

GEO feeder links with Onera's Optical Ground Station FEELINGS: analysis of 2 years of results and operation and perspectives brought by point ahead turbulence mitigation

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ABSTRACT

Future GEO optical feeder links are expected to play a central role in high-capacity space communication networks, provided that atmospheric propagation effects can be accurately characterized and mitigated. While current mitigation techniques on the telecom layer rely on statistical models of the optical channel, atmospheric turbulence remains a major source of power fluctuations, especially for Optical Ground Stations (OGSs) operating in near-urban environments.

To address these challenges, ONERA has developed the FEELINGS optical ground station, a demonstrator combining a 600 mm telescope, adaptive optics, and a 28 W optical amplifier. Commissioned early 2024 near Toulouse, FEELINGS is designed to assess the performance of high-data-rate optical communications under representative atmospheric conditions.

Over the past two years, the station has been tested with Airbus' TELEO payload, enabling bidirectional optical transmissions with 10Gbaud downlink. Five one-week GEO feeder link campaigns were completed, leading to the final qualification of the station early 2026. We show in this paper that the collected data enabled a detailed analysis of atmospheric propagation and its impact on uplink and downlink optical carrier quality. Comparisons with FEELINGS's digital twin, combined with real-time turbulence estimation, showed excellent agreement with measured link performance and availability. The paper also discusses the main operational lessons learned and outlines the next development phase of FEELINGS, focused on predictive point-ahead turbulence mitigation strategies to further improve optical link performance.

Keywords: Adaptive optics, optical links, atmospheric turbulence, propagation channel

1. INTRODUCTION

Information systems requirements are evolving rapidly due to the massive volume of processed data and the growing number of users. To meet these demands, Free Space Optical (FSO) technology, and specifically satellite-based FSO communications, is emerging as a disruptive solution for the future global network. Its very high throughput capabilities enable information technologies to reach a new stage of advancement. This major asset, which will drive the civilian world toward ultra-fast connectivity, is also a strategic resource for military purposes. Beyond increased bandwidth, optical technology offers resilience against jamming and superior stealth compared to RF transmissions—two critical advantages in modern warfare theaters. Armed forces rely on numerous digital tools to support mission preparation and execution. These systems require high-resolution imagery, high-volume data streams, and secure access to large databases to implement AI processes. Moreover, this connectivity must be accessible near the front lines to provide a tactical advantage. This is only possible thanks to the high directivity of optical signals, which minimizes the risk of interception and jamming. Furthermore, the lack of international regulation regarding optical frequencies allows for immediate operational deployment without administrative constraints. For these reasons, FSO technology offers a critical advantage for the agility of modern military strategy, and information superiority is today the key asset for managing international conflicts.

Bi-directional optical links between ground-based facilities and Geostationary Earth Orbit (GEO) satellites, commonly referred to as GEO-feeder links (GEO-FL) [1], represent major step in this context. They offer a promising option for achieving high-throughput communication links (Terabit per second) between ground and space and a backbone for future space-to-ground communication networks. The feasibility of GEO-FL relies on the capacity to mitigate signal degradation induced by atmospheric turbulence. Adaptive Optics (AO) based pre-compensation has emerged as a game changer, potentially providing the additional margin required to ensure consistent link budget at all time. For downlink, AO daytime correction at a controlled performance level and compatible with permanent exploitation needs to be demonstrated. On the uplink, AO pre-compensation efficiency is compromised by the angular decorrelation of phase and amplitude perturbations. Additional challenges are to be considered such as precise calibration and optimization of the Point-Ahead Angle (PAA), design and integration of high-power sources compatible with Wavelength Division Multiplexing (WDM), choice of architecture (mono or bistatic) and related isolation and/or co-alignment issues.

