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# FEELINGS, ONERA's optical ground terminal for AO pre-compensated GEO Feeder links demonstration

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## ABSTRACT

These last years have seen a raising interest for ground to GEO satellites optical very high throughput links, i.e. GEO-feeder links, or GEO-FL. However, despite their potential, these applications have to overcome atmospheric turbulence, which requires the development of mitigation techniques, such as adaptive optics (AO). In the case of GEO-FL, AO performance is limited by the Point-Ahead Angle (PAA) induced anisoplanatism. We describe here how our feedback on our field experiments helped us to design ONERA's AO-compensated ground station, FEELINGS, and the status of said ground station in the fall of 2022.

**Keywords:** optical ground station, GEO feeder links, adaptive optics

## 1. INTRODUCTION

Optical technologies are a very competitive candidate to achieve very-high throughput links between ground and GEO satellite, the so-called GEO-feeder links (GEO-FL) [1]; however, their feasibility relies on the ability to mitigate channel impairments due to atmospheric turbulence. 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 at all time. It implies, among other things, the development of performant, cost effective and highly operational optical ground stations equipped with AO pre-compensation.

On the downlink several demonstrations including long-term exploitation [2] have demonstrated that a commercial exploitation is already possible. For the uplink point ahead anisoplanatism compromises the link performance [3] [4]. Feeder link ground station projects are now under development with tradeoffs to be made on baseline architectures and key performance drivers.

In that respect, some critical scientific and technological issues need to be addressed, such as fine calibration and optimization of the point-ahead angle, mitigation of turbulence effects through AO, including anisoplanatism, both downlink and uplink. Instrument stability over time, over a wide range of weather and turbulence conditions, is also a challenge. There's also the question of how to design high power sources compatible with wavelength division multiplexing (WDM) and high frequency modulation, but also integrating them within the OGS, ensuring shape of the beam, isolation of up and downlinks, diffusion on optics.

Development and dimensioning of OGS also means a precise understanding and estimation of link budget on sky down to detection, including atmospheric transmission, actual pointing errors, turbulence conditions and AO performance. All these elements shall be monitored or evaluated, and compared to models, in order to refine systems design (in a numerical twins approach).

To address these challenging issues, ONERA is currently developing a research optical ground station, FEELINGS (FEEder LINks optical Ground Station). Its goal is to tackle the scientific and technological risks related to (GEO-FL), propose and validate concepts, components or algorithms to pave the way of future operational OGS, with high capacity and operability. FEELINGS also aims at addressing LEO links.

In this presentation, we'll present how we used the learnings from FEEDELIO and VERTIGO experiment to design the FEELINGS OGS, and discuss its current status.

## 2. FROM FEEDELIO AND VERTIGO TO FEELINGS

Before going on-sky with the FEELINGS optical ground terminal, our team at ONERA performed slant-path experiments in order to validate models and technical choices, especially regarding AO precompensation. The first one was the FEEDELIO experiment, performed in the frame of an ESA project, and the second one took place during the outdoor demonstration of the H2020 project VERTIGO.

### 2.1 The FEEDELIO experiment

The FEEDELIO experiment aimed to perform a ground experiment that demonstrates turbulence pre-compensation by AO under conditions representative of a GEO-FL scenario. In practice, the objective was to demonstrate the capacity of AO to increase the average transmitted power and drastically reduce the power fluctuations of the optical signals over a wide range of turbulence conditions, and to identify among them the conditions that were the closest to a real GEO-FL. It took place in Tenerife during two sessions: the first one in April 2019, the second one in October 2021. The optical signal was not modulated, since the goal of this work was to emulate the effect of the pre-compensated atmospheric channel on the optical carrier only.

The system consisted of two terminals on both ends of a 13 km slant path with 5° elevation, as depicted in Figure 1. On the OGS ESA side, in Tenerife observatory, we installed an AO system compatible with bidirectional links, called GTB (Ground Terminal Breadboard). In the Teide cable car station we put a satellite emulator called STB (Satellite Terminal Breadboard), that could emulate remotely different point-ahead angles (PAA) thanks to a motorized rail.

