FEEDELIO

EXECUTIVE SUMMARY (D9)

(AER 26905 DOTA)

ESA Contract 4000120300/17/NL/PS

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1.1. Scope of the document

This document is the executive summary of ESA Contract 4000120300/17/NL/PS.

1.2. Applicable documents

[AD1] ESA Contract 4000120300/17/NL/PS.

2. EXECUTIVE SUMMARY

Introduction

The future of very high throughput optical links between the ground and GEO satellites depends on the ability to overcome turbulence channel disruptions caused by the optical propagation through the atmosphere. Pre-compensation by adaptive optics (AO) has been identified as a game changer, as it could theoretically provide for the uplink the additional margin necessary to secure the link budget.

However, experimental demonstrations are needed in order to prove that theoretical performance of such a link can indeed be achieved, especially regarding angular decorrelation due to the 18 µrad point-ahead angle, and its effect on link budget and reciprocity of the downlink and uplink signals. Thus several experimental activities have been reported lately, to investigate the practical increase that can be expected from AO pre-compensation [1,2,3], demonstrating very promising results.

Due to the proximity of the line of sight from ground in these experiments, and the strong variability of turbulence conditions, these results would benefit from a confirmation on a more representative line of sight, comparison to theoretical performances, and extrapolations to actual GEO-feeder link performances. These are the goals of the FEEDELIO experiment.

AO Pre-compensation

Because of spatial and temporal fluctuations of the local index of refraction that affect light propagation through the atmosphere, turbulence has two effects on the optical links: first a decrease of the mean received power, second temporal fluctuations of the received power around its mean, possibly leading to deep fadings, and thus communication disruptions. AO pre-compensation of the feeder link consists in emitting from the ground, in real time, a beam with the opposite aberration that is anticipated to be brought by turbulence, in order to obtain a quasi-diffraction limited beam at the exit of the atmosphere.

The FEEDELIO experiment has been designed to demonstrate the ability of AO to increase average power and reduce power fluctuations of optical signals due to atmospheric turbulence, in concordance with experimental conditions representative of a GEO feeder link. Two acquisitions campaigns were conducted at different period of two different years: the first one took place in April 2019, the second in October 2021. The experiments consisted in a bidirectional AO compensated link on a 13 km slant path in Tenerife, Canary Islands, between a Ground Terminal Breadboard (GTB) set in ESA's OGS in Tenerife observatory, and a Satellite Terminal Breadboard (STB) set on top of Mount Teide (see figure 1).

Figure 1 : FEEDELIO line of sight between ESA OGS (left) and Teide's accommodation building (right).

The theoretical background and principle of the FEEDELIO experiment were presented in [4], the experiment in itself in [5].

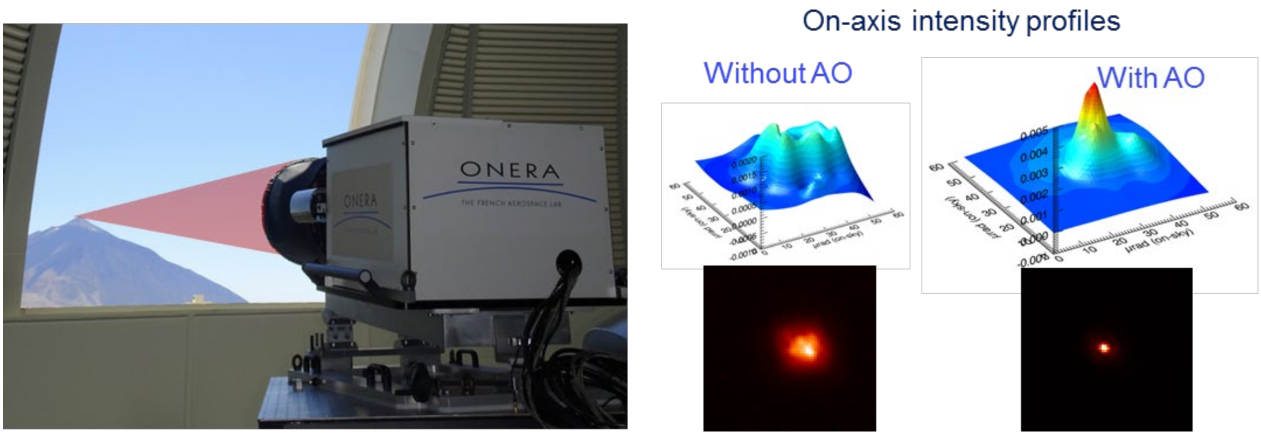

Figure 2 : On the left: view of the GTB on the south pilar of ESA's OGS. On the right: example of mean signal and intensity profiles measured with on the uplink (top) and the downlink (bottom), without and with Adaptive optics. In this case, the gain of using AO compensation was around 10 dB.