The feasibility of pre-compensation by AO in the point-ahead direction has been demonstrated experimentally in a representative environment [2], and a feasibility demonstration was carried out on a GEO satellite with a reduced aperture (20 cm) at 1,064 nm [3]. These demonstrations did not include uplink data transmission, which is nevertheless essential for mastering the relationship between the statistical properties of the received signal and the information it carries, and received optical power on satellite was not yet compatible with high throughput operation. To address these challenges, ONERA has developed a research-oriented optical ground station, FEELINGS (FEEDer LINKs optical Ground Station) [4]. Its primary objective is to confront the scientific and technological uncertainties associated with GEO-feeder links, propose and validate innovative concepts, components, or algorithms, and thus pave the way for future operational OGS systems characterized by high capacity and operational efficiency. The project, started in 2019, came to fruition with first light in March 2024. Within the framework of the TELEO demonstration initiated by CNES and Airbus in 2018 [5], FEELINGS enabled pre-compensated optical uplinks on a 60 cm aperture since 2024 [6][7][8]. A second OGS, developed by the The French National Centre for Space Studies (CNES), in collaboration with industrial partners, FrOGS [9], has also performed GEO-feeder tests within this framework [10].

After two years of testing, FEELINGS has passed its final acceptance session in March 2026 and it is now the opportunity to propose an overview of the main results and achievements of FEELINGS, as well as its limitations. During these 2 years of operation, 5 runs of GEO-feeder links, of 1 week each, have been performed, leading to final acceptance. Based on the data acquired, extensive analysis of the propagation channel and its impact on the bidirectional link have been performed [6][7][8]. Comparison with in-house digital twin of the system, combined with real-time estimation of turbulence conditions [11] have shown that the overall performance and link availability can be properly explained in details, both on the downlink and uplink. We discuss here some additional recent results. We also come back on the limitations as well as operational issues faced during these 2 years, providing, we hope, some valuable feedback for future OGS. Finally, we present some perspectives for FEELINGS, as the next major step of the OGS is to test point ahead turbulence mitigation strategies, thanks to dedicated control solution. We propose first insight into the possible gain in performance to be expected.

2. EXPERIMENTAL SET-UP AND CONDITIONS

2.1 TELEO Payload

TELEO is a technological demonstrator developed by Airbus Defence and Space, co-funded by CNES, dedicated to in-orbit testing of optical uplink and downlink, and mitigation techniques for error free telecom links [12]. The TELEO payload is composed of a TOP-M laser terminal based on a 260 mm diameter telescope, a 5W optical amplifier and a data transceiver capable of 10 Gbaud downlink non-return to zero differential phase shift keying (NRZ-DPSK) and 10 Gbaud uplink NRZ on-off keying (OOK). The TOP-M pointing acquisition and tracking system employs a beacon at 1600.22nm. During 2024 and 2025 experiments, the on-board metrology of TELEO allowed the received signal to be digitized at high frequency during the links (4kHz). More details on TELEO and characteristics of the uplink measurement chain are proposed in [12]. The variations of irradiance measured uplink provide valuable insights into the influence of point ahead anisoplanatism.

2.2 FEELINGS general presentation

The FEELINGS OGS has been designed as a research platform to develop, test and validate the ground segment building blocks for the future of future space-ground optical links. It is illustrated Figure 1 (telescope on the left, picture of the dome and shelter on the center, internal setup in the shelter on the right). More details on FEELINGS design and integration can be found in [4]. It is composed of a 600 mm Astelco Ritchey Chrétien Telescope with a completely opened tube; an ONERA designed AO bench located at the Coudé focus of the telescope for versatility, allowing test of various configurations. It however increases transmission losses. FEELINGS includes also a high power amplifier designed and built at ONERA (BOOster for FEEDer a.k.a BOOFEE) to bring 50 W of output power with good beam quality ($M^2 \sim 1.04$). In practice, BOOFEE has been used initially at 20 W. An upgrade allowed to reach 50W (with peak value of 60W), for possible multichannel links, though this power is not necessary for single channel link. In addition, some instabilities were observed at high amplification regime, threatening the proper ageing of the system. Thus, it has been used only at 28W maximum. It provides linear and distortion free amplification of On-Off Keying (OOK) and differential phase-shift keying (DPSK) signals [4] in that regime.



Figure 1 : Key components of the FEELINGS ground station. Left: 600 mm telescope, center: dome and shelter, right: control electronics, AO bench and communication setup location in the shelter.

