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Adaptive Optics pre-correction for Optical Feeder Links – breadboard performance

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ABSTRACT

For the next generation of very high throughput communication satellites, TNO and DLR envision optical free-space communication between ground stations and geostationary telecommunication satellites to replace the traditional RF links. To mitigate atmospheric turbulence, an Adaptive Optics (AO) system will be used to apply uplink pre-correction. OFELIA, an ground terminal breadboard was developed to demonstrate the pre-correction principle over an realistic link. Currently, integration tests have been performed to verify the AO performance. Also a laser link experiment over 10 km distance has already been established, in a scenario relevant to ground-to-satellite links. The paper shows that AO is clearly beneficial for the downlink performance. In addition the first preliminary experimental results of the pre-correction show it is also beneficial for the uplink.

Keywords: Optical satellite communication, adaptive optics, wave front sensor, deformable mirror

1. INTRODUCTION

Achievable data rates for satellite communications based on radio frequencies (RF) will very soon reach its limits, due to the limited availability of the RF spectrum [1]. In order to overcome this limit for bi-directional links between ground stations and very high throughput satellites at geostationary orbits, TNO and DLR envision optical free-space communication [2], [3]. Currently, an optical ground terminal (OGT) is being designed by TNO for terabit/s optical feeder links, with a physical layer for the communications system, which is developed by DLR.

In an optical channel, atmospheric turbulence induces strong signal fluctuations. This limits the minimum available optical power at the receiver, which can degrade the communications performance in terms of throughput and bit error rate (BER). Therefore, atmospheric turbulence has a large impact on the link loss. This implies either to increase the optical power of the transmit beam or to mitigate the loss due to atmospheric turbulence.

Adaptive optics (AO) has been proposed to mitigate the atmospheric turbulence in various publications, for instance [4]. In Figure 1 (a) the AO system is presented, which effectively pre-corrects the optical wavefield before it travels through the turbulent atmosphere, via a wave front measurement over the downlink beam [5]–[7]. This will lead to an improved signal stability at the satellite receiver.

Pre-correction AO is based upon the reciprocity principle, which is only partly fulfilled for optical feeder links. Due to the point ahead angle (PAA), the downlink beam partly travels through different atmospheric turbulence than the uplink beam. This causes the performance of the pre-correction to be limited due to the turbulence isoplanatic angle (IPA). The consequence on the link budget is estimated by analytic formulas in [5]. A lab demonstration is presented by [6]. And in [7] the AO performance is evaluated at an outdoor test site for a single PAA and over a relative short distance.

The experiments presented in this paper, aim to evaluate the AO pre-correction performance over a significantly longer link distance and a broad range of PAAs. The AO performance of the ground terminal breadboard (GTB) is evaluated in

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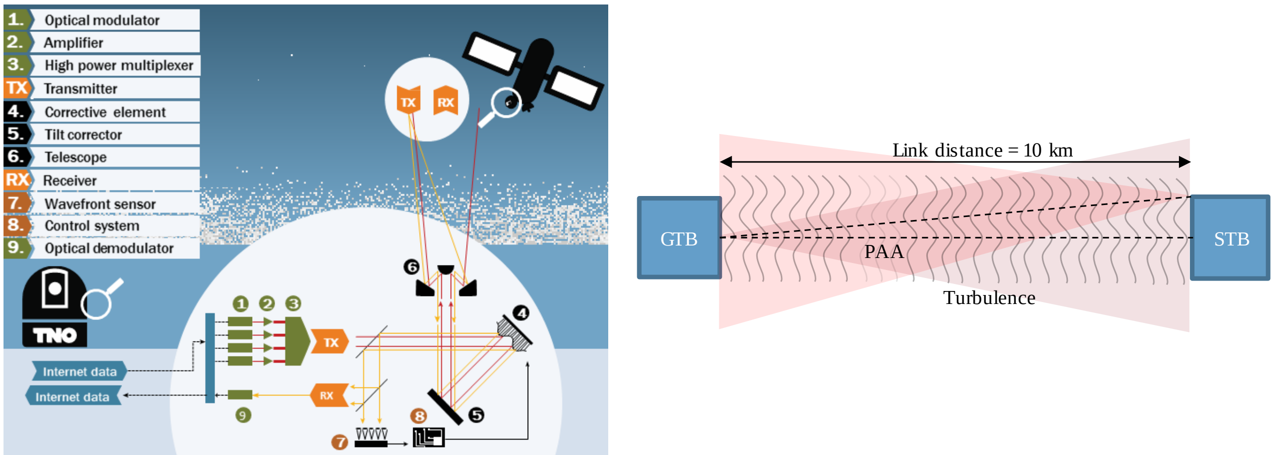


