International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

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International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111802C · © 2018 ESA and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536003

Adaptive Optics pre-compensation for GEO feeder links: the FEEDELIO experiment

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ABSTRACT

Adaptive-Optics (AO) pre-compensation of atmospheric turbulence effects is one of the most promising technologies for achieving very high throughput optical GEO feeder links. However, its great performance has been proven mostly through numerical simulations until now, and experimental work on the subject is still at a very preliminary stage [1]. The FEEDELIO experiment (FEEDELIO for FEEDEr Link adaptive Optics), contracted to ONERA by ESA and described in this paper, goes one step further towards an experimental validation of this concept.

This paper describes the experimental implementation of an AO pre-compensated link on a 13 km slant path in Tenerife, Canary Islands. This experiment is designed to be representative of a GEO feeder link, and aims at demonstrating a significant increase of the mean received power and decrease of the power fluctuations thanks to AO. It will also allow to study the impact of the point-ahead angle on overall performance of the AO system.

The FEEDELIO experiment is planned for spring 2019.

Keywords: Adaptive Optics, pre-compensation, GEO feeder links, point-ahead angle, free-space optics

1. INTRODUCTION

In the context of an increasing need for very high throughput Ground-to-GEO satellite data links, optical communication systems appear as a very promising candidate: the most cited advantages are a regulation free spectrum, the technological maturity of the optical components for the ground segment (detectors, MUX/DEMUX, optical amplifiers) thanks to the 40 years of development in fibered technologies, and intrinsically more secured communications due to extreme directivity. Moreover, several studies [2][3] demonstrate that the joint use of a dozen ground stations disseminated in Europe enables one to overcome the potential occultation of the line of sight (LOS) caused by nebulosity (site diversity concept).

However, the impact of atmospheric turbulence on the optical signal propagation is a major hurdle to the development of such technology: considering a 38 000 km propagation range, the signal power undergoes more than 90 dB total loss and dramatic variations of the signal power due to spatial and temporal fluctuations of the local index of refraction, that affect both the uplink beam, unless it benefits from some form of pre-compensation.

For this reason, adaptive optics (AO) pre-compensation of atmospheric turbulence has been identified as a key strategy to achieve such links: by significantly improving the link budget, it allows the use of sources with reasonable output power. However, experimental work on the subject is still at a very preliminary stage [1].

This paper describes the experimental implementation of an AO pre-compensated link on a 13 km slant path in Tenerife, Canary Islands, that is planned for spring 2019. This experiment aims at demonstrating significant increase of the mean received power and decrease of the power fluctuations thanks to AO, as well as measuring the impact of the point-ahead angle (PAA) and turbulence strength on the overall performance of the link. The theoretical background and principle of the FEEDELIO experiment were presented at ICSOS 2017 [4]. In this paper, we go one step further and present the final design of the experiment including the PAA.

2. EMULATING AO PRE-COMPENSATION FOR GEO FEEDER LINKS

2.1 AO pre-compensation and Point-ahead Angle

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 ("coupling losses"), second temporal fluctuations of the received power around its mean, possibly leading to deep fadings ("scintillation losses").

The 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 principle is recalled on the left diagram in Figure 1. We also recall on the right diagram on this figure that the downlink pilot beam and the uplink pointing direction are separated by an angle called point ahead angle (PAA). PAA is about 18 µrad for a GEO satellite. One can show from the reciprocity principle that the PAA introduces a limitation on AO performance that corresponds to the anisoplanatism error between two descending beams separated by PAA [5].

