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Pre-correction Adaptive Optics performance of a 10 km Laser Link

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ABSTRACT

For the next generation of very high throughput communication satellites, free-space optical (FSO) communication between ground stations and geostationary telecommunication satellites is likely to replace conventional RF links. To mitigate atmospheric turbulence, TNO and DLR propose Adaptive Optics (AO) to apply uplink pre-correction. In order to demonstrate the feasibility of AO pre-correction an FSO link has been tested over a 10 km range. This paper shows that AO pre-correction is most advantageous for low point ahead angles (PAAs), as expected. In addition, an optimum AO pre-correction performance is found at 16 AO modes for the experimental conditions. For the specific test site, tip-tilt pre-correction accounted for 4.5 dB improvement in the link budget. Higher order AO modes accounted for another 1.5 dB improvement in the link budget. From these results it is concluded that AO pre-correction can effectively improve high-throughput optical feeder links.

Keywords: Optical satellite communication, adaptive optics, free space optical communications

1. INTRODUCTION

Free space optical (FSO) communications is a well-positioned technology to increase the data-rate of high throughput feeder links for telecommunication satellites beyond the limits of radio frequencies (RF) [1]. At TNO, an optical ground terminal (OGT) is being designed for terabit/s optical feeder links, with a physical layer for the communications system, which is developed by DLR [2].

FSO links through the atmosphere are known to be disturbed by atmospheric turbulence, which reduce the average received optical power and induces strong irradiance fluctuations. Optical turbulence is a strong contributor to the link loss, which reduces the available optical power at the receiver. This degrades the communications performance in terms of throughput and bit error rate. This effect can either be reduced by increasing optical power, or mitigating the effects of atmospheric turbulence.

Adaptive Optics (AO) is a well-known technique originating from astronomy, which can effectively compensate atmospheric turbulence over a downlink [3, 4]. Pre-correction AO has been proposed in various publications to mitigate the atmospheric turbulence in the uplink [2, 5, 6, 7, 8, 9]. Pre-correction AO is based upon the reciprocity principle, which is only partially 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 limits the performance of the pre-correction due to anisoplanatism. The consequence on the link budget is estimated by analytic formulas in for instance [6]. A lab demonstration is presented by [7]. And in [8] the AO performance is evaluated at an outdoor test site for a single PAA and over a relative short distance of 494 m.

In the endeavor to verify the AO pre-correction performance, TNO and DLR have prepared breadboard experiments over a significantly longer link distance of 10 km [10]. First experiments have been presented in [11], which shows pre-correction is able to reduce the link loss. In order to verify the AO pre-correction experiments, an additional measurement campaign has been carried out, which results are presented in this paper.

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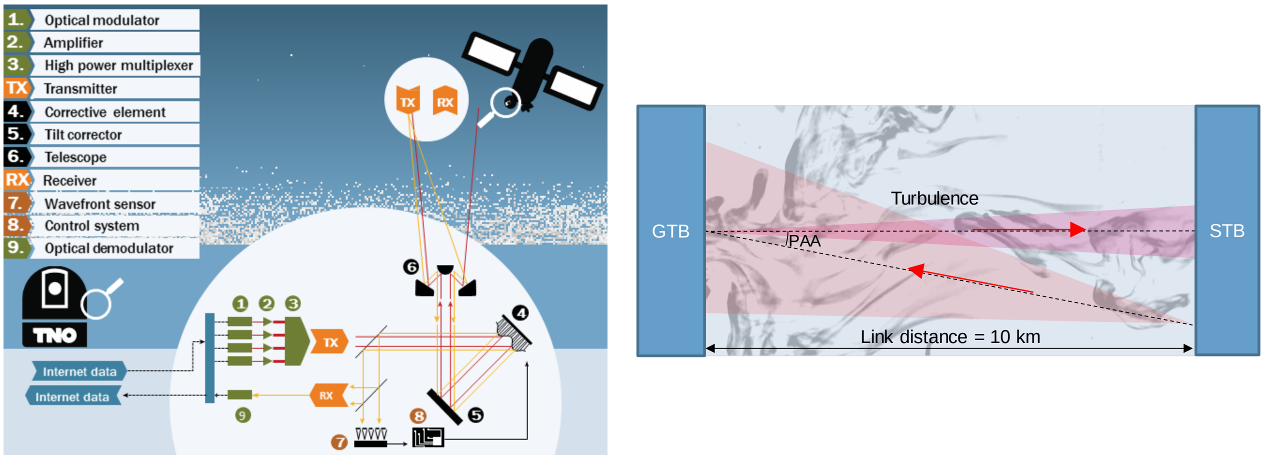