Figure 1. Summary of the FEEDELIO experiment (© G. Artaud). The ground station emulator (GTB) is inside the ESA OGS, while the satellite emulator (STB) is in Teide cable car station.

An example of a one second time series, recorded at 20 kHz on the uplink beam at STB, with no PAA, is shown in Figure 2. In that example, even though scintillation is pretty strong ($\sigma^2_\chi$=0.3), the improvement of signal statistics thanks to AO is evident compared to no correction at all, and to tip-tilt only correction.

As for the evolution of performance with regard to PAA, an example of experimental result is shown in Figure 3: we can see qualitatively how the number and depth of fades increases with the PAA, even reaching statistics close to the open-loop operation depicted in Figure 2. This illustrates the loss of performance induced by anisoplanatism.

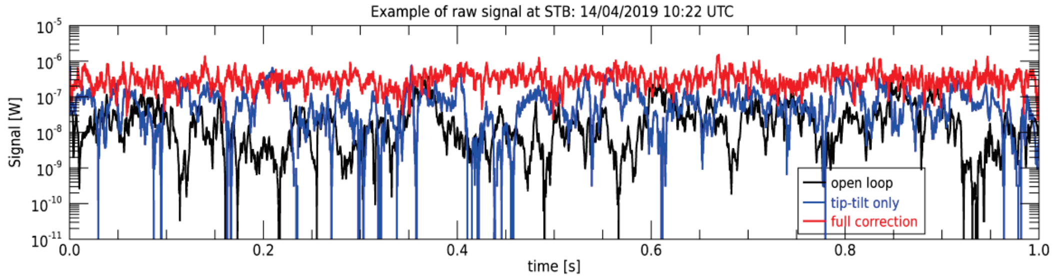


Figure 2. Example of experimental uplink time series obtained during the FEEDELIO experiment, without PAA. Black plot is without adaptive optics, blue plot is beam wander correction only, red plot is AO correction. (source: ref [5])

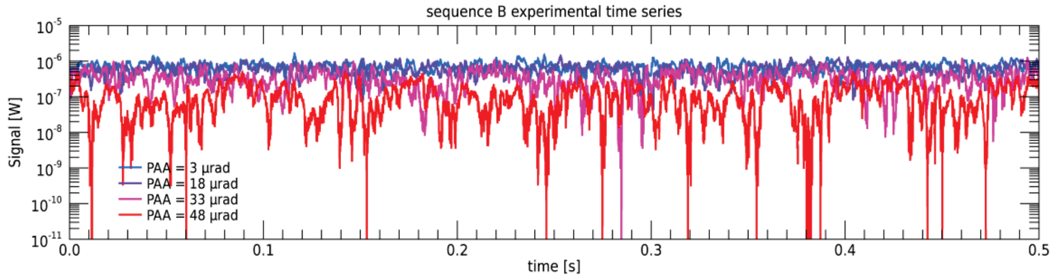


Figure 3. Example of experimental uplink time series obtained during the FEEDELIO experiment, with regard to the PAA. Blue is a small PAA, red is large PAA. (source: ref [5])

Almost perfect reciprocity between the downlink and the uplink without PAA was also obtained, as discussed in ref [6].

Thanks to the high-quality database we were able to gather through this experiment, with very different kinds of turbulent conditions, we were able to cross-validate our models with experimental signal statistics [5], before using them on GEO-FL scenarios to design ONERA's FEELINGS OGS.

More details about the FEEDELIO experiments can be found in refs [3-9].

### 2.2 The VERTIGO demonstration

In the framework of the VERTIGO H2020 project, an outdoor demonstration of a high data rate optical transmission over a 53 km slant path (elevation 2°) took place, in June and July 2022. Its goal was to validate the feasibility of very high throughput feeder links, addressing some of the advanced concepts studied in the frame of this project, in particular modulation schemes and adaptive. In addition, the setup allowed to compare these different techniques and technologies and consolidate theoretical models for the performance prediction in a relevant environment.