Results

Both experiment campaigns were successful. As shown in figure 2, on-axis (i.e with no point-ahead angle) the AO precompensation led to gains in link budgets up to 10 dB depending on the turbulence strength. As illustrated by figure 3 signal fluctuations were significantly reduced compared to a tip/tilt only correction including for variable turbulence conditions encountered during the two campaigns (from few centimeters to dozen of centimeters for Fried diameter and from few microradians to dozens of microradians for the isoplanatic angle. A 95 % correlation between uplink signal and downlink signal was obtained thanks to reciprocity (see figure 4). This corresponds to our knowledge to the first demonstration of this level of correlation reported in the literature with an AO system (to the best of our knowledge). The precompensation performance degradation due to PAA has been clearly observed (see figure 5 were the temporal evolution of the received optical power in the STB has been plotted for measurements performed on 21/10/16). The average degradation has been successfully compared to models demonstrating the relevance of such models (figure 6). The results of the FEEDELIO experiment were presented in [6,7].

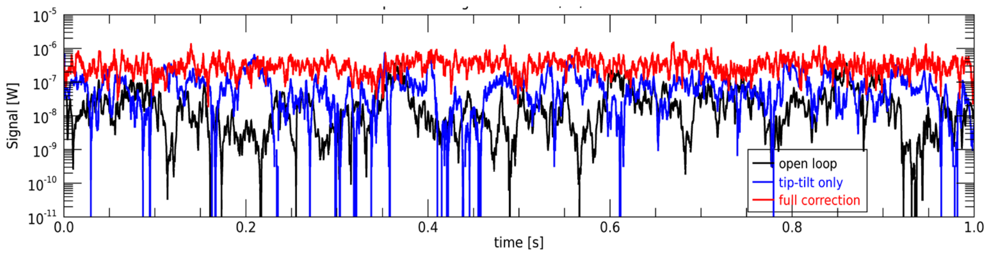

Figure 3 : Received optical power in STB without adaptive optics correction (black), with tip/tilt only correction (blue) and with AO (red) on 19/04/14 10:22 UTC.

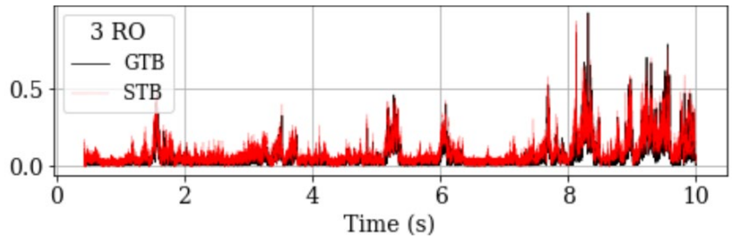

Figure 4 : Example of the strong correlation of the uplink (in red) and downlink (in black) signals (on-axis, without PAA) due to the reciprocity of the link.

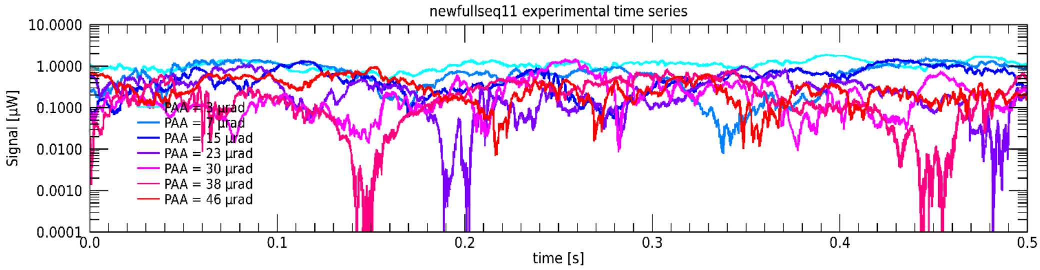

Figure 5 : STB instantaneous optical power as a function of time for different PAA angles recorded the 21/10/16, recording beginning at 07:37 UTC. Fried parameter: from 16 cm to 25 cm during the acquisition sequence, isoplanatic angle: from 8 to 10 µrad.

