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Demonstrated pre-compensation of a focused laser beam with up to 0.27 mrad point-ahead-angle over a 1 km horizontal communication path

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1. ABSTRACT

In the development of laser communication networks, atmospheric turbulence remains an obstacle in the efficiency optimisation of bidirectional optical links. Post-compensation of the downlink signal through adaptive optics (AO) has been verified as a method of increasing the efficiency of satellite-to-ground optical links, however, similar efficiencies have yet to be achieved in the opposite direction (uplink) largely due to the shower curtain effect and the consequent impossibility of conducting post-compensation over the smaller receiver aperture at the satellite terminal. Pre-compensation is anticipated to be a promising method of increasing the efficiency in uplink communications for Earth-to-GEO optical feederlinks, by pre-distorting the uplink wavefront prior to propagation through the atmosphere using measurements of the downlink. Here, we present the recent modifications to our current experimental setup and initial results of a pre-compensation experiment conducted over a 1 km horizontal path. The experiment aimed to investigate pre-compensation under a point-ahead-angle for the special case of a focussed uplink beam. Two optical terminals were developed, a “ground terminal breadboard” (GTB) consisting of a commercially available 30 cm reflective telescope in combination with an AO-box [3] capable of simultaneous post-and pre-compensation and a “satellite terminal breadboard” (STB) with separate transmission and receiving apertures for measurement of the uplink beam under a point-ahead-angle (PAA). We present a first look at and discussion of the experimental results which show that AO pre-compensation increased the measured intensity of the uplink beam over the receiving aperture of the STB for a PAA of up to 0.27 mrad.

Keywords: adaptive optics, pre-compensation, laser communication

2. INTRODUCTION

Adaptive optical pre-compensation refers to the predistortion of an optical signal so that following propagation through a turbulent medium, the wavefront is optimized at the target. It is based on the reciprocity principle and can be achieved by measuring and applying via adaptive optics the aberrated wavefront of a beacon or incoming beam (downlink) to that of an outgoing beam (uplink) which travels through the same atmospheric turbulence. Pre-compensation is anticipated to be a promising method of increasing the efficiency in uplink communications for Earth-to-GEO optical feeder links. Until now, pre-compensation research has largely been implemented via simulation¹⁻⁴ or in laboratory setups using emulated aberrations^{5,6}. Before it can be integrated into optical feeder link systems it requires extensive experimentation using real atmospheric turbulence. In 2016, this group integrated our adaptive optical (AO) system as developed in laboratory conditions into a portable AO-box and successfully demonstrated pre-compensation using real atmospheric turbulence over a horizontal 0.5 km path. Development of the experimental system has culminated in a second measurement campaign which has furthermore allowed for the measurement of pre-compensation under a point-ahead-angle (PAA). Here, we present the changes to the setup which have improved the system reliability and allowed for additional methods of analysis and the remote operation of the system.

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In section 2 we present the baseline scenario and summarise our experiments to date, in section 3 we discuss the system modifications which have been implemented, in section 4 we present the most recent measurement campaign and take a first look at one measurement sequence from that campaign and in section 5 we present our conclusions.



Figure 1. The original STB during a measurement campaign in Berlin, November 2016.

3. BASELINE SCENARIO AND PREVIOUS EXPERIMENTS

The baseline scenario and the application towards which pre-compensation is in this instance being advanced, is vertical Earth-to-GEO communication and integration in an optical feederlink terminal. As a pre-cursor to Earth-to-Satellite communications experiments, horizontal experiments over shorter distances are a necessary developmental step. They are also fundamentally different from the application scenario due to the layer structure of atmospheric turbulence. Accurate representation of the shower curtain effect is not possible over a horizontal path of relatively constant turbulence strength. In order to better approach the application scenario, instead of using plane wave propagation we altered the beam geometry in order to limit the effects of atmospheric turbulence with propagation. We implemented this using a downlink beam which acted as a beacon and expanded in space due to diffraction and atmospheric turbulence and a focused uplink beam. We have selected this hypothesis as the ratio of beam diameter to the Fried parameter, D/r_0 , and consequent atmospheric wavefront aberrations changes with propagation distance so that turbulence had a greater influence near the optical terminal which represented the ground station⁸. This approximation will be discussed in future publications. The optical terminals which were used in this experiment have been outlined^{7,8} and the adaptive optics system has been detailed⁶. A wavelength of 1064 nm and circularly polarized light during propagation was chosen to match the Alphasat laser communication terminal (LCT) which we hope may prove to be a future communication partner.