The AO bench is equipped with a 17x17 Shack-Hartmann WaveFront Sensor (WFS), an Alpao DM292 Deformable Mirror (DM) and a Real Time Computer (RTC) provided by Shakti able to drive the loop with up to 4.7 kHz sampling frequency and a 2.2 frame delay. The AO control architecture is very similar to the one developed for SPHERE AO, SAXO, except for the Tip-Tilt (TT) control [13]: classic least square based reconstruction coupled to leaky integrator for TT and DM, SAXO-like separation of TT and DM control, use of DM influence function based Karhunen Loeve basis or system eigen modes, truncation of the basis depending on conditions, slaving of edge actuators. In the GEO configuration it is used at 2kHz (TT and higher order modes). The AO bench provides both downlink correction for SMF injection and uplink precompensation in a monostatic configuration, using the full pupil. A 10W, 1600nm beacon, with 150 μ rad divergence, using the same aperture and a 20cm pupil, is also used for pointing and tracking protocol (PAT). Details of the acquisition sequence, including PAT is described in [12]. Thus, the downlink and uplink beams, as well as the beacon, share the same common path and pupil. This monostatic architecture was selected to reduce co-alignment and pointing issues, though requiring fine isolation of uplink and downlink paths due to huge discrepancy between the emitted uplink beam (typically

of the order of 25W) and downlink beam (typically a few nW). It also induces additional losses to uplink beams, that go through the common path. The overall system only uses a single telescope. The AO bench is illustrated on the left of Figure 2.

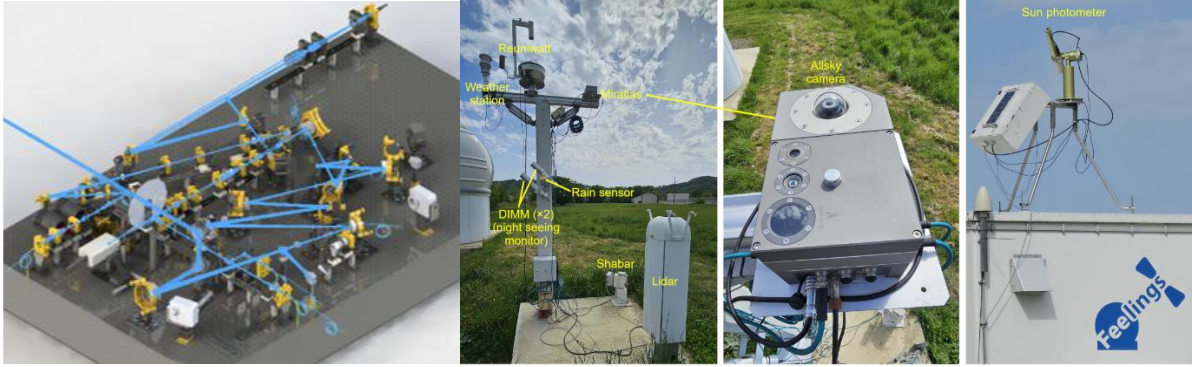


Figure 2 : from left to right: AO bench, MIRATLAS weather station and lidar ceilometer, all sky camera and sun photometer.

A Ground Optical Communication Chain (GOCC) provided by Airbus allows demodulation and decommutation of the downlink telecom signal, including the high frequency irradiance information as measured and embedded on board TELEO on the downlink signal [12]. Finally, the station comes with a MIRATLAS weather station, including a visible all-sky camera, a VAISALA's CL51 lidar ceilometer for characterization of atmospheric aerosols and clouds, and a CIMEL CE318 Sun-Sky-Lunar spectral photometer providing information about the column-integrated radiative properties of the aerosols (Figure 2 right).

The FEELINGS OGS is located at ONERA's facility in Fauga-Mauzac, southern France, in a rural peri-urban area approximately 30 km from Toulouse. Commissioning of the ground station occurred in March 2024 slightly before the first links with the TELEO payload.

