Adaptive Optics pre-correction Demonstrator for Terabit Optical Communication

Broekens, Kristiaan; Klop, Wimar; Moens, Thijs; Eschen, Martin; do Amaral, Gustavo Castro; Silverstri, Fabrizio; Visser, Martijn; Kaffa, Lauren; Saathof, Rudolf; More Authors

DOI
10.1117/12.2689933

Publication date
2023

Document Version
Final published version

Published in
International Conference on Space Optics, ICSO 2022

Citation (APA)
Broekens, K., Klop, W., Moens, T., Eschen, M., do Amaral, G. C., Silverstri, F., Visser, M., Kaffa, L., Saathof, R., & More Authors (2023). Adaptive Optics pre-correction Demonstrator for Terabit Optical Communication. In K. Minoglou, N. Karafolas, & B. Cugny (Eds.), *International Conference on Space Optics, ICSO 2022* Article 127771R (Proceedings of SPIE - The International Society for Optical Engineering; Vol. 12777). SPIE. https://doi.org/10.1117/12.2689933

Adaptive optics pre-correction demonstrator for terabit optical communication

Kristiaan Broekens, Wimar Klop, Thijs Moens, Martin Eschen, Gustavo Castro do Amaral, et al.

Kristiaan Broekens, Wimar Klop, Thijs Moens, Martin Eschen, Gustavo Castro do Amaral, Fabrizio Silverstri, Aleid Oosterwijk, Martijn Visser, Niek Doelman, Lauren Kaffa, Rudolf Saathof, Ivan Ferrario, "Adaptive optics pre-correction demonstrator for terabit optical communication," Proc. SPIE 12777, International Conference on Space Optics — ICSO 2022, 127771R (12 July 2023); doi: 10.1117/12.2689933

Event: International Conference on Space Optics — ICSO 2022, 2022, Dubrovnik, Croatia

International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

ICSO 2022
International Conference on Space Optics
3 – 7 October 2022 | Dubrovnik | Croatia

Adaptive optics pre-correction demonstrator for terabit optical communication

icso proceedings

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 127771R · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2689933

Adaptive Optics pre-correction Demonstrator for Terabit Optical Communication

Kristiaan Broekens[a], Wimar Klop[a], Thijs Moens[a], Martin Eschen[a], Gustavo Castro do Amaral[a], Fabrizio Silverstri[a], Aleid Oosterwijk[a], Martijn Visser[b], Niek Doelman[ac], Lauren Kaffa[d], Rudolf Saathof[d], Ivan Ferrario[a]
[a]TNO Technical sciences, Delft, The Netherlands; [b] Airbus Defence and Space, the Netherlands [c] Leiden Observatory, Leiden University, the Netherlands; [d] Aerospace Engineering, Delft University of Technology, the Netherlands

ABSTRACT

For the next generation of very high throughput communication satellites, free-space optical (FSO) communication between ground stations and geostationary telecommunication satellites is a potential solution to overcome the limitations of RF links. To mitigate atmospheric turbulence effects, TNO proposes Adaptive Optics (AO) to apply uplink pre-correction. As a successor of Optics Feeder Link Adaptive Optics (OFELIA) breadboard [1], [2], the Terabit Optical Communication Adaptive Terminal (TOmCAT) project phase 2 aims to demonstrate the AO pre-correction technology for a terabit Optical Ground Station (OGT) in a ground-to-ground link field test over 10 km. Within this demonstrator an upgraded version of the OFELIA breadboard is used as optical bench for the AO (pre-)correction, but moreover the demonstrator enables the (future) integration of equipment for the final OGT configuration including the Beam Multiplexer (BMUX) and communication equipment. Apart from the OGT demonstrator, the overall layout of the field test has been upgraded, including the test site and the Ground Support Equipment (GSE), with the goal to create a better understanding of the encountered link phenomena and the instant (turbulence) conditions at which it was measured. New additions to the GSE are several weather stations placed along the link path to quantify the local turbulence and to relate the measured link performance to the instant turbulence conditions. The test campaign is split in two successive field tests: First the AO Demonstrator evaluates the upgraded AO pre-correction performance with a single non-modulated link, followed by the OGT Demonstrator which will include the multiplexing of multiple uplink channels and RF end-to-end modems to prove the technical feasibility of supporting a terabit communication link. This paper covers the design of the AO demonstrator and GSE, the field test layout and the preliminary results for the AO demonstrator field test. For the downlink correction the residual Wave Front Error (WFE) is presented. The pre-correction performance is depicted in the uplink transmission loss and scintillation, all as function of the encountered turbulence conditions.