A starting point for the system changes outlined here coincides with the system as it is described for our November 2016 measurement campaign⁸. The adaptive optics loop is based on measurements of the downlink wavefront using a Shack-Hartmann wavefront sensor (WFS) and is implemented using tip tilt and deformable mirrors (TTM, DM). The optical terminals consist of a ground terminal breadboard (GTB) including the AO-box and 8" consumer telescope and a satellite

terminal breadboard (STB) consisting of a downlink source and uplink analysis camera. The STB as it was in November 2016 is depicted in Figure 1.

Experimental results established that adaptive optics pre-compensation delivered a 7.1 decibel increase in received intensity at the satellite terminal under a small PAA of $28 \mu\text{rad}^8$, however, this result was limited by a number of design and systematic limitations which presented themselves during the measurement campaign.

4. SYSTEM MODIFICATIONS

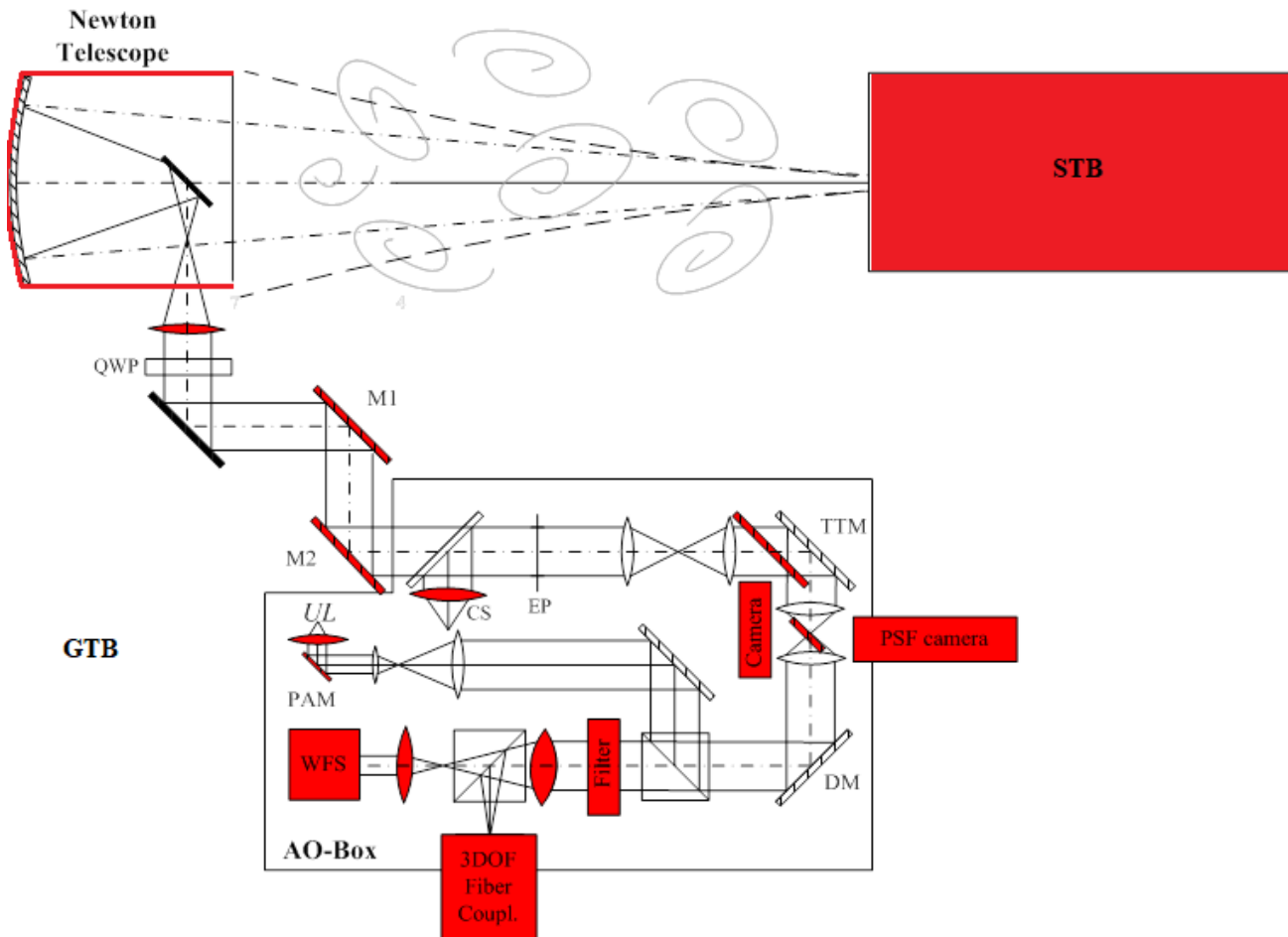


Figure 2. A simplified sketch of the experimental setup. Element positions and sequences are approximate. Some of the most significant modifications to the setup are indicated in red. The STB underwent a complete redesign. The GTB now includes a new 12" telescope courtesy of ASA GmbH. The interface optics were consequently changed, and the mirrors M1 and M2 in the periscope are now motorized. Two extra cameras (Camera, PSF camera) have been included to allow for fine alignment of these two mirrors. A filter wheel has been integrated in the wavefront sensor (WFS) path and the WFS itself is now integrated in a way which increases the long term stability, reducing the frequency of alignment. Additionally, a motorized 3 degrees of freedom fiber coupling unit has been included, which will allow for future integration in communication experiments. STB = satellite terminal breadboard, GTB = ground terminal breadboard, QWP = quarter-wave plate, CS = calibration source, EP = entrance pupil, TTM = tip tilt mirror, DM = deformable mirror, PAM = point ahead mirror, UL = uplink source.

A number of changes have been made to the experimental system. The GTB modifications enlarged the system aperture, enhanced the mechanical stability and advanced the system towards an optical feeder link application scenario. Elements of the GTB which were changed or replaced are indicated in red in figure 2. Meanwhile, the STB underwent an almost complete optical design and mechanical overhaul. A summary of these changes is presented below.

4.1 Improved Analysis Methods