ONERA was in charge of providing the adaptive optics equipped optical ground terminal, which was in fact the GTB bench from the FEEDELIO experiment, as well as a small alignment equipment called OCTAT on the mountain side. TAS-Switzerland was in charge of the Satellite Terminal, and ETHZ and TAS-France of the signal modulation and demodulation/detection. The setting of the experiment is shown on figure 4.

Note that the experiment also involved multi-aperture emission provided by HHI, and coding/interleaving was also studied by CREONIC in the frame of the same project, but not during the outdoor demonstration.

The experiment was without a doubt a success, with record-breaking data rates obtained by ETHZ [10] and TAS [11], for that kind of line of sight – up to more than 1 Tb/s on a single channel obtained over the 53 km line of sight on an AO-compensated link. On ONERA's side, it allowed us to test the FEEDELIO bench over even wider perturbation conditions range, in particular very strong scintillation, and with signal modulation.

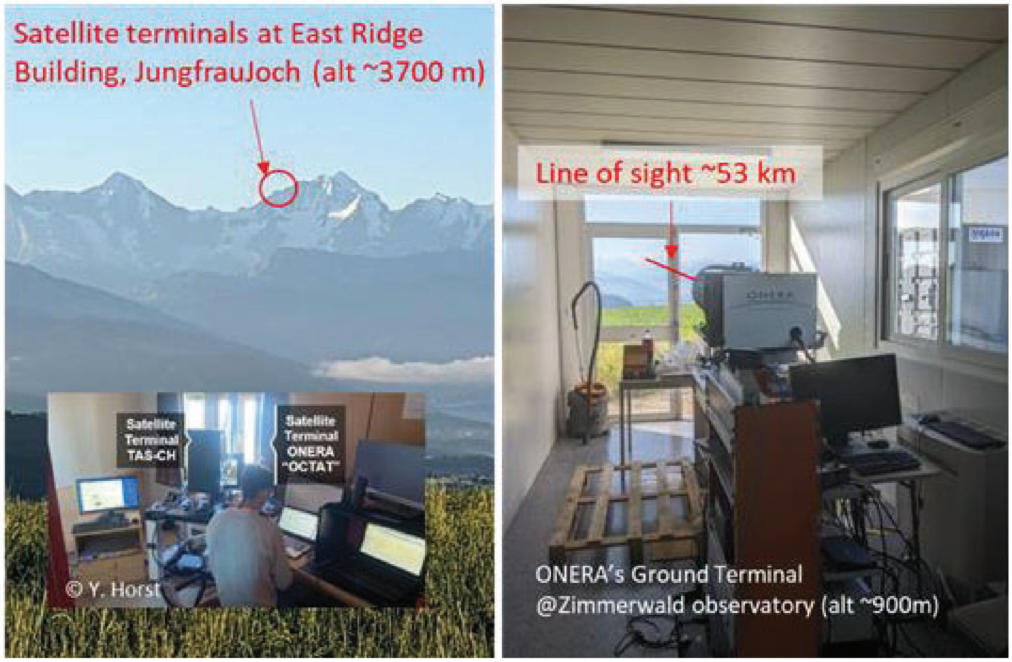


Figure 4. Setting of the VERTIGO outdoor demonstration. Both optical terminals were coupled to various telecom terminal provided by ETHZ and TAS, allowing to test a large panel of modulation formats over a wide range of turbulence conditions and SNRs.

More details about the VERTIGO project can be found in refs [10-12].

### 2.3 Learnings from slant-path experiments: pointing accuracy specifications

Both FEEDELIO and VERTIGO allowed us to validate our models as well as our design choices and alignment procedures on a slant path experiment. Thanks to this we could perform an in-depth system analysis that led to the current design of the FEELINGS optical Ground Terminal.