(a) (b)

Figure 1 (a) Schematic overview of the optical feeder link adaptive optics system (b) the experiment with the ground terminal breadboard (GTB) and space terminal breadboard (STB).

laboratory conditions, and over the downlink path. In addition, the effect of irradiance fluctuations over the uplink path, received by the space terminal breadboard (STB) is presented.

2. OPTICAL FEEDER LINK ADAPTIVE OPTICS (OFELIA) BREADBOARD PLAN

Pre-correction of the uplink beam is based upon the measured wave front distortion of the downlink beam, as depicted in Figure 1 (a). The deformable mirror is placed in the common path of the transmit and receive beam. Besides the improvement of the point spread function of the downlink beam, its correction will also pre-distort the uplink beam. By the reciprocity principle, the pre-distortion will correct for the uplink beam, provided that the downlink beam travels through the same atmospheric turbulence as the downlink.

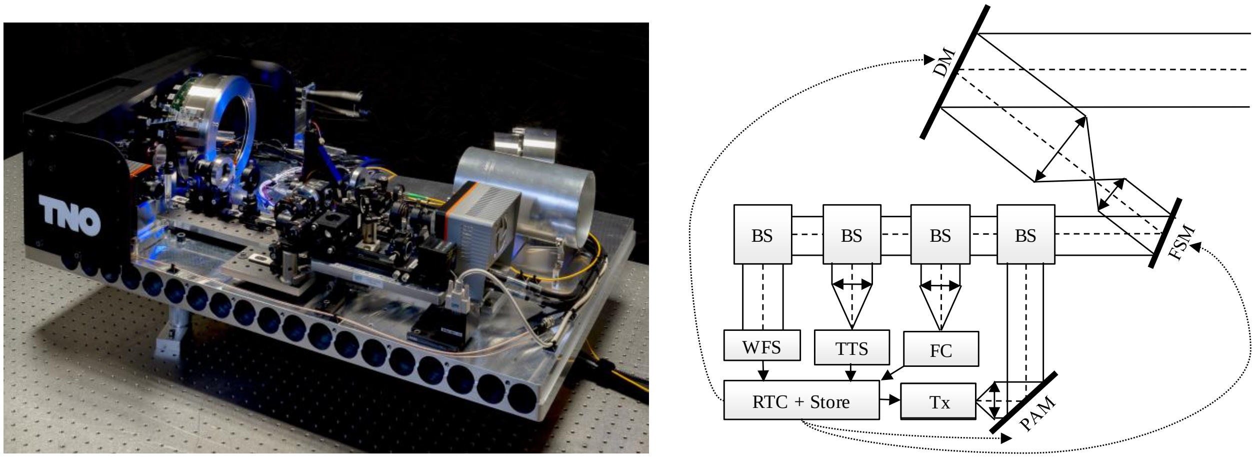
A clear compromise on the reciprocity principle is the presence of the point ahead angle (PAA), which indicates the angle between the uplink beam and the downlink beam, indicated in Figure 1 (b). This causes the downlink beam to partly travel through different atmospheric turbulence column than the uplink beam. The degree of correlation between the turbulence-induced wave front distortions can be characterized by the IPA. Since the degree of correlation is inherently coupled to the possible AO performance, the combination of the PAA and the IPA forms the fundamental limit of the AO pre-correction performance in the uplink.

The main goal of the optical feeder link adaptive optics (OFELIA) breadboard experiments as presented in this paper is to prove that AO precorrection is effectively improving the uplink performance. To this end, this has been formulated in 4 sub-goals. First, the ground terminal breadboard (GTB) is tested as a predecessor of the optical feeder link product. Second, adaptive optics and turbulence models will be verified under real turbulence conditions. Third, to better understand the validity of reciprocity principle. And fourth, to understand the effect of the PAA on the AO performance.

2.1 Test description

Since the OFELIA GTB is designed as a predecessor of a ground terminal product it uses a system architecture close to the intended product. One of the main risks identified in the project is the validity of pre-correction AO. Although it is well known that AO works for a downlink, pre-correction AO has not been tested over a relevant link distance with optical turbulence. Since high throughput data communication over a turbulence channel is known to be feasible [8], data communication functionality is omitted for these tests. Instead, the breadboard tests will focus on the full AO correction chain for a bi-directional link.