For the first experiment using real turbulence, infrared cameras were chosen for analysis, enabling easier alignment and facilitating easier measurement small changes to the PAA between the terminals. The limited dynamic range of the camera presented a drawback of this approach and the dramatic difference between measurements with and without compensation lead to overexposure as has been documented⁸. As an alternative analysis method and developmental step towards the application scenario, we have adapted the infrastructure to allow for AO analysis with fiber coupling systems and power meters instead of cameras in both the GTB and STB. This removes the constraints of the cameras' dynamic range and allows for future integration in existing digital communication infrastructure.

4.2 Mechanical Solutions for the GTB

The universal nature of the AO-box is achieved by the conjugation of all AO elements and the telescope aperture to the entrance pupil of the box. This offers itself to coupling with any telescope, provided the correct choice of interface optics and mechanics. We were provided the opportunity to replace the GTB telescope, an 8" Meade LX200-ACF F/10 telescope with a 12-inch ASA Astrograph N200 Newton telescope, courtesy of Astro Systeme Austria GmbH (ASA). The F/3.6 telescope is of much higher quality and increases the receiving aperture of the downlink beam while increasing the theoretical resolution of the focussed uplink beam.

Motorized alignment of critical system components reduces the necessity of human contact with the box allowing for faster and more stable alignment. As an initial step, we made a replacement of manual mounts which were most prone to losing their stability with high quality motorized ones. This allows for a more stable system and facilitates operation of the system remotely, reducing the risk of accidental misalignment. The ASA Astrograph 12" F/3.6 was provided with the Direct Drive DDM85 Standard Mount with motorized right ascension and declination axes and Autoslew software, facilitating high accuracy pointing and tracking and for our purposes, enabled the motorized alignment of the AO-box and telescope. Additionally, the periscope in the telescope to AO-box interface optics (Mirrors M1 and M2) was also motorized for tip and tilt which allowed remote fine alignment of the complete telescope and AO-box optics via the use of the two new cameras, one for the point spread function (PSF) and one for the collimated beam. The Standa 8MBM24 motorized mirror mount were selected for this purpose, with a resolution of less than 1 arcsecond and a large tilt range of +/- 4:50. This almost completely removes the need for physical human contact during alignment of the interface optics, the one exception being the need to introduce and remove the flip mount mirrors which have been added to the original optic design in order to divert the beams to the alignment cameras.

The point ahead mirror (PAM) mount was also replaced with the motorized mirror mount Standa 8MKVDOM-1 to allow for a larger positioning range of an effective +/- 7 mrad at the ASA telescope aperture.