(a) (b)

Figure 1 (a) Schematic overview of the optical feeder link adaptive optics system (b) schematic overview of the experiment with the ground terminal breadboard (GTB) and space terminal breadboard (STB): The laser from the STB has an offset to emulate the point ahead angle at the GTB. Hence, the laser beams partly travels through different atmosphere.

The experiments presented in this paper, aim to evaluate the AO pre-correction performance over a broad range of PAAs. To this end, the experiment is described in section 2. In section 3, both the effect of the PAA and the effect of the AO is evaluated, by measuring the irradiance at the STB. From these measurements the link loss improvement for a ground-to-ground link has been obtained.

2. OPTICAL FEEDER LINK ADAPTIVE OPTICS (OFELIA) EXPERIMENT

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 downlink performance, its correction will also cause wavefront deformation of the uplink beam. By the reciprocity principle, this wavefront deformation will partially correct for the uplink beam, provided that the downlink beam travels through the same atmospheric turbulence as the uplink.

Amongst others, the presence of a PAA compromises the reciprocity principle. The point ahead angle (PAA) indicates the angle between the uplink beam and the downlink beam, indicated in Figure 1 (b). Due to the PAA, the downlink beam party travels through different atmospheric turbulence column than the uplink beam. The degree of correlation between the turbulence effects in the uplink beam and the downlink beam can be characterized by the isoplanatic angle (IPA). Since the degree of correlation is inherently coupled to the potential 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 pre-correction is effectively improving the uplink performance. To this end, four objectives have been formulated. 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.

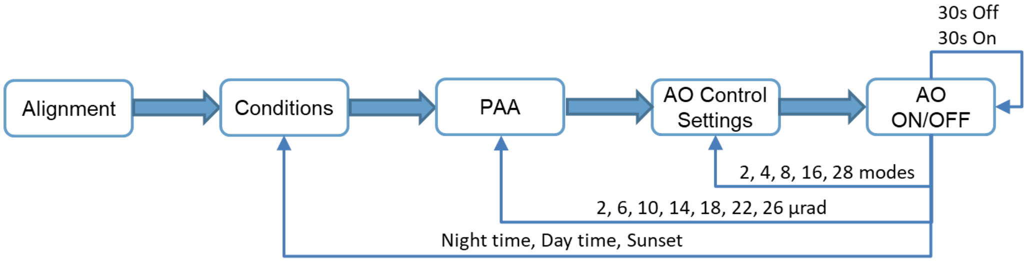
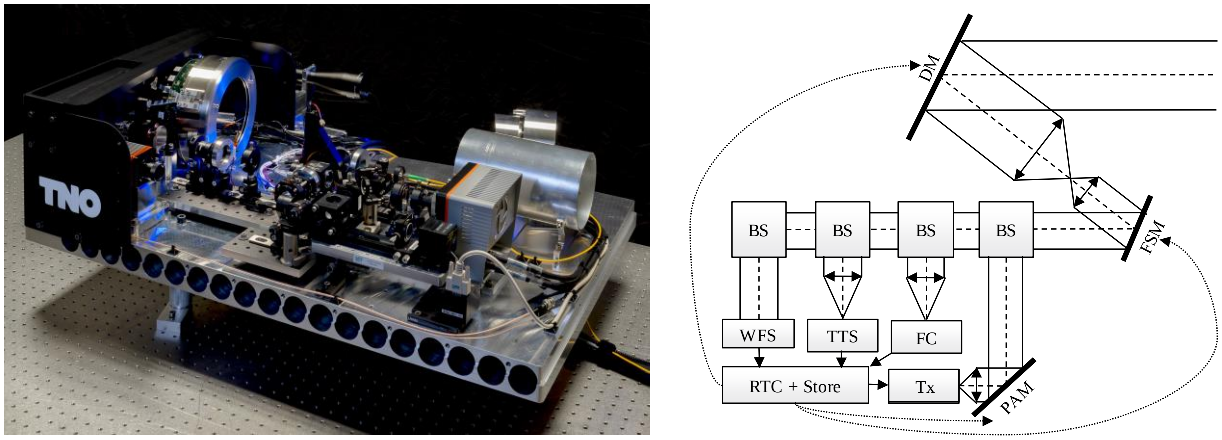