The design of the optical feeder link terminal is based upon models of the AO system and the atmospheric turbulence. The turbulence modeling for downlink purposes is widely known from astronomical observations, but in combination with AO over the return path, only limited literature is available. It is therefore important to have a situation which is sufficiently realistic towards an optical feeder link. Cn2 profiles, such as the HV57 model, show most dominant turbulence at the ground level, with one or more turbulence layers, typically at a few km's altitude. A test range of 10 kms seems a valid approach to have the realistic propagation effects and wave front errors. The turbulence parameters, such as the angle of



(a) (b)

Figure 2 OFELIA breadboard (a) fully integrated breadboard (b) schematic overview of the breadboard with several beam splitters (BS), a focus camera (FC), a tip-tilt sensor (TTS), a wave front sensor (WFS), a real time computer (RTC), the transmitter (Tx), the point ahead mirror (PAM), the fast steering mirror (FSM) and deformable mirror (DM).

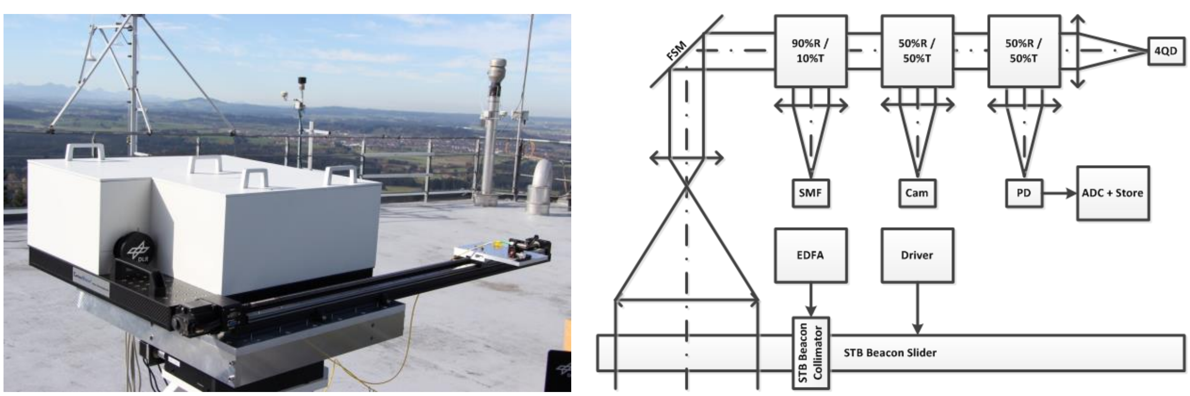
arrival, the scintillation index and the wave front error are measured with a wavefront sensor (WFS) at the GTB and the photo detector (PD) at the STB, so they can be compared with modeling results.

To measure the turbulence effects, the aperture sizes of the GTB and STB are adapted to the expected coherence radii of the turbulence. The GTB receiving aperture is dimensioned to receive multiple coherence radii of turbulence atmospheric distortion. On the STB side, the size of the aperture is sufficiently small to limit aperture averaging, but large enough to collect a sufficient amount of photons. The optical feeder link is supposed to work at a variety of turbulence conditions, to guarantee robust link performance. Hence, the test campaign has a duration of multiple days, and includes day and night conditions to cover this variation in conditions.

The effect of the PAA and the impact of number of AO modes on the achievable AO performance is evaluated at the STB and GTB. The impact on the AO correction is measured with the irradiance sensor on the STB and the wave front sensor at the GTB. The irradiance at the STB will give the main input of the validity and usefulness of the reciprocity principle.

2.2 Ground terminal breadboard description

Figure 2 shows the OFELIA GTB is equipped with a fast steering mirror (FSM) and a tip tilt sensor (TTS) to correct for tip-tilt aberrations [3]. The deformable mirror (DM) and the wave front sensor (WFS) corrects the high order wave front aberrations. The PAA is applied by a point ahead mirror (PAM). Also a focus camera (FC) is added to monitor the downlink



(a) (b)

Figure 3 STB picture and schematic overview, with a single mode fiber (SMF), erbium doped fiber amplifier (EDFA), Focus camera (CAM), 4 quadrant detector (4QD), a photodetector (PD), the transmit beam (Tx) a slider to generate a point ahead angle, an analogue digital converter (ADC), and the possibility to store information.

beam. The entrance pupil is re-imaged multiple times across the optical path onto the plane of the FSM, the DM, the PAM, the TTS, the WFS and the FC. The FSM and DM are placed into the common path of the Tx and Rx beam.