An example of the kind of feedback we got from our slant path links is the following: during the FEEDELIO experiment, we witnessed how sensitive to pointing accuracy the performance on the uplink is, and we could validate that our models predict accurately the loss of performance due to mispointing [5]. We could thus perform a sensitivity study, shown in figure 5, to set the specification of the pointing accuracy (or more precisely of the accuracy needed for the differential angle between the downlink and the uplink). We then designed the uplink path accordingly: while a 1 µrad rms accuracy on PAA is provisioned as a baseline, a 0.2 µrad rms accuracy is considered as a goal. More information on the mispointing sensitivity can be found in [13].

In the end, the design of the optical system of FEELINGS, and in the first place of the AO system, is a compromise between high performance and robustness in the one hand, versatility and ability to address GEO feeder links and LEO downlinks in the other hand.
Detailed description of the system analysis and design is not addressed here and will be the object of a dedicated article.

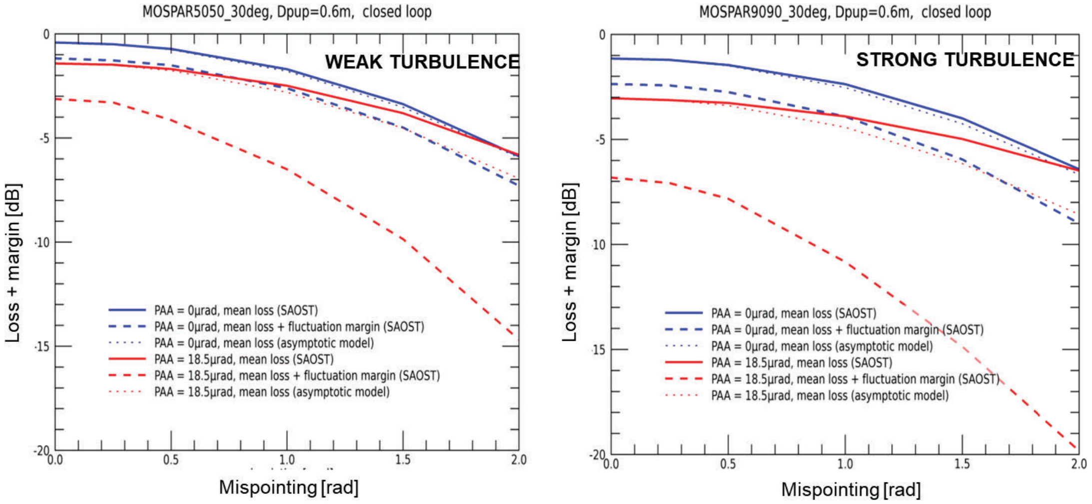
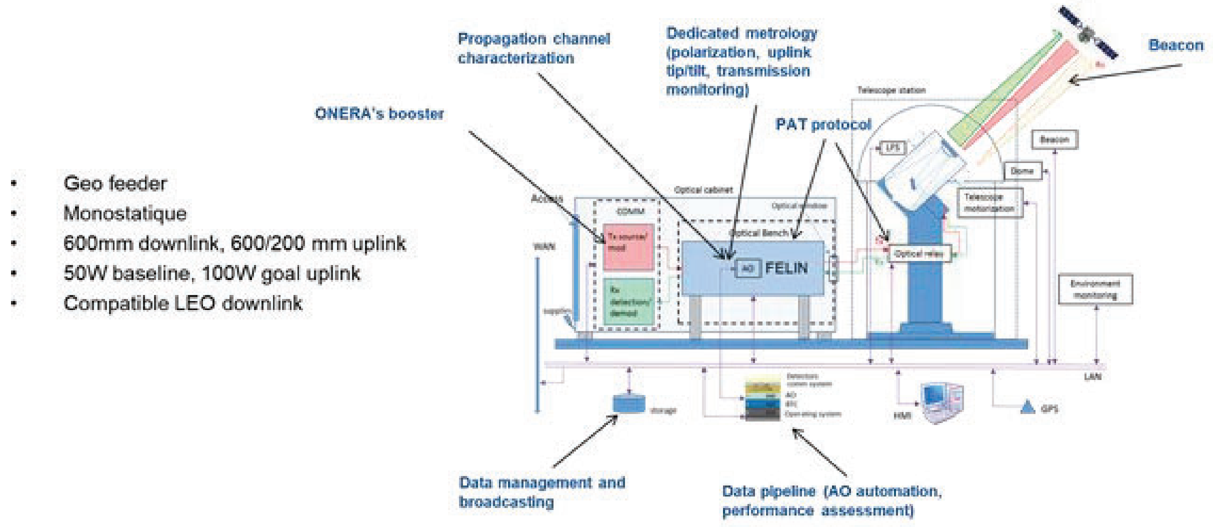