Figure 2 Test sequence of the effect of the AO modes. The AO modes are changed over the inner loop, whereas the PAAs are changed over the larger loop. To investigate the effect of the PAA, the PAA loop and AO control loop have been exchanged.



(a) (b)

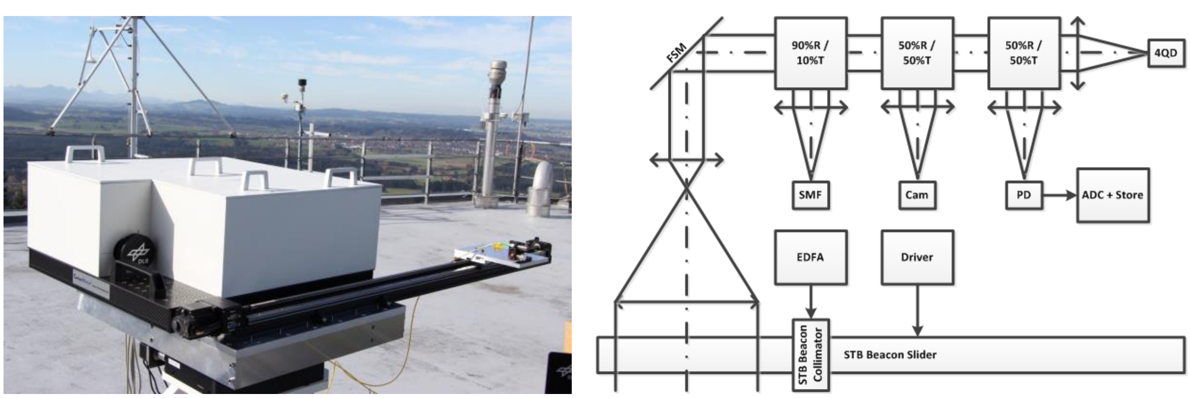
Figure 3 OFELIA breadboard (a) fully integrated breadboard (b) schematic overview of the breadboard with several beam splitters (BS), a focus camera (FC), a tip-tilt sensor (TTS), a wave front sensor (WFS), a real time computer (RTC), the transmitter (Tx), the point ahead mirror (PAM), the fast steering mirror (FSM) and deformable mirror (DM).

2.1 Test description

Since it is well known that AO can improve the downlink performance [4], the experiments mainly focus on pre-correction AO. Since high throughput data communication over a turbulence channel is known to be feasible [8], data communication functionality is omitted for the presented experimental results. The AO performance is estimated as a function of the PAA and the number of AO modes (c.f. Figure 2). To support this, the number of AO modes can be changed and the PAA can be modified at the STB and the GTB. Since the optical feeder link is supposed to work at a variety of turbulence conditions, to guarantee robust link performance, the test campaign has a duration of multiple days, and includes day and night conditions to cover this variation in conditions.

2.2 Ground terminal breadboard description

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 resembles the ground terminal, having an aperture size of multiple coherence radii of atmospheric turbulence. Figure 3 shows the OFELIA GTB is equipped with a fast steering mirror (FSM) to correct for tip-tilt aberrations [3]. The control loop with the deformable mirror (DM) and the wave front sensor (WFS) handle the high order wave front aberrations. The PAA is applied by a point ahead mirror (PAM) and a focus camera (FC) is added to monitor the downlink beam. The turbulence parameters, such as the angle of arrival, the scintillation index and the wave front error are measured with a wavefront sensor (WFS) at the GTB.



(a) (b)

Figure 4 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.