2.3 Space terminal breadboard description

Figure 3 shows the STB, which is adopted from the THRUST testbed [8]. The receive aperture and transmit aperture are separated to account for the PAA. The transmit aperture is on a rail, to enable variation of the PAA. The separation distance goes up to 1 m between the transmitter and receiver, which is 100 μrad over a link distance of 10 km. The STB is equipped with a single mode fiber (SMF) coupling system, a focus camera (CAM) for beam diagnostics a quadrant detector (4QD) and an FSM to correct for tip-tilt aberrations and a photodetector (PD). The optical power measured by the PD is used to evaluate the AO performance on the uplink.

2.4 Test site description

Figure 4 gives an impression of the test site is at the DLR premises in Weilheim (Germany). The link distance is 10 km, and is over an area with a hill top and a lake. Since the GTB is located at an altitude of 600 m and the STB is of 900m, the altitude difference is 300 m, with a maximum clearance of 150 m between the laser beam and the underlaying ground. The smallest clearance is obviously present at both the STB and GTB, which causes ground layer effects at both locations. Hence, also the scintillation effects will be prominent at the GTB entrance pupil. This also effects the control loop, e.g. scintillation effects are clearly visible on the WFS.

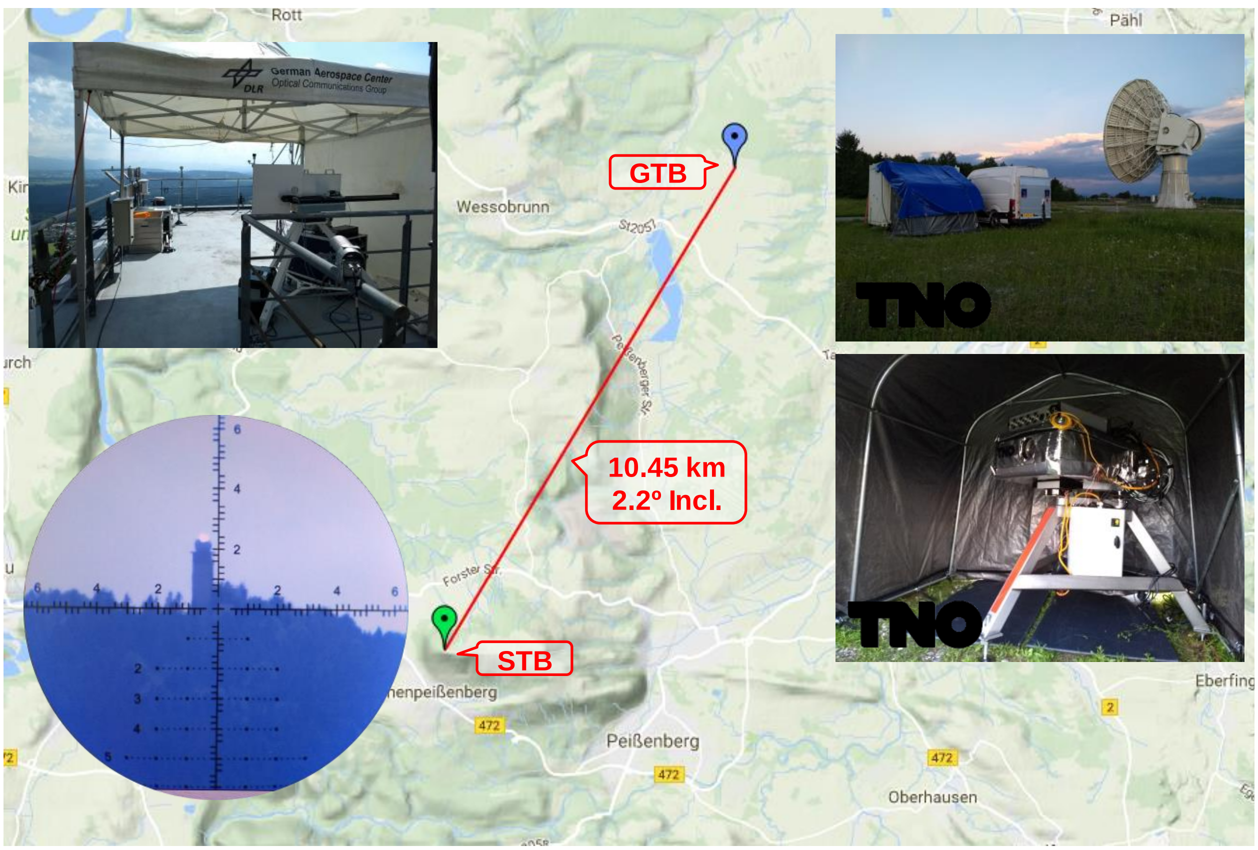
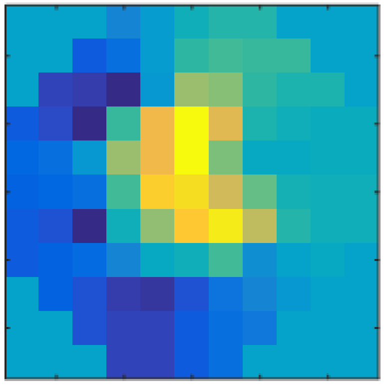
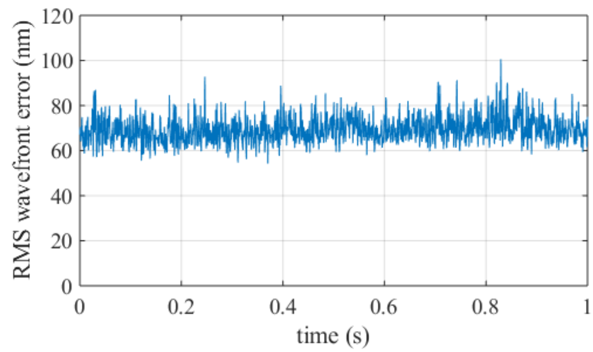