Keywords: Optical satellite communication, adaptive optics, pre-correction, wave front sensor, deformable mirror, ground-to-ground link demonstrator

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 [3]. In order to overcome this limit for bi-directional links between ground stations and very high throughput satellites at geostationary orbits, TNO envisions optical free-space communication [1], [2], [4]. Within the TOmCAT project an optical ground terminal (OGT) is being developed by TNO for terabit/s optical feeder links, for which a demonstrator has been built to prove a RF end-to-end communication link.

The TOmCAT project is implemented under the ESA's ARTES programline Skylight and is co-funded by ESA with the support of the Netherlands Space Office. Within the first phase of the project the Ground Terminal Breadboard (GTB) named OFELIA was developed, showing the principle of Adaptive Optics and added value of pre-correction [1],[2]. By pre-correcting the uplink based on the measured wavefront on the downlink, the signal stability at the satellite receiver is improved. This reciprocity principle only holds if the up- and downlink path overlap and therefore experience similar turbulence induced disturbances. The performance of pre-correction and the underlying mechanisms under various turbulence conditions and AO configurations is key for improving the design of future optical communication terminals.

TOmCAT phase 2 is a continuation on the (OFELIA) breadboard and focusses on the development of a RF end-to-end optical communication link demonstrator. The test campaign was split in two separate tests: AO demonstrator and OGT demonstrator. The AO demonstrator focusses on verifying the AO performance in the new configuration, while for the OGT demonstrator the setup is later upgraded to facilitate the communication link. This paper aims to describe the transformation from the existing Ground Terminal Breadboard (GTB) to an Optical Ground Terminal (OGT) demonstrator (Section 2). The preliminary results of the AO demonstrator test are presented and discussed as verification of the AO control and pre-correction (Section 3).

For the design of the OGT demonstrator a fully integrated approach was selected, whereby OFELIA and all peripheral equipment have been assembled into a custom trailer as shown in Figure 1. The evolution of the GTB to AO demonstrator and the ability to accommodate the later expansion to the final OGT demonstrator configuration is discussed in Section 2.1.

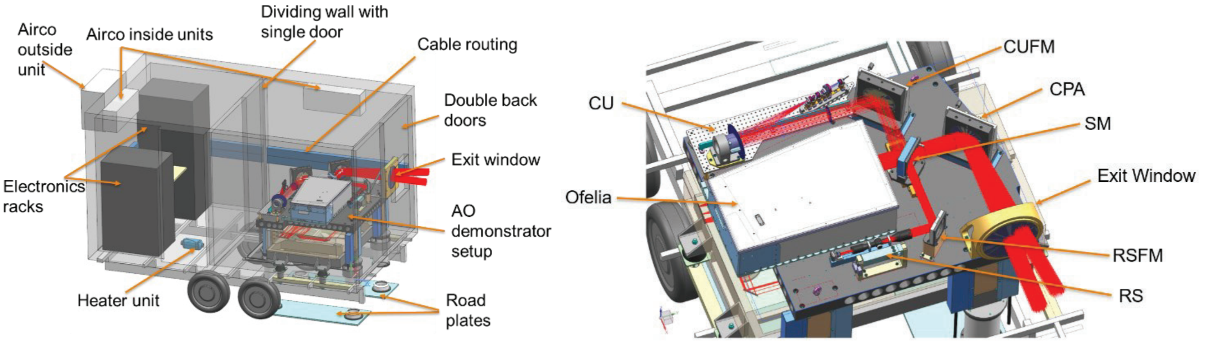

Figure 1: Schematic overview of (a) a side view of the OGT trailer, and (b) a top view of the main breadboard

The equipment to enable the ground-to-ground field test, referred to as Ground Support Equipment (GSE), includes an upgraded design of the STB and the addition of four Turbulence Monitors (TM's). The STB is used as the counter terminal for the ground-to-ground link to simulate the receiving satellite. The modular design of the STB is described more detail in Section 2.3. The Turbulence Monitors (TM's) measure the turbulence effects along the link in real-time, such that the link performance can be related to the turbulence conditions. More detail about the TM's can be found in Section 2.4. Furthermore, an alternative test site was selected due to its more beneficial geography (dominantly level grass lands) and linear increase of link altitude, which is expected to improve the predictability of the turbulence profile (Section 2.5).