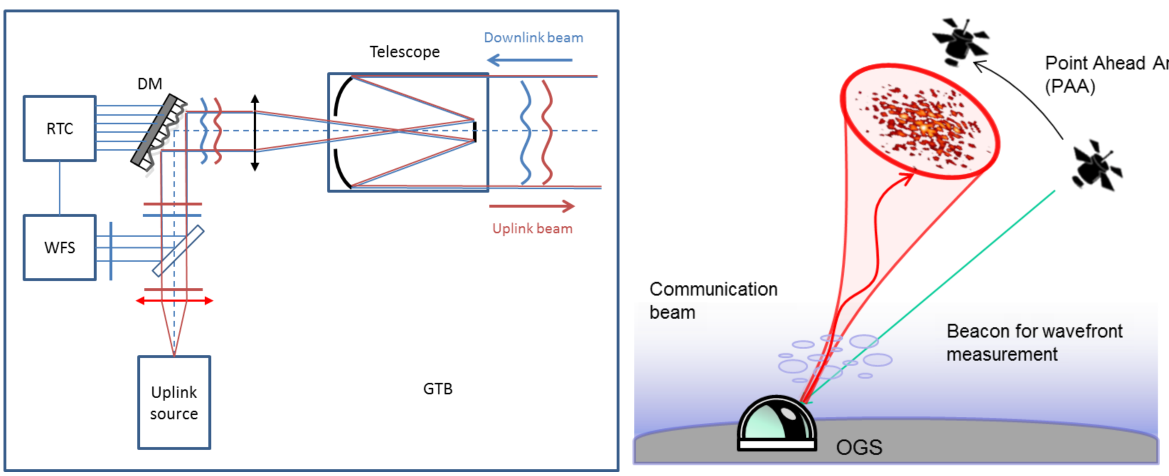

Figure 1. Left : principle of uplink pre-compensation by adaptive optics (AO). Right : The Point Ahead Angle is due to earth rotation. Because of the PAA, the turbulence layer seen by the downlink beam, which is used for wavefront analysis, is not exactly the same as the one seen by the uplink beam, hence limiting the performance of AO precompensation.

We performed thorough studies of the theoretical performance of AO pre-compensated feeder links thanks to end-to-end numerical simulations, whose main results are discussed in detail in ref [4]. Among those, the graph on Figure 2 clearly shows the improvement that AO can bring to the availability of an optical feeder link, even with a very simple three radial orders AO correction: in this case and with a tip-tilt only configuration, a 99,9% availability requires the source power to be more than 6 dB higher than in the 3-order AO pre-compensation case.

Those results, however, are theoretical; an experimental validation is needed. Such experiment should be held on the ground because it is convenient and more versatile – but it should still be representative of a real GEO feeder link regarding turbulence effects on the uplink and downlink beam, including PAA. The next paragraph describes how to achieve this.

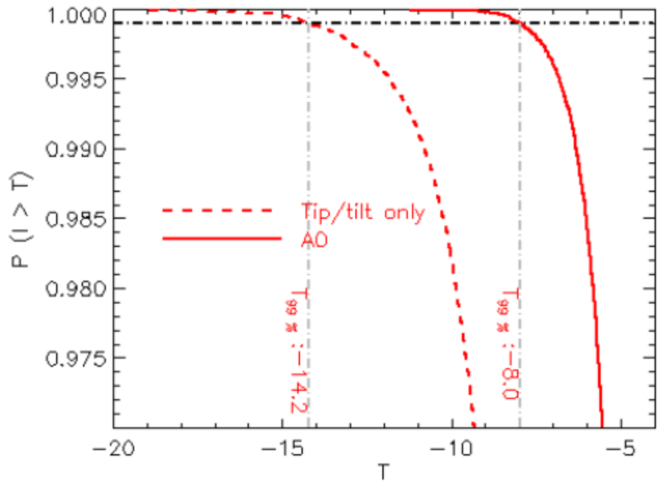

Figure 2. Cumulated fading probability as a function of threshold in dB for a 20 cm aperture system, considering an AO correction of either nr = 1 (tip-tilt) (dashed line) or nr = 3 radial orders (solid line). We indicate the threshold $T_{99\%}$ corresponding to a 0.999 cumulated probability (hence a 99.9% link availability). This threshold, expressed in dB, is the power loss one has to accept compared to the diffraction limited case.