Figure 5. Example of output from the system analysis that led to FEELINGS design – showing how the performance of the system varies with the pointing accuracy. SAOST is a quick performance model that was validated thanks to FEEDELIO [5], that takes into account turbulence and adaptive optics. Asymptotic model is the purely geometric model.

# 3. STATUS OF THE FEELINGS GROUND STATION, AS OF SUMMER 2022

## 3.1 Optical Ground Terminal overview

The main features and hypothesis of the design choices that were made for FEELINGS can be found in [14]. An overview is given on Figure 6.



- Geo feeder
- Monostatique
- 600mm downlink, 600/200 mm uplink
- 50W baseline, 100W goal uplink
- Compatible LEO downlink

Figure 6: FEELING's main features summary.

The FEELINGS OGS is based on a 60 cm telescope, able to withstand up to 100W average uplink at least. To allow addressing GEO–FL as well as LEO downlinks a coudé focus has been selected. The telescope provides tracking ability for LEO satellites. Nasmyth focus can also be exploited for specific experiments if needed.

While downlink is always ensured by the full aperture, two different configurations are considered for GEO feeder links: a 60 cm full aperture, or a 20 cm decentred aperture, each configuration providing potential advantages that will be investigated. An Astelco 600 mm telescope (see Figure 7), with a coudé path has been selected, ensuring both GEO and LEO high precision tracking. It is equipped with a motorized slit dome.

The OGS is equipped with a Miratlas Integrated Sky Monitor to provide detailed weather and turbulence conditions monitoring.

The optical and communication systems are installed into a refurbished 20 feet container. The overall installation can be operated from a close-by control room.

Figure 7. View of the future FEELINGS Telescope. Delivery is expected first quarter of 2023 (© Astelco)

## 3.2 Adaptive Optics compensated terminal overview

The AO system is based on a 17x17 sub-aperture Shack-Hartmann wavefront sensor, and a 292 actuators ALPAO deformable mirror coupled to a fast Tip-Tilt mirror. The overall AO loop is controlled at a 4.7 kHz, this value being mostly driven by the LEO case.

The AO system provides turbulence mitigation for the downlink signal and precompensation of the uplink beam, either on the 60 cm full aperture (for both the downlink and the uplink) or the 20 cm reduced aperture (for the uplink only). The Real-Time-Controller, provided by Shakti, shall allow investigation of various algorithms for both wavefront sensing and control.

The optical system provides single mode fiber injection of the downlink signal that can host any client detection system. In addition, various diagnosis tools are included to finely evaluate the real-time performance and the characteristics of the channel. Polarization is controlled all along the path to ensure proper management and injection of polarized signals.

Considering the uplink beam, the system embeds as a baseline a 30 W (goal 50 W) laser source, with one or two wavelengths, based on an optical fiber amplifier (BOOFEE) developed at ONERA. Optical modulation of the uplink signal is performed, DPSK modulation is considered. However, the optical bench can also interface with host sources. Telecommunication system can also be interfaced with BOOFEE to propose a fully operational telecommunication system.

As mentioned previously, PAA is a key driver in the final uplink performance. A typical 18.5 µrad PAA is introduced on the uplink laser. While a 1 µrad rms accuracy on PAA is provisioned as a baseline, a 0.2 µrad rms accuracy is considered as a goal, leading to a dedicated design and calibration strategy, as seen in part 2.