2. AO DEMONSTRATOR

The AO demonstrator is defined as the intermediate step in the transformation from GTB (OFELIA) to OGT demonstrator. The accompanied AO field test targets to test the upgraded configuration and to verify its operation in comparison test campaigns. The evaluation of the results emphasis on the performance of the AO control and pre-correction. This is considered as a verification at system level of the terminal for the OGT demonstrator.

Additionally, the number of AO modes are varied to obtain insight in the added gain of various AO configurations, which serves as input for developing cost effective optical terminals in the future. To evaluate the AO performance, each measurement is preceded by a tip-tilt reference as was performed in [2]. By evaluating the observed relative gain between the measurement and corresponding reference, the effect of the AO control can be isolated.

Apart from the AO performance of the OGT, a set of four subgoals were defined. First, the upgraded configuration of the Optical Ground Terminal (OGT) is tested as a predecessor of the optical feeder link product. Second, the effective operation of the GSE is verified. Third, the link and turbulence measurements serves as input for link budgets and simulation verification. Fourth and last to ensure that the system is capable to support an actual communication link for the future OGT demonstrator tests.

2.1 Ground Terminal Breadboard description

The OFELIA adaptive optics breadboard was upgraded to fit the requirements and interface of the OGT demonstrator. The main components of the AO hardware have been unaltered: a Fine Steering Mirror (FSM) enables tip-tilt corrections and a Deformable Mirror (DM) corrects the higher order mode disturbances.

The Wave Front Sensor (WFS) is upgraded with a Xenics Cheetah 640 TE1 1700 version, allowing higher sample rates with improved latency performance compared to the initial 800 version. The WFS readout and AO control have been replaced by the Optical Communications Control Platform (OCCP), which was developed by Airbus Defence and Space, Netherlands. The OCCP is a control platform based on a FPGA and allows WFS readout and AO control up to 40 modes at 5 kHz. With the renewed setup higher AO bandwidths up to 180 Hz have been attained.

2.2 Optical Ground Terminal description

OGT trailer shown in Figure 1a is specifically designed to accommodate the complete setup and consists of two separate compartments. The front compartment contains all control electronics and a workspace for the operator, while the back compartment houses the adaptive optics and affiliated optics. Both compartments are individually temperature controlled by two double purpose air-conditioning units and includes an interlock to ensure laser safety.

The back compartment of the trailer houses a double layered breadboard mounted on a rigid frame which is supported on four individual legs (Figure 1b). In operation these legs are extended through the trailer floor, allowing it to stand separately from the trailer to ensure mechanical stability. The OFELIA breadboard is placed on the top breadboard, which can send and receive the up- and downlink via a Coarse Pointing Assembly (CPA) mirror through the exit window.

A collimator is included as Calibration Unit (CU), which can be used as reference for calibration and verification purposes by moving the Sliding Mirror (SM) in front of the exit aperture of OFELIA. While the system is in calibration mode, the rifle scope can be used for course pointing of the Course Pointing Assembly (CPA) mirror, reflected by the backside of the double coated SM.

The bottom breadboard layer is designed to fit the Beam Multiplexer (BMUX), which is designed to multiplex up to 20 wavelength separated channels for allowing the Terabit communication rates. The BMUX is developed in parallel and discussed in [5]. For the AO Demonstrator test the BMUX is not integrated yet and only a single Tx channel at 1551.33 nm was used for the OGT.