2.2 Scaling GEO feeder scenario to a slant-path experiment

In order to design the FEEDELIO experiment, one has to specify the notion of "relevance", alias "representability", of FEEDELIO with respect to the GEO-feeder link case. The question may therefore be formulated as follows: "Can we find a FEEDELIO configuration so that FEEDELIO and GEO-Feeder link lead to similar power fluctuations (mean loss and standard deviation) with similar AO designs in terms of number of corrected modes and sampling frequency?"

The answer is yes, as was explained in [4]. More precisely, in the case of the slant-path 13 km link in Teide that was suggested by ESA, and with some assumptions on turbulence conditions taken from literature, we found that a GEO-Feeder link with a 20 cm emitter aperture has strong similarities with the FEEDELIO ground experiment in daytime turbulence conditions with the following characteristics: a 35 cm ground terminal emitter aperture and an angle separation between downlink pilot beam and detector of ~ 60 µrad to emulate the PAA.

In practice, in order to face various turbulence conditions, we chose the following AO design: correction up to 7 radial orders, wavefront measurement with 8x8 subaperture Shack-Hartmann WFS, loop sampling frequency up to 1.5 kHz.

3. DESIGN OF THE FEEDELIO EXPERIMENT

3.1 Experiment purpose and overall architecture

The FEEDELIO experiment has been designed to demonstrate the capacity of AO to increase average power and reduce drastically power fluctuations of optical signals due to atmospheric turbulence, in concordance with experimental conditions representative of a GEO feeder link. Our purpose is triple. We want to :

- measure metrics of interest in several scenarios: the mean power loss (*uplink coupling losses*), and received power fluctuations, for instance characterized by its standard deviation (parameter that is related to the *scintillation losses*);
- quantify the gain brought by AO pre-compensation on these metrics, for various choices of the number of correction modes (including tip-tilt only);
- and of course we want to verify the influence of anisoplanatism brought by the PAA on the correction.

In order to achieve this, the experiment will consist in two terminals, as described in Figure 3 : the Ground Terminal Breadboard (GTB), which emulates an optical ground station equipped with wavefront analysis of the downlink beam and AO pre-compensation of the uplink beam; and the Satellite Terminal Breadboard (STB), which emulates a satellite emitter and receiver, including the PAA, and measures coupling and scintillation losses on the uplink beam.