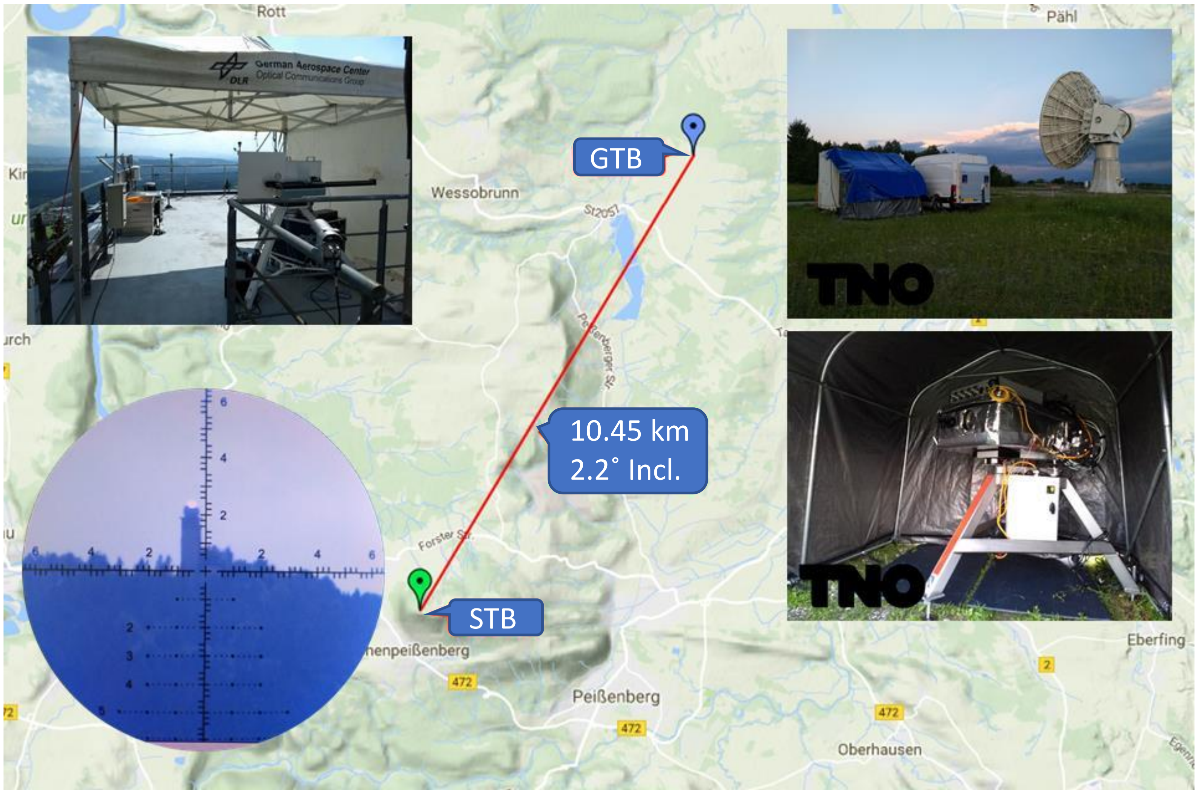


Figure 5 Test site at DLR in Weilheim. The laser beam travels over a length of 10 km distance, from a valley at 600 m, to a hill-top at 900 m.

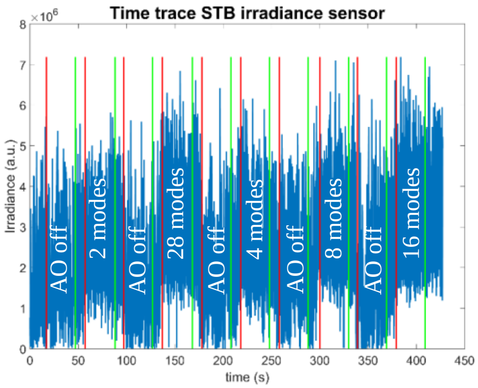
2.3 Space terminal breadboard description

The size of the STB aperture is sufficiently small to limit aperture averaging, but large enough to collect a sufficient amount of photons. Figure 4 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 sits on a rail, to enable easy 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. Adjustment of the beacon easily leads to misalignment of the beacon with respect to the GTB, since the divergence angle is in the order of only 100 µrad. In the measurement sequence as depicted in Figure 2 the beacon alignment was optimized for point ahead angles in the central range, i.e. from 6 to 22 µrad.