2.3 Atmospheric conditions

Atmospheric conditions directly affect the link budget and thus the global performance. Thus, monitoring of atmospheric conditions is compulsory to understand and validate the link budget. It would be necessary also in an operational framework to adjust the link parameters or foresee handovers. It includes atmospheric transmission as well as turbulence conditions. As explained in [6], we implemented an atmospheric transmission assessment using MATISSE-v3.6 with Météo-France forecast data, 12 to 36 hours in advance. The MATISSE-v3.6 code [14] is developed by ONERA and is the French Defence Procurement Agency (DGA) reference code for modeling atmospheric radiative transfer on a global scale. Using various databases (standard or climatological thermodynamic profiles, optical properties of aerosols and cloud types, reflectance of the ground, sea temperature ...), it provides atmospheric radiance and transmission over the entire optical spectrum. Accuracy is limited to forecasts accuracy as shown in [6]. To complement this numerical analysis, on-site instrumentation is required. As explained in Sect. 2.2, FEELINGS is equipped with various instruments for transmission estimation, either spatially distributed or integrated along a Line of Sight (LoS). While the combined analysis of the various data collected can provide a fair estimate of actual conditions, none of them provides direct estimation of atmospheric transmission in the LoS at the relevant wavelength. We have thus developed a synergistic analysis combining numerical and instrumental data analysis: local atmospheric measurements are gathered to feed the atmospheric propagation model. This approach allows a local description of the atmosphere through measurements and brings flexibility to the modeling by selecting the spectral bands calculation scenarios, among others.

We have tried to compare the three approaches (full numerical, full instrumental, combined numerical-instrumental) in various sky conditions, the numerical analysis being done in the ceilometer conditions (910nm at zenith). For the experimental data, ceilometer information is used to derive cloud cover and the sun photometer provides aerosol information. We observe that in stable condition, with clear sky, all approaches are equivalent, the numerical one being the easiest and fastest to use. But, in case of heterogenous clouds the combined approach proves to bring a significant gain in transmission estimation. It indeed makes it possible to better capture the temporal and spatial variability of transmission, thanks to the inclusion of local measurements. This is illustrated in Figure 3, on data acquired in July 2024. The day includes cloudy conditions from 07:00 to 09:30 (altocumulus between 3 and 7km) that are then replaced by cirrus until

some 10h15, then sky is clear. On this figure, we compare experimental, full numerical and synergistic analysis: experimental data (lidar and sun photometer) are in pink solid line. Full numerical are red and orange crosses, assuming two ranges of analysis (0 to 7km -red- or 0 to 13km -orange-). The 0 to 7 km range accounts for the same cloud layer as seen by the lidar, while the 0 to 13km range accounts for cloud layers around 9 km modeled by the Météo France weather forecast though it was not measured by the lidar. Finally, synergistic analysis is provided in blue and green lines with two types of clouds. A good match is observed between experimental and synergistic analysis, with significant discrepancy with full numerical analysis, except when the sky becomes clearer. In that case the various methods converge, except the full numerical simulation with the 0-13km range, probably due to the absence of the 9km layer modeled by the weather forecast. These results are encouraging but many limitations need further progress: cloud cover is estimated only over the ceilometer, various types of clouds exist not fully addressed in the databases, finally, one has to evaluate the condition at 1550nm, meaning improving the conversion between these 2 wavelengths.

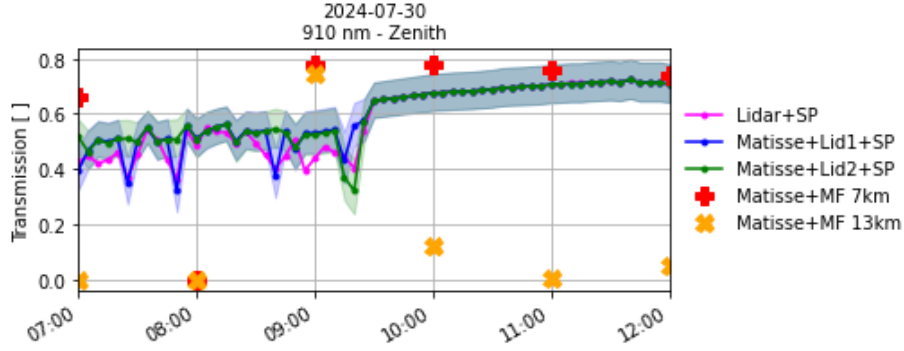


Figure 3 : Transmission estimated from Lidar and sun photometer measurements (pink), synergistic analysis with first type of clouds (blue) and second type (green), compared to full numerical analysis between 0 and 7km (red crosses) or between 0 and 13km (orange crosses). All results given at zenith at 910nm.