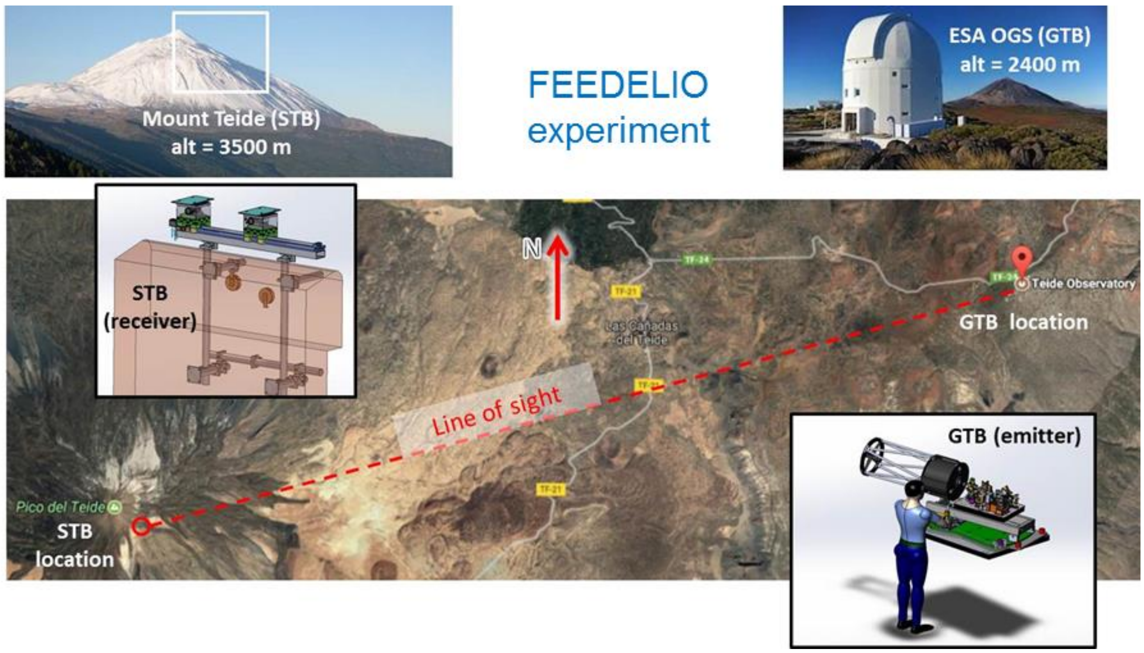

Figure 3.Principle of the FEEDELIO experiment: The Satellite Terminal Breadboard emulates the optical beam coming from a satellite, with an adjustable PAA, and performs signal fluctuations measurements. The Ground Terminal Breadboardemulates an optical ground station equipped with AO pre-compensation of the feeder beam.

The design must take into account several difficulties: for instance, a smaller than 1 µrad pointing accuracy is needed to truly benefit from the nearly diffraction limited uplink beam brought by AO pre-compensation. Moreover, uplink and downlink optical separation is quite demanding, as AO requires that downlink and uplink beams share the part of the optical path that includes the deformable mirror while the ratio between the emitted and received power is greater than 10^9. To address turbulence non stationarity, the line of sight will have to be alternatively changed between on-axis and off-axis thanks to a fast steering mirror (FSM), with a time period small enough to ensure turbulence conditions stationarity (ie below 1 minute) and long enough to ensure rich statistics of power fluctuations (greater than a few seconds, typically 10 s).

Other constraints were taken into account: a variable distance from 10 to 100 µrad between downlink beacon and uplink detection is implemented for a precise study of anisoplanatism effects and to cope with the turbulence conditions variability expected from ground proximity of the line of sight.. The optical setup has been designed to cope with the challenging power difference between up and downlink. Evolution of the line of sight during the day was also taken into account. In operation, on the GTB side, the AO loop performance will be monitored thanks to long exposure point spread functions acquired with a focal plane camera and Real Time Computer (RTC) telemetry. The received optical power from downlink will be injected in a single mode fiber and a bit-error-rate (BER) evaluation will be conducted on the received signal at a 10 Mbps data rate. Turbulence conditions will be inferred from post processing of the loop telemetry.

Other constraints were taken into account: a variable distance from 10 to 100 µrad between downlink beacon and uplink detection is implemented for a precise study of anisoplanatism effects and to cope with the turbulence conditions variability. As for the optical design, especially the deformable mirror, it is compatible with high power in order to be representative of a real GEO feeder link, even though the optical power in the case of the FEEDELIO experiment quite low (a few milliwatts); Evolution of the line of sight during the day was also taken into account. In operation, on the

GTB side, the AO loop performance will be monitored thanks to long exposure point spread functions acquired with a focal plane camera and RTC telemetry. The received optical power will be injected in a single mode fiber and a BER evaluation will be conducted on the received signal at a 10 Mbps data rate.

The functional diagram of the experiment is given on Figure 4.