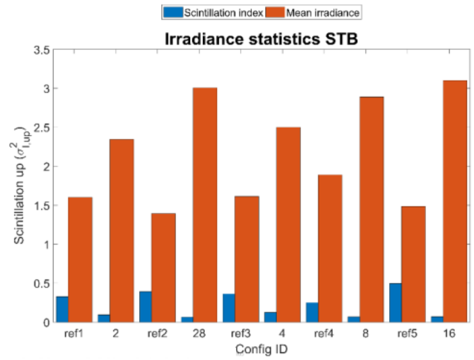
Furthermore, the STB is equipped with a single mode fiber (SMF) coupling system, a focus camera (CAM) for beam diagnostics a quadrant detector (4QD) and an FSM to correct for tip-tilt aberrations and a photodetector (PD). The optical power measured by the PD is used to evaluate the AO performance on the uplink. The PD has a temperature dependence, which would require regular calibration cycles. To avoid these regular calibration cycles, a calibration has been done only once to check the link budget of the test location. To assess the AO performance, relative measures have been taken, i.e. the mean irradiance and scintillation index have been compared to the reference measurements of 30 s.

2.4 Test site description

In order to have representative turbulence conditions, the link distance and test site have been been choosen to match the GEO feeder link case reasonably well. The test range at the DLR premises in Weilheim of 10 km match these conditions sufficiently, i.e. scintillation indices and wave front errors are considered worst case in comparison to the GEO feeder link. Figure 5 gives an impression of the test site at the DLR premises in Weilheim (Germany), covering a hill top and a lake. Since the GTB is located at an altitude of 600 m and the STB is at 900 m, 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. The small clearance at the STB side will exaggerate the scintillation effects at the GTB entrance pupil. This effects the control loop, e.g. scintillation effects are clearly visible on the WFS.



(a)



(b)

Figure 6 Data processing of the STB irradiance sensor (a) raw measurement data. Red vertical lines indicate the start of the time-trace and the green vertical lines indicate the end of the time-trace. (b) mean irradiance and the scintillation index are extracted from the raw measurement data as depicted in (a). Numbers on the x-axis refer to the number of AO modes as indicated in (a).

3. AO PRE-CORRETION PERFORMANCE

To verify the AO pre-correction performance, the performance is evaluated by the irradiance sensor at the STB. The effect of the PAA on the AO performance and the effect of the number of AO modes is evaluated. Of the 1800 measured time traces of 30 s, almost 70% of the measured data is used for the following analysis.

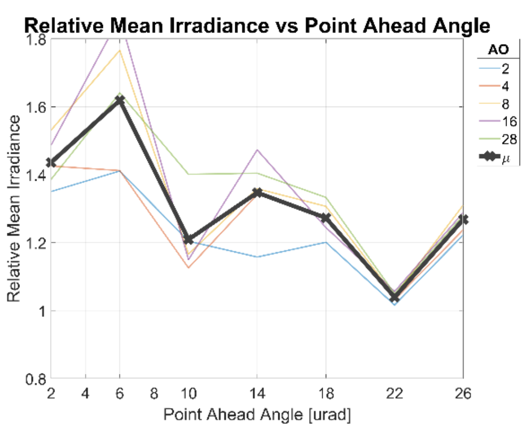
3.1 Data processing

A measurement of the irradiance sensor is depicted in Figure 6 (a). From this measurement it is clearly seen when the AO is turned off and on. The measurement with AO off is used as the reference measurement. From this measurement, separate time traces are evaluated, which are indicated by the red vertical line (start) and green vertical line (end). From these time traces the mean irradiance and the scintillation index are evaluated.

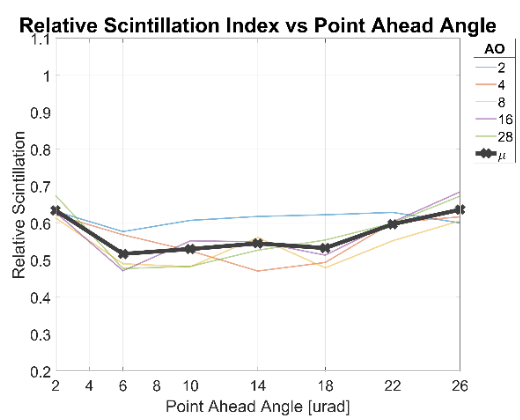
To evaluate the AO performance, a relative measure is taken. The relative mean irradiance and relative scintillation index are taken as ratio of the AO-on measurement and the reference measurement (AO-off) prior and when possible after the AO-on measurement. These relative measures enable to compare AO performances at different levels of atmospheric turbulence, and variations in the irradiance sensors due to thermal fluctuations.