Concerning atmospheric turbulence, a significant work has been done to develop and validate turbulence estimation methods based on AO telemetry (slopes and intensity measurements), to be combined with local meteorological instrumentation (Miratlas' ISM) providing integrated parameters. This work has been described in details in [11][15] [16]. A first method provides a fast estimation of integrated parameters, and a second one, based on the SCO-SLIDAR approach, provides C_n^2 and wind speed profiles estimation. Both methods are embedded in a real-time data pipeline to provide on a regular time basis the respective information. These two methods have been tested in the lab and on sky showing relevant estimation of turbulence conditions when compared to system performance evolution. Illustration of typical outputs for FEELINGS is provided in Figure 4 and are described in [11]. Comparison with other sources has been also carried out and are described in [17].

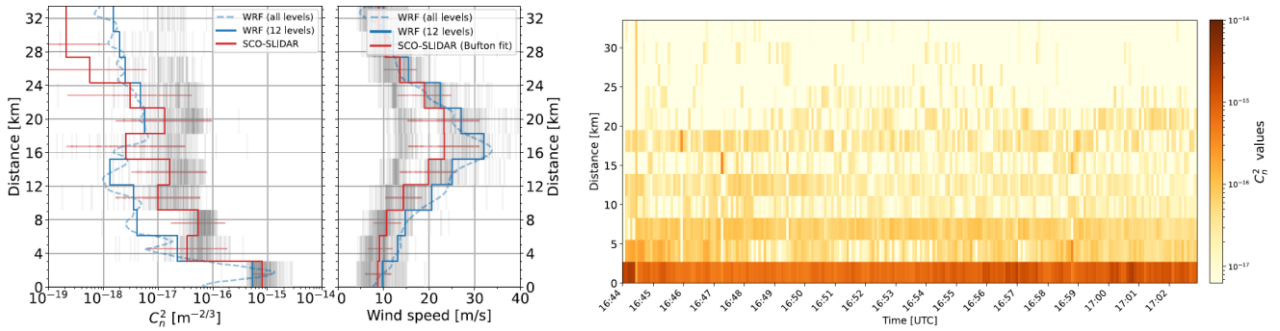


Figure 4 : Illustration of turbulence and wind profiling. Left: time averaged C_n^2 and wind profiles as estimated by the profiling code on a typical experimental dataset from FEELINGS (12 layers between 0 and 35km, 5s data sets averaged over 15min data) (solid red), compared to Weather Research and Forecasting software with all (dashed blue) or only 12 layers (solid blue). Right: example of C_n^2 profiling along time on FEELINGS data, same data set. More details in [11].

2.4 Data management

FEELINGS has been progressively equipped with a real-time data pipeline, that allows monitoring of the system and its performance and data exchange via VPN (Virtual Private Network) with Airbus. The data pipeline provides both commands and measurements for the various subsystems as well as contextual information. Information is gathered in a database. Most information and data are exchanged on a low data rate basis (1Hz) with time averaged data (over 1s), though high temporal resolution data can be also retrieved and exchanged (10kHz for downlink coupling and 4 kHz for TELEO received irradiance).

It includes:

- Weather station information: wind speed, temperature, pressure etc.
- System commands and status: telescope position and status, sources power and status etc.
- OGS measurements: downlink injection monitoring
- Turbulence monitoring: it provides not only turbulence integrated parameters (r_0 , θ_0 , τ_0 and scintillation index σ_χ^2 on a 0.2 Hz rate) but also turbulence profiling as described in [11], including C_n^2 and wind profiles as described in previous section.
- AO telemetry

Reciprocally, on board telemetry can be accessed with a low or high data rate measurement, the high data rate measurement being transmitted optically via the downlink. Most of these data can be graphically monitored on HMI.

3. RESULTS OVERVIEW

3.1 Link sessions overview

FEELINGS OGS was on sky in march 2024 and performed its first pointing test with TELEO, though without optical link (session 0). Since then, it has undergone 5 sessions of testing with the TELEO payload, with incremental complexity, till final acceptance in March 2026 (session 5). This relatively long testing period is due to weather conditions, optimization of the system and availability of the TELEO payload, that was not accessible during almost one year. Each session covers approximately one week. Link sessions are conducted during daytime, with possible interruption when the sun crosses the line-of-sight. Using a 15° sun avoidance limit, this can lead to up to 3 hours of interruption. This aspect has not been optimized so far. We synthesize in Table 1 each session main objectives, conditions, main achievements and cumulated duration of available data.