2.3 Space terminal breadboard description

Figure 2 shows the STB developed by TNO as a reconfigurable breadboard and is part of the test hardware for the Optical Communications (OC) Lab. The STB is equipped with an Acquisition and Tracking Sensor (ATS) and a FSM to correct for tip-tilt aberrations. The optical power measured by the free-space Power Meter (PM) is used to evaluate the uplink AO performance. The ATS is operated at a 5 KHz sample rate to enable tip-tilt closed loop bandwidths of 160 Hz. Contrary to the previous field test, this STB contains an internal beacon to enable zero PAA and an external beacon placed on a mechanical stage which can simulate PAA up to 30 µrad over the 10 km link distance.

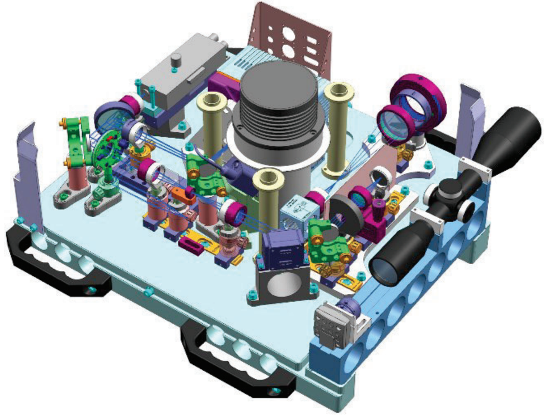

Figure 2: Optomechanical STB design (excluding the PAA stage)

2.4 Turbulence monitors

Local turbulence effects along the link can have large effects on the received wavefront and therefore monitoring of these effects is key during the field test. Therefore four Turbulence Monitors (TM's) are placed along the link path as schematically represented in Figure 3(a). The turbulence monitors contain a sonic wind meter (for measuring wind speed and direction) and a weather station (pressure, temperature and humidity). These TM's are placed at a link height and are synchronized with a GPS timestamp to allow to match turbulence data with the other measurements.

2.5 Test description

The measurement campaign was performance over 3 consecutive days in spring at day time (10 to 7 pm CET). The tests were executed over a distance of 10 km at the test site shown in Figure 3, located southwest of the city Utrecht, Netherlands. The OGT is placed at the KNMI site in Cabauw which offers a variety of weather data monitoring systems to measure the local weather conditions.

The STB is placed in the Gebrandy tower in Lopik at a height of 226 meters, imposing an incline of 1.3 degrees. The test site was selected since the area between Cabauw and Lopik is flat and consists mainly of grassland, which should improve the predictability of the turbulence profile.

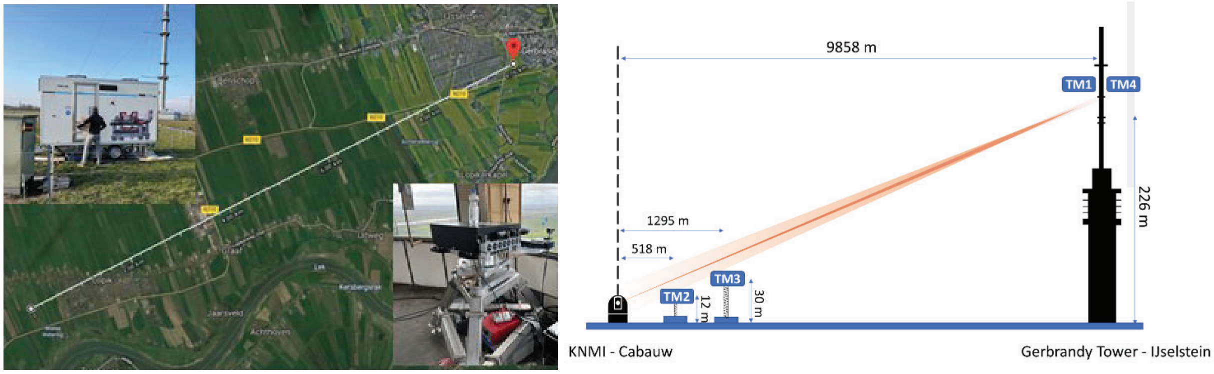

Figure 3: Test site (a) location between Cabauw and Lopik and (b) height profile and location of TM's

3. AO DEMONSTRATOR TEST RESULTS

3.1 CN2 measurements

One of the key parameters for quantifying the turbulence strength is the refractive index parameter C_n^2. The C_n^2 and the affiliated temperature structure parameter C_T^2 are calculated respectively based on equations 1 and 4 found in [6]. The surface layer is generally encountering the strongest turbulence conditions. Therefore TM2, which at a height of 12 meters closest to the surface layer, is taken as reference. Note that by basing the analysis on a single turbulence measurement, variations in the turbulence profile are not taken into account.