Figure 4 Test site at DLR in Weilheim. The laser beam goes over a length of 10 km distance, from a valley at 600 m, to a hill-tip of 900 m.



(a)



(b)

Figure 6 (a) Wave front error of the non-common path using a corner cube of 54.7 nm RMS. (b) Time trace of the AO in laboratory conditions

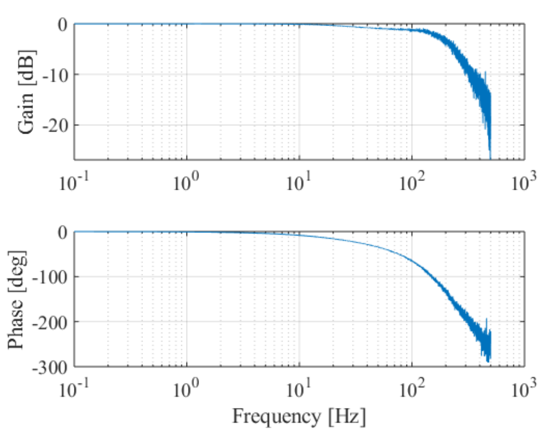
3. SYSTEM PERFORMANCE

3.1 OFELIA system test results

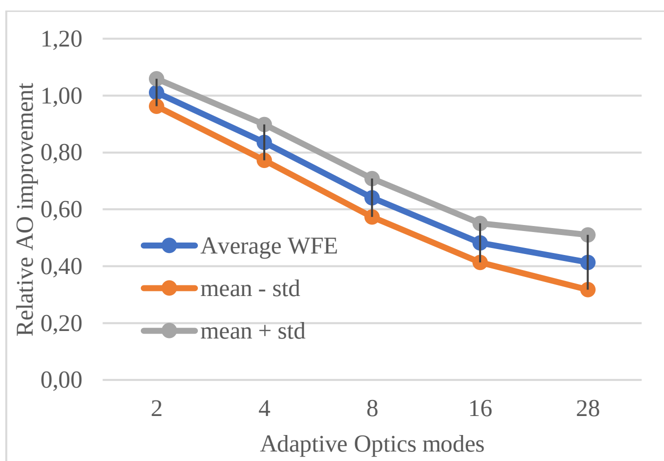
In order to verify that the system level performance is sufficient for successful measurements, several system level tests have been carried out to determine the performance of the AO system. The performance parameters that are most relevant are the non-common path wave front error, the residual AO RMS error and the bandwidth of the AO system.