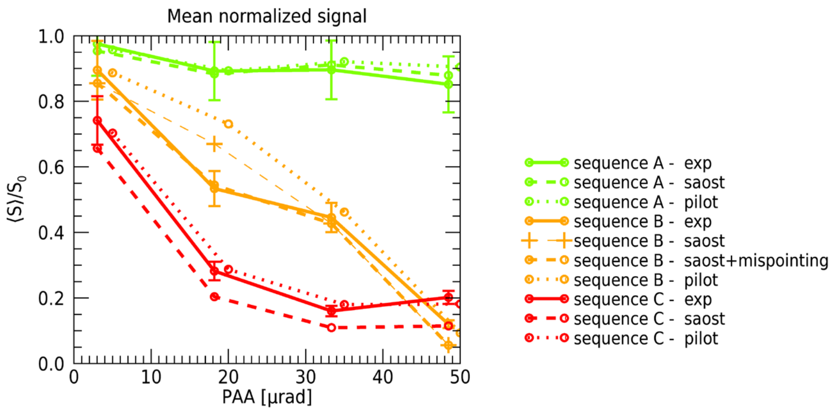

Figure 6 : Mean normalized signal recorded at the STB as a function of PAA Off-axis performance for three sequences with increasing anisoplanatism and turbulence strength (sequence A : r_0 = 89 cm, θ_0 = 46.7 µrad; sequence B : r0 = 12 cm, θ_0 = 18.5 µrad; sequence C : r_0 = 15 cm, θ_0 = 7.8 µrad. Experimental values (full AO) in plain lines, theoretical values with simplified model SAOST in dashed lines, theoretical values with end-to-end PILOT model in dotted lines.

Conclusion

We reported here the results of the first experimental demonstration of pre-compensation for GEO – FEEDER links in a relevant environment. Two experiment campaigns were successfully conducted, the first one in April 2019 and second one in October 2021. The performance of AO pre-compensation has been investigated in highly variable turbulence conditions on a 13.2 km slant path line of sight between ESA's OGS and top of Mount Teide in Tenerife. Restricting the analysis to smooth perturbations case, more relevant for GEO-FEEDER links, the feasibility of a pre-compensation by adaptive optics has been confirmed. The influence of PAA has been quantified experimentally and compared successfully to anisoplanatism error evaluation. Performance models to estimate the average power penalty fit well with measurements. Depending on the approach to provide a GEO-FEEDER link analogy the gain brought by pre-compensation in the presence of anisoplanatism is variable depending on turbulence conditions. Most of the time AO bring a significant gain in terms of instantaneous received power at the expense of sometime strong residual fluctuations due to anisoplanatism. Particular interest shall be granted to temporal signature and power fluctuations characteristics so that to properly design error correcting codes and interleavers to cope with these residuals power fluctuations. Anisoplanatism highly restricts the potential gain of AO with significant size telescopes. Appropriate strategies must be investigated to circumvent this limitation. Among others, the use of a free flyer satellite to provide the beacon for wavefront sensing in the direction of the PAA is conceptually the most promising one.

[1] A. Brady et al., "Experimental validation of phase-only pre-compensation over 494 m free-space propagation," Opt. Lett., vol. 42, no. 14, pp. 2679–2682, Jul. 2017.

[2] R. Saathof et al., "Pre-correction adaptive optics performance for a 10 km laser link," in Free-Space Laser Communications XXXI, 2019, vol. 10910, p. 109101H.

[3] Calvo, Ramon Mata, et al., "Optical technologies for very high throughput satellite communications ", Free-Space Laser Communications XXXI. Vol. 10910. International Society for Optics and Photonics, 2019.

[4] N. Védrenne, et al., "Adaptive optics pre-compensation for GEO feeder links: Towards an experimental demonstration ", Proc. of IEEE ICSOS, 77-81 (2017).

[5] A. Montmerle Bonnefois et al, "Adaptive Optics pre-compensation for GEO feeder links: the FEEDELIO experiment ", Proc of ICSO 2018

[6] N. Védrenne et al., "First Experimental Demonstration of Adaptive Optics Pre-Compensation for GEO Feeder Links in a Relevant Environment ", in 2019 IEEE International Conference on Space Optical Systems and Applications (ICSOS), oct. 2019, p. 1-5. doi: 10.1109/ICSOS45490.2019.8978970.

[7] P. Lognoné et al., "New results from the 2021 FEEDELIO experiment - a focus on reciprocity ", in 2022 IEEE International Conference on Space Optical Systems and Applications (ICSOS), March 2022.