The varying turbulence conditions and weather conditions are subject to change within a measurement sweep. Additionally, other weather conditions have an influence on the link performance, such as smog, fog and precipitation. By comparing the results to the preceding reference where a reference is a tip/tilt corrected measurement only, the results are normalized to minimize the spread due to external conditions.

3.2 Adaptive optics downlink results

The performance of the AO control can be analyzed by observing the residual RMS Wave Front Error (WFE) of the downlink based on the reconstructed wavefront measured by the WFS. The absolute residual RMS WFE as function of the number of controlled AO modes is shown in Figure 4a. In weak turbulence conditions a 75 nm residual with the 28 mode controller is attained, which is in line with the performance achieved in lab conditions. In this figure an overall increase in residual RMS WFE is visible with increased turbulence strength, which is expected as the overall disturbance is increasing.

In Figure 4b the relative residual RMS WFE as function of the turbulence strength is displayed for various AO modes with tip-tilt as reference. From this plot a clear reduction in residual WFE is observed with increasing number of modes, while the gain remains roughly constant in the full range of encountered turbulence conditions.

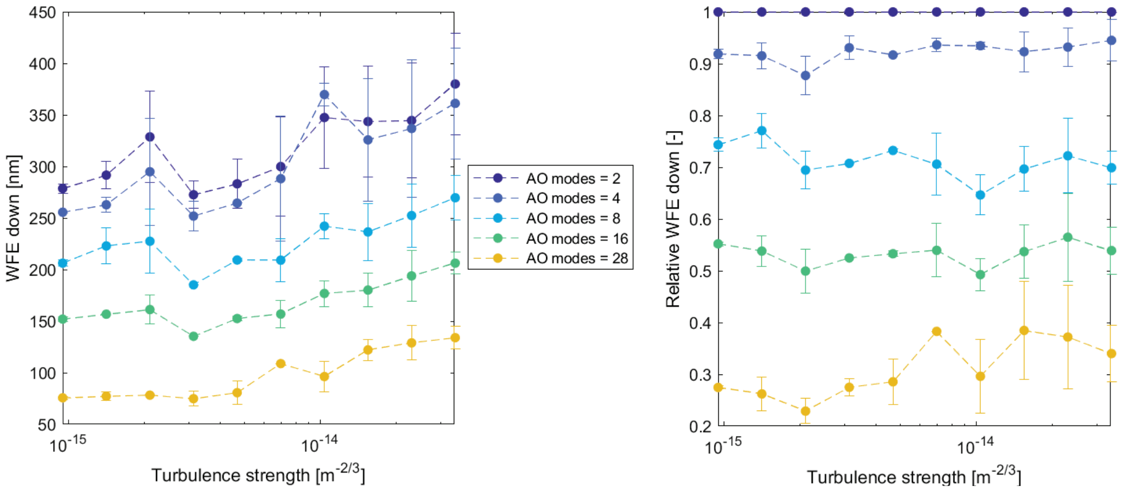

Figure 4: (a) Residual RMS WFE and (b) Relative residual RMS WFE as function of the turbulence strength for various AO modes

3.3 Adaptive optics uplink results

A similar analysis can be performed on the uplink to verify the pre-correction performance. During the measurement the PAA was swept between 0 and 29 urad, thereby applying an angular offset between the up and downlink. The results show all PAA's combined for the sake of improved statistical representation. To normalize the (relative) results the tip-tilt reference in the same PAA configuration was used, therefore still being representative for achieved AO gain.