The non-common path wave front error is the difference between the wave fronts at the Tx fiber and the wave front sensor. The non-common path error in closed loop operation, could limit the performance in the uplink. By introducing a corner-cube, the non-common path can be measured by the wave front sensor. Figure 5 shows the wave front sensor data and the measured wave front. This is 55 nm RMS including the corner-cube itself which is expected to be contributing the most. Overall, this is significantly lower than the aberrations expected to be induced by turbulence, which are expected to be in the order of 400 nm RMS.

The residual wave front error after correction also is a performance determining factor. This is caused by the error sources in the AO loop, such as the limited spatial correction bandwidth, amplifier noise of the DM, and the wave front sensor noise. This performance can be measured in the lab, by turning the AO system on using a flat field source, taking a measurement trace and determine the RMS wave front error. A measurement with the AO system on, yielded 80 nm RMS. Adding the residual AO error to the 55 nm non-common path error, it is 97 nm RMS, which is corresponds to a diffraction limited case. Note that generating a perfect wave front with no wave front error is not trivial, since it also includes the

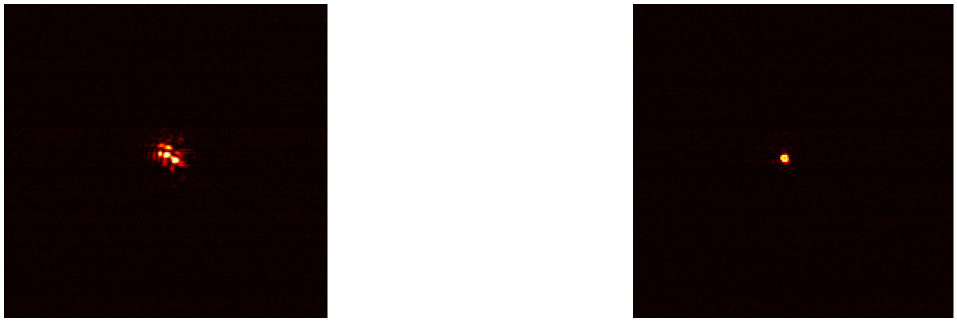


(a)



(b)

Figure 5 (a) Closed loop transfer function of the AO higher order modes. (b) Adaptive optics performance improvement over a 10 km link with turbulence at night time.



(a) (b)

Figure 7 image of the focus camera (a) AO off and (b) AO on.

source error, which is estimated to be at least 20 nm RMS. At last, proportional integral (PI) control is used as feedback controller. Figure 6 (a) shows the measured complementary sensitivity function of the AO system. From the -3 dB point, it shows a closed loop bandwidth of 125 Hz, which corresponds to an open loop crossover frequency of 80 Hz.

3.2 Adaptive optics downlink results

The AO results presented on the downlink are recorded under night time conditions, which are relatively good conditions compared to day time. This allows to see how well the AO system is performing.

The clearest proof of a working AO system is to inspect the point spread function (PSF) of the system. When perfectly corrected, the PSF approximates an airy disk, whereas for no correction, it is blurred and broad due to the wave front distortion. Figure 7 shows two images of the FC at day time conditions, which exactly shows this effect. It is clearly seen that the PSF is smaller when the AO is turned on. The improvement on the downlink during night time can go from 260 to 80 nm RMS, which is a reduction of a factor of 0.3, and for day time conditions 350 to 180 nm RMS, which is an reduction of a factor of 0.5 with respect to the RMS wavefront error. This includes the removal of the systematic error of the STB, which is present due to residual misalignment, thermal drift etc.. The improvement of the PSF and the reduction of the WFE shows that the AO-system is working.

In addition, the AO performance improvement is tested per mode. For each AO measurement, there is a 20 s of AO off, and 120 s of AO on in consecutive order. In this fashion, the AO on can be compared with AO off with approximately the same turbulence conditions. For a fair comparison of the AO performance in the presence of turbulence, the systematic wave front error is removed to determine the residual RMS wave front error. The performance improvement shown in Figure 6 (b) gives the relative improvement of the residual RMS wave front error of the turbulence. When applying more AO modes, the AO performance is improved up to an average improvement of 0.4 for 28 modes. This result gives the conclusion that the AO system is working properly.