Uplink and downlinks are typically considered respectively in the [1540, 1550] nm and [1560, 1570] nm bands, with a 5 nm bandgap (though 10 nm would be less demanding). However, the current design allows flexibility and these ranges can be modified in some extent.

Particular attention has been paid to the optical isolation of the various optical path due to the significant discrepancy between uplink and downlink optical powers. While our OGS is not dedicated to the 1 kW range uplinks, our goal is to demonstrate the ability to manage such discrepancies and implement dedicated beam shaping and isolation solutions that could be extended to higher power designs.

The OGS provides a 10 W beacon, with adjustable divergence and wavelength, in the [1570, 1605] nm band, to ensure proper Pointing Acquisition and Tracking (PAT) protocol. While the telescope ensures coarse pointing, and the AO system the ultimate fine pointing, an intermediate stage allows medium pointing accuracy and stabilization in particular during the PAT protocol, in the optical relay between telescope and AO system.

Finally, the operating system is a home-made software, derived from FEEDELIO and VERTIGO experiments.

### 3.3 OGS current status

The FEELINGS OGS has passed its final design review. A drawing of the bench can be seen below.

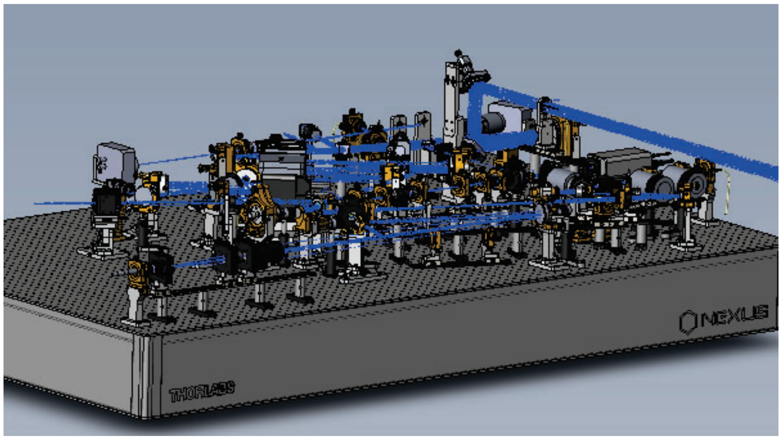


Figure 8. CAO drawings of the AO bench of FEELINGS OGS (© Probent)

The telescope and its dome will be delivered first quarter of 2023.

Key AO components such as main sensors (cameras, wavefront sensor) and actuators (deformable mirror, beam-steering actuators) are received and under testing.

Remaining optical, mechanical and electronical have almost all been delivered, so Assembly, Integration and Testing (AIT) of the bench are about to begin. We consider both in lab and on sky testing. The laboratory tests shall rely on our turbulence simulator, PICOLO [15], that allows to reproduce low elevation LEO turbulence cases, but can be compatible with the GEO case, or used for functional validations.

The OGS should be assembled in Paris area for convenience purpose, and then be tranfered in the south of France – though ability to displace the OGS shall remain possible if needed.

Our goal is to have a functional ground station by mid 2023.

## 4. CONCLUSIONS AND PERSPECTIVES

Thanks to our experience with field experiments, we were able to design on optimized Research Ground Station, which should be available around mid 2023. Its main goal is to address the main scientific and technological challenges of these two applications to pave the way for future operational systems.

That would mean, to test different AO concepts and to participate to GEO and LEO links demonstrations, with a specific interest on:

- Mitigation solutions to address the key challenges of GEO feeder links: PAA and anisoplanatism handling, optical isolation, high power optical sources and modulation etc;
- Mitigation solutions or new concepts for LEO downlink and uplink optimization for telemetry, communications and Quantum Key Distribution based protocols: low elevation links, agile AO solutions and alternatives;
- Development and testing of concepts for automated AO based OGS;
- Simultaneous characterisation and modelling of the optical link and atmospheric models with a joint identification and optimization process of the correction;
- Participation to atmospheric characterization databases;
- Assess multi-point architecture and hand-over strategies.

## 5. ACKNOWLEDGEMENTS

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