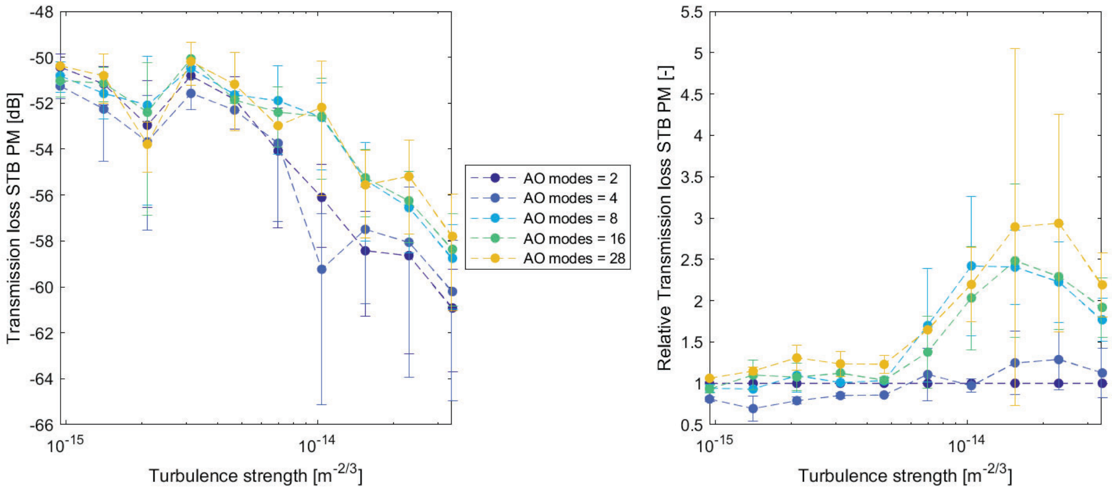

Figure 5: STB (a) PM transmission losses and (b) relative PM transmission losses as function of the turbulence strength for various AO modes

The PM transmission path losses at the STB are shown in Figure 5a. The figure shows a gradually increasing fall-off in transmission loss as the turbulence strength increases.

The relative transmission path losses are shown in Figure 5b, which shows an overall improvement for increasing number of AO modes. The relative transmission gain increases with the turbulence strength, indicating that the AO precorrection becomes more effective in stronger conditions. Although the 4 AO mode controller shows only minimal gain over tip-tilt, the 28 modes show a gain up to a factor 3 depending on the turbulence conditions. Overall, the absolute transmission loss increases with stronger turbulence, which can only be partially counteracted by the pre-correction.

Apart from the mean irradiance, the stability can be quantified by the variation of the uplink irradiance, i.e. the longitudinal or on-axis scintillation, which is given by:

$$\sigma_I^2 = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1$$

With scintillation index σ_I^2 and received irradiance I. The encountered on-axis scintillation is presented in Figure 6a, which shows an increasing scintillation index for increasing turbulence strength. Note that in all configurations the additional scintillation caused by beam wander has been compensated by the tip-tilt pre-correction.

Figure 6b shows the relative gain in scintillation with respect to the tip-tilt reference case. The curves representing the 8, 16 and 28 AO modes follow a similar behavior, showing slight improvement in longitudinal scintillation to the reference case. In contrast, the 4 AO modes curve show slightly worsened behavior with respect to all other AO modes. All-in-all, the relative longitudinal scintillation remains close to 1 for the AO modes over the full turbulence range, therefore only showing a minor effect of the AO pre-correction on the scintillation of the uplink.