The 5 degrees of freedom stage used to support the wavefront sensor (WFS) is necessary for precise alignment, but suboptimal mechanical loading of the element in the original mechanical design lead to loss of alignment. This was amended by a slight change to the optic design which allowed for hanging of the stage from the edge of the AO-box breadboard and consequently a better weight distribution.

4.3 STB Redesign

The new STB design addresses operational difficulties of the previous design, such as back reflections, long term mechanical stability and allows for measurement of large PAAs with variable displacement of the transmitting aperture and receiving aperture by up to 50 cm. For a 1 km separation of the GTB and STB, this allows for measurement of up to 0.5 mrad. The STB has been split into two subsystems - the STB DL which included the transmitting downlink laser and facilities for measurements of the uplink without a PAA, and the STB UL for measurement of the uplink signal under a PAA.

4.4 The STB DL

In the original STB design, the downlink beam was provided by a collimated laser beam with a polarizer and analysis of the uplink beam was made using a 10:1 telescope and an infrared PSF camera. The downlink and uplink channels were separated via a polarizing beam splitting cube with an anti-reflection coating which lead to on-axis back reflections of the downlink in the uplink analysis camera. These reflections exceeded the uplink signal in intensity and could not be excluded via apertures. Changes to the optical design have avoided the use of a polarizing beamsplitting cube instead using a plate, enabling the separation of the back reflections from the optical axis and providing the opportunity to use a field stop. Additional optics have been included to allow for variable divergence of the downlink beam and the rough alignment of the entire STB and GTB has been simplified by the inclusion of a VIS camera for greater pointing accuracy.

4.5 The STB UL

In order to measure large PAA values, a second aperture with variable position was necessary. This is achieved using a mirror which is mounted on a motorized linear stage diverting the uplink signal into the STB UL box via a second mirror. In order to correct the internal angular error which arises from changing PAA, the first two mirrors in the path are motorized for tip and tilt. For analysis of received light, we integrated a powermeter (Thorlabs PM100 with S122C Sensor).

4.6 Environmental Insulation

In our previous measurement campaign, experienced temperatures were in the range of -40 C to +100 C and unsettled conditions such as rain, wind and fog were frequent. Both terminals must be equipped for relatively high exposure. It was seen that the laser diode temperature controllers could not maintain a temperature of 150 C when the environmental temperature was below approximately 50 C, leading to an unstable laser source. In order to most efficiently solve this problem and to avoid overheating of the atmosphere surrounding the terminals contributing to additional artificial turbulence, we used smaller heating elements and 3D printed insulation boxes specifically for use with the laser diodes.

The STB container was not bolted down, and therefore relatively unstable. It was our experience that a small redistribution in weight, such as when a person in the container stood up, lead to a loss of alignment. Though these conditions are specific to this measurement site, it was further motivation for the remote control of the optical setup. Remote control also permits for isolation of the optics with a more robust dust and water proof housing, allowing for greater choice in the location of future measurement campaigns.

5. LATEST MEASUREMENT CAMPAIGN

5.1 Measurement Campaign

The most recent measurement campaign took place in Germany in late 2017. It was performed on a horizontal 1 km path, over a largely green landscape. Local weather conditions were recorded including air temperature, wind, air pressure and humidity. Measurement times were typically in the evening in the absence of daylight.

The coarse alignment of the system was aided significantly by the integration of the VIS camera in the STB as well as the motorised and controlled ASA telescope in the GTB. Overall mechanical stability was satisfactory enough that the coarse alignment needed to be performed at most once per day. The time required for fine alignment of the GTB was also reduced through the use of the motorised periscope optics and additional beam and PSF cameras. The overall mechanical stability at the GTB was greatly improved on that of November 2016, so that realignment over the course of a measurement day was largely unnecessary.

The scientific goal of the measurement campaign was to investigate pre-compensation under a PAA. Here, we present a first look at a sample measurement sequence for a PAA of 0.273 mrad, corresponding to a displacement of the transmission aperture and receiving apertures of approximately 27 cm at the STB. We compare consecutive measurements with and without compensation at both the GTB and STB. Post-compensation and the general functioning of the AO is analysed using a Zernike analysis of the reconstructed wavefront as measured at the GTB. Pre-compensation is analysed using powermeter measurements from the STB UL. At the time of the reported measurement weather conditions were cold (2.5 °C) and calm (1007 hPa) with little wind (< 3 km/h).