3.2 Point ahead penalty

The effect of the PAA is assessed by evaluating the AO performance on each of the PAAs. Figure 7 (a) shows the general trend that the relative mean irradiance is higher for lower PAAs and vice versa. The result for a PAA of 2 and 26 μrad

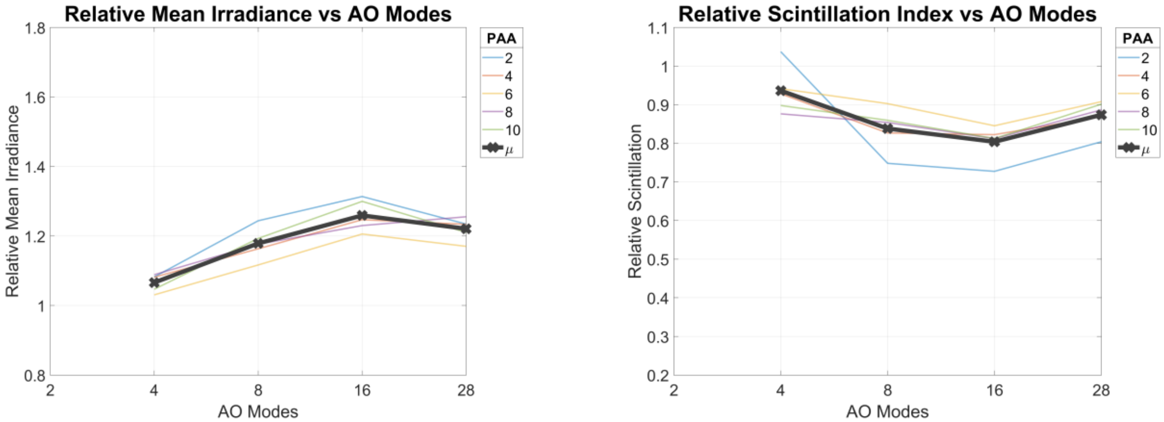


(a)



(b)

Figure 7 The point ahead penalty: (a) relative mean irradiance vs. PAA and (b) relative scintillation index vs. PAA.



(a) (b)

Figure 8 The point ahead penalty: (a) relative mean irradiance vs AO modes and (b) relative scintillation index vs AO modes.

seem to be not completely consistent with this conclusion. This can be explained by the non-optimized alignment for these PAAs during the measurement campaign. The results confirms that the PAA plays a significant role on the mean irradiance.

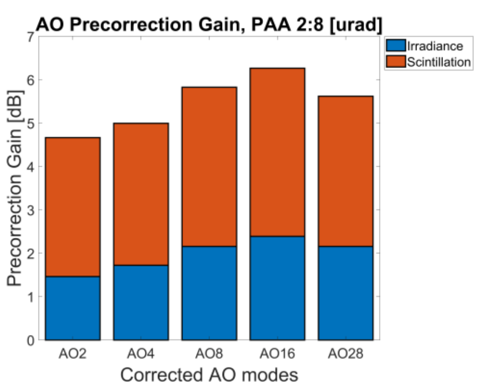
Figure 7 (b) shows that this effect is consistent in the scintillation index. For higher PAAs, the scintillation effect is higher, indicating that the AO pre-correction is most effective for low PAAs. Also in this measurement, the PAA of 2 μrad seems to be off, which can also be counted as an anomaly, due to the alignment. Also from this measurement it is concluded that the PAA plays a significant role on the scintillation index.

3.3 Adaptive optics performance on the uplink

The effect of the AO performance on the uplink is evaluated in Figure 8, by changing the number of AO modes successively, Figure 8 (a) shows that there is a maximum relative mean irradiance at sixteen modes. In addition, the relative scintillation index shows a minimum at 16 AO modes. So from these results, 16 AO modes seem to be optimal for AO pre-correction for these Weilheim experimental conditions and the given Rx Tx apertures.