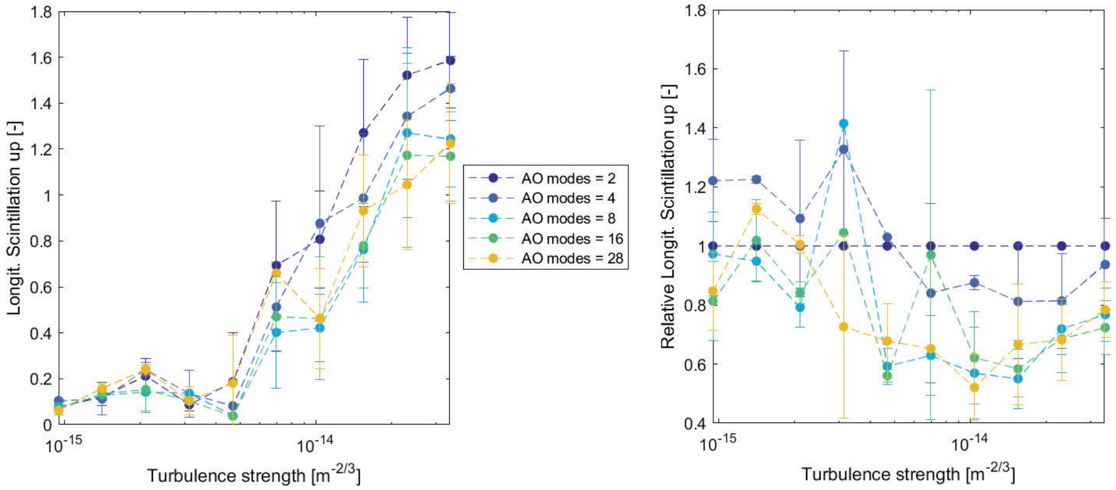

Figure 6: STB (a) longitudinal scintillation and (b) relative longitudinal scintillation of the uplink as function of the turbulence strength for various AO modes

4. CONCLUSION

The OFELIA breadboard has been upgraded and integrated with all peripheral equipment in the AO demonstrator, which was successfully tested over a 10 km ground-to-ground link. The AO control has been proven to operate effectively, as the observed residual RMS WFE of 75 nm at weak turbulence conditions coincide with the measurements in lab conditions. The AO performance showed a decrease of the residual RMS WFE up to a factor 4 for 28 modes AO control with respect to the reference case. This is a significant improvement with respect to the results of the OFELIA test campaign presented in [2] in which a factor 2 at daytime was reported. The improved performance can be attributed to the upgraded AO bandwidth and the upgraded design of the terminal. In addition, the TM's now allow the performance to be related to the encountered turbulence conditions.

The uplink shows a gain in received mean irradiance which increases with the number of applied AO modes for the pre-correction. The achieved average gain increases with the turbulence strength, thereby significantly reducing the experienced irradiance loss in stronger turbulence conditions. At strong turbulence conditions ($2 \cdot 10^{-14}$ $m^{-2/3}$) an average gain of 5 dB for 28 AO modes with respect to the tip-tilt reference case could be obtained. The effect of AO on the uplink scintillation shows only a minor improvement. This corresponds to the results obtained previously [2], in which the main reduction in uplink scintillation was accounted to the tip-tilt pre-correction or beam wander correction. Also based on simulations it was known that for an adaptive optics design with (single) phase correction only the expected gain for on-axis scintillation is neglectable or even negative.

Although the analysis of the field test data is ongoing, it can be concluded based on the presented results that the AO control and pre-correction is properly functioning over a range of turbulence conditions. The transmission losses are within bounds foreseen in our link budgets, leaving sufficient optical power for the communication equipment to operate. The system is therefore ready for its upgrade to the OGT configuration by adding the BMUX and communication equipment for the follow-up RF end-to-end communication demonstrator.

REFERENCES

[1] R. Saathof et al., "Adaptive Optics pre-correction for Optical Feeder Links – breadboard performance" in International Conference on Space Optical Systems, 2018.
[2] R. Saathof et al., "Pre-correction Adaptive Optics Performance for a 10 km Laser Link", Spie Proc. Free-Space Laser Communications XXXI (Vol. 10910, pp. 325-331), March 2019
[3] H. Hemmati, Near-Earth Laser Communications. CRC Press, 2009.
[4] R. Saathof et al., "Optical technologies for terabit/s-throughput feeder link," in International Conference on Space Optical Systems, 2017.
[5] F. Silvestri et al., "High-Power Free-Space Bulk Multiplexer for Satellite Communication Optical Ground Terminal" in International Conference on Space Optical Systems, 2022.
[6] D. Sprung et al., "Stability and height dependant variations of the structure function parameters in the lower atmospheric boundary layer investigated from measurements of the long-term experiment VERTURM (vertical turbulence measurements)," Proceedings of SPIE Vo. 8178: Optics in Atmospheric Propagation and Adaptive Systems XIV , 2011.