5.2 Downlink analysis

The downlink analysis has been made by performing a Zernike polynomial deconstruction of the reconstructed wavefront as recorded in the AO-box of the GTB. Figure 3 presents the results of this analysis for a sample measurement sequence with (blue) and without (orange) AO compensation. The black line represents a derived theoretical value for D/r_0 equal to 1^9 . A best fit of the measurement without AO compensation suggests a value of D/r_0 of 5.8, corresponding to a r_0 value in space of 5.2 cm. The blue curve corresponds to a D/r_0 value of 0.4, indicating that the use of AO improved the effective D/r_0 by approximately 5.3. It can be seen from this measurement that the AO was particularly effective in the compensation of modes 5 to 8, astigmatism and coma.

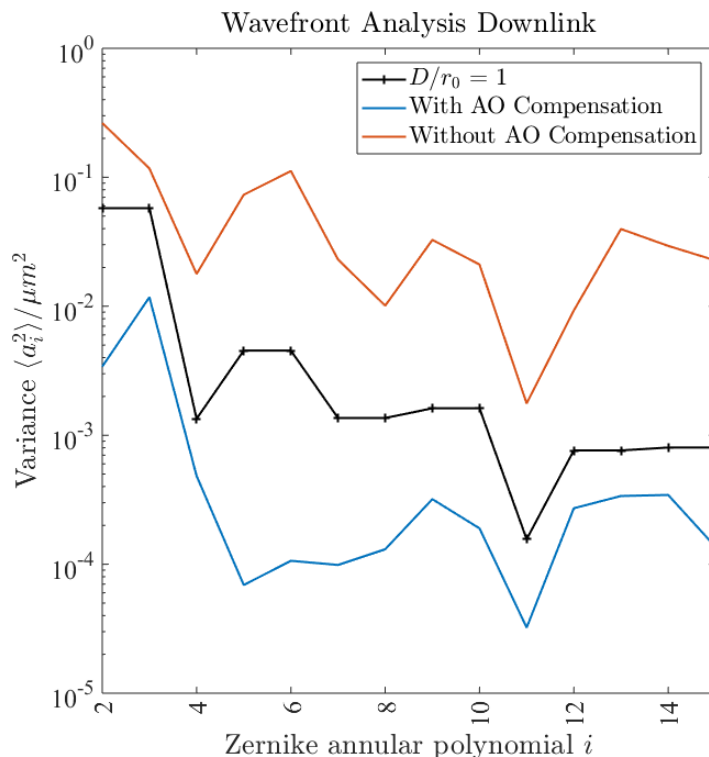


Figure 3 The wavefront as measured with the WFS was first reconstructed and then deconstructed as part of a Zernike annular polynomial analysis. The results were then compared to theory as indicated in black for $D/r_0 = 1^9$. In blue, the compensated wavefront analysis has a best fit D/r_0 equal to 0.4 whereas the uncompensated wavefront in orange has a best fit D/r_0 equal to 5.8.

5.3 Uplink Analysis

In Figure 4, measurements of the power received at the STB under a PAA of 0.273 mrad are plotted. The orange curve represents the measurement in the absence of pre-compensation and was made simultaneously to the measurement in Figure 3. The blue curve represents the measurements taken with pre-compensation, and likewise corresponds to the blue curve in Figure 3. The mean value of each curve is depicted with a broken black line. The time scale is relative to each measurement, as they were not performed simultaneously.

With the application of pre-compensation, the overall mean power is increased from 58.6 μW to 136.6 μW or 3.7 dB. The absolute standard deviation of the measurement is also reduced from 40.2 μW to 32.8 μW . There has been an overall increase in the received power and a measurable increase in the stability of the signal.

This is a single sample measurement sequence at a large PAA of 0.273 mrad. During the measurement campaign, measurements were performed with a PAA of up to 0.32 mrad, at which no further benefit of pre-compensation could be measured. While these results are preliminary, they are very promising for the application of pre-compensation and moreover, they support the hypothesis of using focussed uplink beams in horizontal turbulence scenarios for the sake of increased PAA.