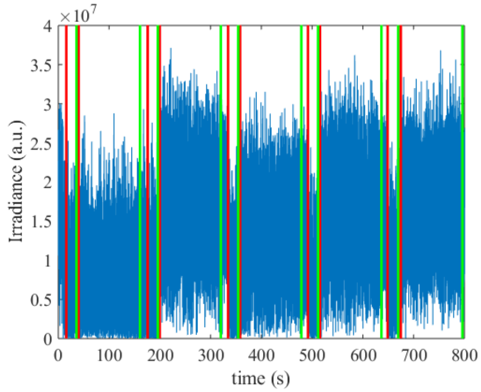
3.3 Adaptive optics uplink results

The most relevant parameters for testing the AO performance of optical feeder links is the mean irradiance and the scintillation index at the STB. The mean irradiance is directly related to the link loss. Via the outage percentage, the scintillation index can also be related to link loss. Obviously a higher mean irradiance, and a lower scintillation index, are related to a better link performance. Both the mean irradiance and scintillation index can be derived from the irradiance sensor at the STB.

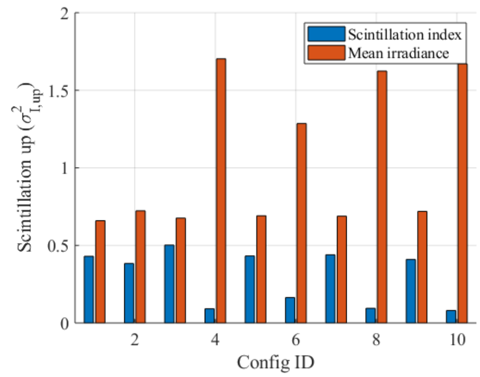
Figure 8 gives the result of the irradiance measurement at the STB. The measurement sequence is divided in 11 traces, which are indicated by the red and green lines, i.e. the red line indicates the start and the green line the end of a trace. All traces with AO turned on, have a duration of 120 s. In between these AO measurements, there is a reference measurement

Table 1 Config IDs of the experiments

CONFIG ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
AO MODES	2	2	2	28	2	4	2	8	2	16
BANDWIDTH	low	high	low	high	low	high	low	high	low	high
DURATION	20 s	120 s	20 s	120 s	20 s	120 s	20 s	120 s	20 s	120 s



(a)



(b)

Figure 8 Adaptive Optics performance for a PAA of 6 µrad: (a) irradiance measurements at the STB, (b) mean irradiance and scintillation index derived from the STB irradiance data. Even config IDs have 2, 28, 4, 8 and 16 AO modes activated consecutively (see Table 1 for the config IDs).

of 20 s, with only low bandwidth tip-tilt control, and no higher order AO modes, to compare the AO performance with respect to its corresponding turbulence conditions. The PAA of these measurements was 6 µrad, which represents a similar fraction of the PAA and the IPA as for an optical feeder link to a GEO stationary satellite.

From the irradiance measurements in Figure 8 the effect of the positive effect of the AO system is clearly visible. Figure 9 (b) translates this figure into the mean irradiance is and the scintillation index. For this specific result, the mean irradiance improves with a factor of 2.5 and the scintillation drops with a factor of 4.5 for 28 AO modes. The improvement of the mean irradiance can be partly attributed by the removal of the systematic wave front error, and the scintillation index improvement due to the correction of atmospheric turbulence. Hence, it can be concluded that the adaptive optics system is significantly reducing the link loss.

4. CONCLUSION

TNO and DLR have carried out optical feeder link adaptive optics (OFELIA) breadboard activities to prepare for a ground terminal product for optical satellite communications. A breadboard plan was devised to test the pre-correction adaptive optics principle over a relevant link distance. With measurements in the lab it is verified that the breadboard and AO performance of the GTB has diffraction limited performance, which is more than sufficient to demonstrate the pre-correction principle for a uplink communication channel. Outdoor tests have been carried out at the test range of 10 km at the DLR premises in Weilheim, Germany. Downlink experiments clearly show that the AO performance of the downlink is improved. The RMS wave front error is reduced by a factor of 0.4 for night time conditions, which is an improvement of a factor of 2.5. From the irradiance measurements at the STB it is made clear that the AO is improving the mean irradiance by a factor of 2.5 and reducing the scintillation index by a factor of 4.4 for a GEO-link representative PAA. Hence, it is concluded that the AO can pre-correct optical turbulence for an optical link with a similar turbulence profile as the one in Weilheim.

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