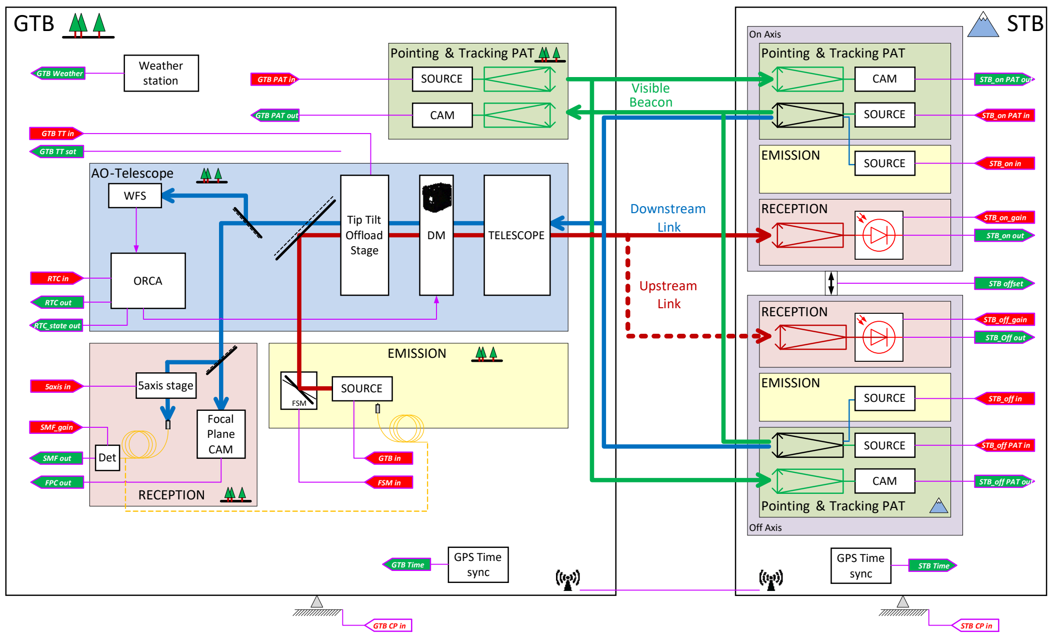

Figure 4. Functional diagram of the experiment.

3.2 STB Design

The purpose of the STB is to emulate on the ground an optical terminal as it would behave if it were on a satellite. It is to be settled on the accommodation building on mount Teide, and must fulfill three functions:

- it must emit the pilot beam at 1550 nm ("downlink beam") toward the GTB, where it will be used for wavefront sensing,

- it must measure the on-axis and off-axis irradiance and scintillation statistics of the 1625 nm beam coming from the GTB ("uplink beam"), in order to estimate the efficiency of turbulence pre-compensation on the uplink beam, as a function of the PAA,

- it must emit a real-time optical signal modulated in NRZ-OOK through the downlink beam, to allow BER measurements at the GTB.

Figure 5.STB design. One module is fixed and aligned with the GTB optical axis ("on-axis module"), the other one ("off-axis module") can be translated through motorization in order to emulate the PAA.

These functions can be achieved through a rather simple optical device, depicted in Figure 5. The off-axis module is motorized in order to adapt the "equivalent PAA" to the turbulence conditions.

3.3 GTB Design

The purpose of the GTB is to emulate an optical ground station equipped with AO pre-compensation. It is to be settled in the OGS at the Tenerife observatory. It must fulfill several functions : emission of the uplink beam ("feeder link") at 1625 nm, pre-compensation of the turbulence aberrations of the said beam thanks to an AO closed loop, wavefront analysis on the downlink beam, control of the quality of the AO correction thanks to a monitor camera, and injection of the pilot beam in a monomode optical fiber.

The GTB AO system will have to be able to correct turbulence with D/r0 ~ 3 (worst cases will also be considered, with D/r0 ~ 8), and handle atmospheric refraction up to approximately 250µrad. Its main characteristics will be :

- correction from 1 (tip-tilt only) to up to 5 radial orders,
- wavefront measurement with 8x8 subapertures to limit the influence of aliasing on wavefront measurement and control up to 5 radial orders.
- up to 1.5 kHz sampling frequency A Fast Steering Mirror must direct the uplink toward the STB on-axis or off-axis module with a better than 1 µm accuracy.
- One uplink wavelength channel.

As can be seen in Figure 6 and 7, GTB is a quite complicated device requiring careful alignment and AO optimization. It is the heart of the experiment.