Table 1: overview of link sessions

Session	Date	Objectives	Conditions	Main achievements	Cumulated data
0	03/2024	Validate pointing	Not relevant	TELEO-OGS coalignment	No data
1	06/2024	PAT validation Downlink correction Uplink preliminary tests	good	System operational Downlink correction and injection First detection of uplink signal Limited performance	Low frequency DL and UL data
2	07/2024	Optimization of system (AO correction, PAA, focusing, polarization) Link budget evaluation	good	Up to -42.5dBW/m ² Received Optical Power (ROP) on board (for 20W amplification) Link budget assessment	Few tens of minutes of AO data and low frequency DL
3	09/2024	Optimization of performance on bidirectional link Telecom link Booster upgrade at 28W	Mostly cloudy, strong turbulence, storms except last day	High frequency data acquisition Tests of various AO loop parameters	Few hours of AO data Tens of minutes at low and high frequency (UL and DL)
4	10/2025	Improve AO robustness Reduce parasitic light Develop data pipeline Prepare remote control	Partly cloudy, good conditions on afternoons (median r_0 between 10 and 20cm)	Data pipeline ok Remote control ok Long term links but with regular interruptions due to RTC bug	AO and DL or UL low and high frequency data over many hours (>6h cumulated)

5	03/2026	Correction of last bugs Final acceptance	Good weather (transmission >0.9) but strong turbulence (median $r_0 < 10\text{cm}$) with wind (up to 47km/h)	System operational Final acceptance ok Long term links	AO and DL or UL low and high frequency data over many hours (>15h cumulated, >4h in a row)
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3.2 Main results and performance analysis

In the following, we propose a synthesis of the main results obtained during these 5 sessions. More details can be found in references.

3.2.1 Analysis of experimental data through numerical simulation

One of the main goals of these experiments was to ensure a proper and thorough understanding of the performance of the system and its limitations. We thus developed numerical tools to assess the expected performance taking as an input the on-site turbulence conditions, as estimated by the various tools presented in Sect. 2.3. First tool is based on SAOST and provides a fast estimation of performance, compatible with real-time diagnosis, computing the various contributors to the AO error budget [8]. The second tool is a numerical twin of FEELINGS based on end-to-end simulation, AOSIM, that provides high precision estimation of the performance of the overall system. AOSIM and its results are described in details in [7]. This last tool also provided a framework to evaluate the impact of various parameters such as optimization of the Shack-Hartmann gain, AO control matrix and slaving parameters etc. that may prove difficult to properly optimize on sky, as conditions are not stable. These tools are illustrated in the following sections.

3.2.2 Downlink coupled flux

We first discuss downlink injected power. The performance of injection depends on the turbulence conditions and the AO loop performance and thus parameters, as well as the optimization of the injection set-up. AO performance optimization has been investigated both on sky and numerically (see Sect. 3.2.1), with respect to various parameters including type of control basis (eigen modes or Karhunen Loeve, - KL - modes), number of controlled modes, slaving strategy for edge actuators and TT or DM gains. The TT and DM gains are of course the most prone to adjustments depending on atmospheric conditions (turbulence and scintillation levels, wind speed ...). In the end, a single configuration is mostly considered, based on use of KL modes with small truncation (about 30 modes), soft slaving (see [7]). The sampling frequency is not modified, only the gains are adjusted. Modal gain optimization has not been performed but off-line computation has not permitted so far to exhibit significant modal gain fluctuations.

We illustrate on Figure 5 the performance of downlink coupled flux during the session 3 (23/09/2024). While the time series presents various fluctuations due to calibrations, tests, and interruptions due to clouds, two time slots include simultaneous optimization of uplink and downlink (around 15:10 and 17:00). The downlink coupled flux reaches a 30 to 35% average efficiency, while the maximal performance is 50% (maximum coupling efficiency including central obscuration and residual static aberrations).

