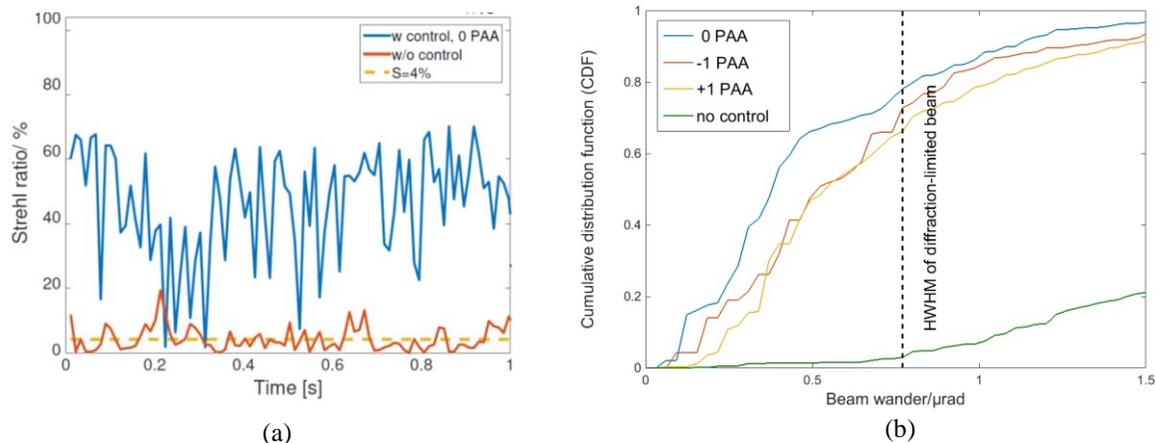


Fig. 4 Cumulative distribution function of the downlink beam wander (scaled to the baseline scenario telescope diameter)

#### IV. COMPARISON OF DOWNLINK AND UPLINK PERFORMANCE

As already mentioned, we found some differences in the performance of the uplink and the downlink beam. Fig. 5 shows the measurements obtained for the uplink beam which were presented in [1]. Both in the measured Strehl ratio (a) and the beam wander (b), we find that the effect of turbulence is much more severe. Additionally, we find that the compensation of the uplink cannot achieve Strehl ratios as high as in the case of the uplink beam and beam wander is also higher.



**Fig. 5** (a) Strehl ratio of the uplink signal over time. (b) Cumulative distribution function of the beam wander. Both (a) and (b) were taken from [1]

## V. CONCLUSIONS

In summary, we have shown new results on the compensation efficiency of our AO testbed which emulates Earth-to-GEO optical communication. In addition to our previous publication, we have evaluated the compensation of the downlink beam and compared these results to the uplink beam results in [1]. Overall the downlink beam is slightly less distorted than the uplink beam in terms of both the Strehl ratio and beam wander. Furthermore, the achievable correction of the downlink beam is also better than for the uplink beam. In the future, we want to investigate these differences in more detail.

## REFERENCES

- [1] N. Leonhard et al., “Real-time adaptive optics testbed to investigate point-ahead angle in pre-compensation of Earth-to-GEO optical communication”, *Opt. Expr.*, vol. 24, pp. 13158-13172, June 2016.
- [2] B. García-Lorenzo, A. Eff-Darwich, J. J. Fuensalida, and J. Castro-Almazán, “Adaptive optics parameters connection to wind speed at the Teide observatory: corrigendum,” *Month. Not. Royal Astronom. Soc.* 414(2), pp. 801–809, 2011.
- [3] S. Mauch, A. Barth, J. Reger, C. Reinlein, M. Appelfelder, and E. Beckert, “FPGA-accelerated adaptive optics wavefront control part II,” *Proc. SPIE* 9343, 93430Y, 2015.