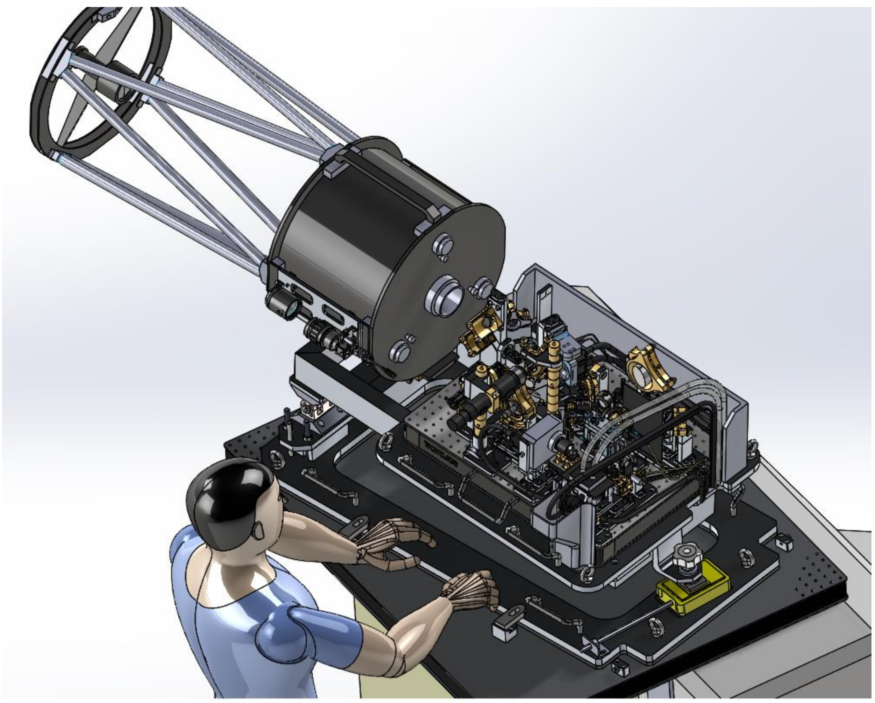

Figure 6. GTB overall design. It is to be settled inside the dome of the OGS of the Teide Observatory.

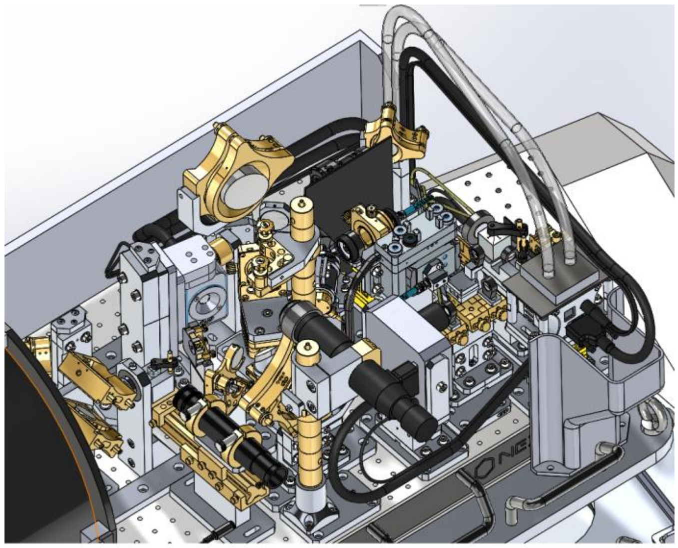

Figure 7. Details of the bench of the GTB.

4. CONCLUSION

In the framework of the FEEDELIO project the ability to leverage turbulence induced fades and surges thanks to uplink pre-compensation will be experimentally investigated in a relevant environment (a 13 km slant path between ESA OGS and top of mount Teide). The design of the bench has been conducted to cope with a wide variability of turbulence conditions and with a high power ratio between up and downlink. Integration of the breadboards is ongoing. The next steps will include standard in lab Assembly Integration and Tests (AIT), and then functional tests on a 4.2 km horizontal link between ONERA site in Châtillon and Meudon Observatory (France) by the end of the year. Then the breadboards will be transferred to Tenerife, for scientific experiments scheduled in spring 2019.

These experiments will provide precious data that will be used to consolidate optical link models, which is essential for the design of future ground and space segments for AO pre-compensated very high-throughput optical feeder links.

5. ACKNOWLEDGEMENT

This work has been contracted to ONERA by ESA to design and carry out the experiment. We would like to thank ESA for their trust and support, and for the always fruitful exchanges.

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