3.4 Consequences on the link budget.

The effect of the AO pre-correction on the link budget is evaluated in Figure 9. The mean relative mean irradiance is simply converted to a decibel (10log10) value. For the scintillation index σ_I^2, the approximation of [12] is taken: $L_{\mathrm{SC}} = \left[3.3 - 5.77\sqrt{-\ln p_{\mathrm{thr}}}\right]\sigma_I^{4/5}$, with an outage probability p_{thr} of 10^{-3}. These results indicate that tip-tilt pre-correction accounts for the majority of the link budget improvement, by a gain of 4.7 dB. The higher order modes do have a positive impact on the link budget, with an addition 1.5 dB for 16 AO modes.



(a)

	AO2	AO4	AO8	AO16	AO28
Irradiance gain [dB]	1.5	0.3	0.4	0.2	-0.2
Scintillation gain [dB]	3.2	0.1	0.4	0.2	-0.4
Total [dB]	4.7	0.3	0.8	0.4	-0.6
Irradiance Σ [dB]	1.5	1.7	2.2	2.4	2.2
Scintillation Σ [dB]	3.2	3.3	3.7	3.9	3.5
Total Σ [dB]	4.7	5.0	5.8	6.3	5.6

(b)

Figure 9 The effect of AO-pre-correction on the link budget for PAAs of 4 – 8 μrad (a) a bar diagram indicating the optimum at 16 AO modes (b) the table with numerical values in dB.

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. Experiments have been performed to verify the pre-correction adaptive optics principle over a relevant link distance of 10 km. It has been verified that for lower PAAs the AO pre-correction performs better than for higher PAAs. In addition, an optimum correction bandwidth of 16 AO modes was found. Over all, tip-tilt pre-corrections accounts for 4.5 dB improvement and the higher order AO modes account for another 1.5 dB improvement. Hence, it is concluded that the AO system can pre-correct optical turbulence in the presence of a PAA. This gives a positive prospect regarding high throughput optical feeder links.

5. REFERENCES

[1] H. Hemmati, Near-Earth Laser Communications, CRC Press, 2009.

[2] R. Saathof, et al., "Optical technologies for terabit/s-throughput feeder links," in *ICSOS*, 2017.

[3] J. Hardy, Adaptive Optics for Astronomical Telescopes, Oxford University Press, 1998.

[4] M. Wright, et al., "Adaptive optics correction into single mode fiber for a low Earth orbiting space to ground optical communication link using the OPALS downlink," *Optics Express,* vol. 23, no. 26, p. 33705, 2015.

[5] R. Tyson and D. Canning, "Indirect measurement of a laser communications bit-error-rate reduction with low-order adaptive optics," *Applied Optics,* vol. 42, no. 21, pp. 4239-4243, 2003.

[6] S. Dimitrov, R. Barrios, B. Matuz and G. Liva, "Digital modulation and coding for satellite optical feeder links with pre-distortion adaptive optics," *International Journal of Satellite Communications and Networking,* vol. 34, no. 5, p. 625/644, 2015.

[7] N. Leonhard, et al., "Real-time adaptive optics testbed to investigate point-ahead angle in pre-compensation of Earth-to-GEO optical communication," *Optics Express,* vol. 24, no. 12, p. 13157, 2016.

[8] A. Brady, R. Berlich, N. Leonhard and T. Kopf, "Experimental validation of phase-only pre-compensation over 494 m free-space propagation," *Optics Letters,* vol. 42, no. 14, pp. 2679-2682, 2017.

[9] N. Védrenne, J. M. Conan, A. Bonnefois and C. Petit, "Adaptive optics pre-compensation for GEO feeder links : towards an experimental demonstration," in *ICSOS,* 2017.

[10] R. Saathof, et al., "Optical feeder link program and first adaptive optics test results," in *Proc. SPIE*, 2018.

[11] R. Saathof, et al., "Adaptive Optics pre-correction for Optical Feeder Links – breadboard performance," in *ICSO*, 2018.

[12] D. Giggenbach and H. Henniger, "Fading-loss assessment in atmospheric free-space optical communication links with on-off keying," *Optical Engineering*, vol. 47, no. 6, p. 069801, 200.