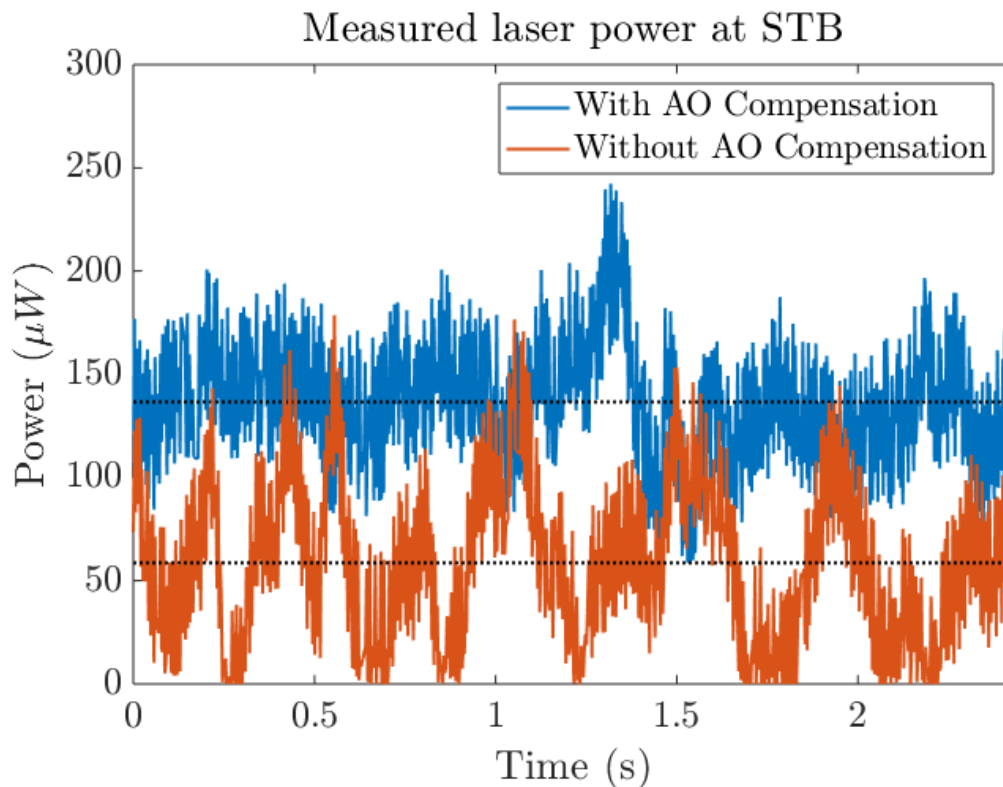


Figure 4 A sample sequence with AO pre-compensation (blue) and without (orange) for a PAA of 0.273 mrad, corresponding to the same measurement sequence as is depicted in Figure 3. The mean value of each data set is depicted with a broken black line. Pre-compensation has increased the mean power measured from 58.6 \pm 40.2 μW to 136.6 \pm 32.8 μW .

6. CONCLUSIONS

After successful demonstration of pre-compensation during a previous measurement campaign, the experimental setup was modified to improve its functionality and mechanical stability in the interests of one day performing a satellite communication experiment and furthermore to allow measurement of large PAAs over horizontal measurement campaigns. Motorization of key elements has led to a system which can largely be remotely operated, has simplified alignment routines and increased stability. A large 30 cm Newton telescope has enlarged the receiving aperture for the downlink signal and increased the theoretical resolution for the focussed uplink. Use of the AO-box with this telescope has confirmed its potential for universal integration. A redesign of the STB allows for measurement of large PAAs with a displacement of the uplink and downlink of up to 50 cm and has resolved earlier measurement difficulties.

These changes to the system culminated in a measurement campaign over a 1 km test range. A sample measurement sequence is presented which demonstrates the efficiency of the adaptive optical compensation at the GTB and the simultaneous increase in the received power at the STB. In this measurement sequence, it could be shown that the effective D/r_0 was reduced from approximately 5.8 to 0.4 at the GTB and the received power at the STB had a 3.7 dB increase, even under a large PAA of 0.27 mrad. The demonstrated 7.1 dB increase in intensity in our last measurement campaign⁸ was for half the propagation distance and only 10% of the PAA, albeit under turbulence conditions which are somewhat more favourable (r_0 of 5.2 cm as compared to 2.9 cm).

These results represent an intermediate step in our overall measurement campaign analysis and provide strong evidence for the efficacy of pre-compensation through AO generally and for the use of focussed beams in short range horizontal communication scenarios.

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