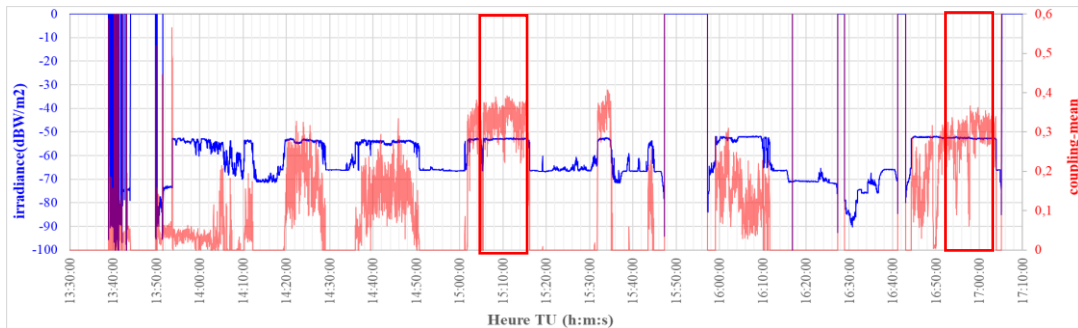


Figure 5 : Received irradiance on FEELINGS (blue) and SMF coupling efficiency downlink (red) during the bidirectional link of 23/09/2024 (session 3). Red boxes indicate time slots during which uplink and downlink were simultaneously optimized.

Based on the estimation of turbulence conditions and using the SAOST numerical tool, we try to account on a time resolved scale (1Hz typ.) for the downlink performance, in the two identified time slots (red boxes). It shows in Figure 6 left that for the first time slot (15:00) a very good fit is observed. Some slight discrepancies are observed and may be related to scintillation induced fluctuations not captured by the numerical tool. On the left plot, higher discrepancy is observed until 16:58: this is fully explained by a mis-alignment of SMF injection on bench, re-optimized progressively till 16:58, visible also in Figure 5 by a sharp increase of performance around 16:50. Additional analysis are available in [8].

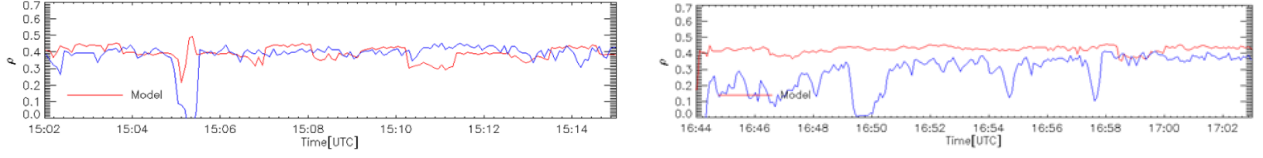


Figure 6 : Experimental (blue) versus numerical (red) SMF coupling efficiency downlink during the bidirectional link of 23/09/2024 (session 3). Left: around 15:10, Right: around 17:00.

The SAOST tool thus provides a very efficient way to analyze the AO performance quickly (few seconds), though not accounting of course for system mis-alignments or defects if not considered. This can provide a real-time assessment of the performance and detection of deviations related to system evolution. Such analysis has also been performed with AOSIM [7]. This tool, though more complex, provides finer estimation of performance, on a finer time scale, due to the simulation of the complete AO system.

3.2.3 Uplink signal

We now focus on the uplink, which is the most challenging. First major results were obtained in June 2024 (session 2). Results in term of received irradiance (averaged over 1s) onboard measured on the 10/07/2024 are shown in Figure 7. BOOFFEE was used at 20W, the AO loop at a nominal 2kHz with a 0.25 gain. Turbulence conditions were estimated through turbulence profiling showing average values of $r_0 = 7.1cm$, $\theta_0 = 3.8\mu rad$, $\sigma_\chi^2 = 0.22$, $\bar{v} = 12m/s$. The successive operations are clearly visible, with a clear gain brought by AO, PAA then focus optimization. A $-42.5 dBW/m^2$ was reached, representing an achievement as this value was more than 10dB of the current state-of-the-art at this time, opening the way toward high-throughput links. More details on these results, as well as comparison to numerical simulations can be found in [6].

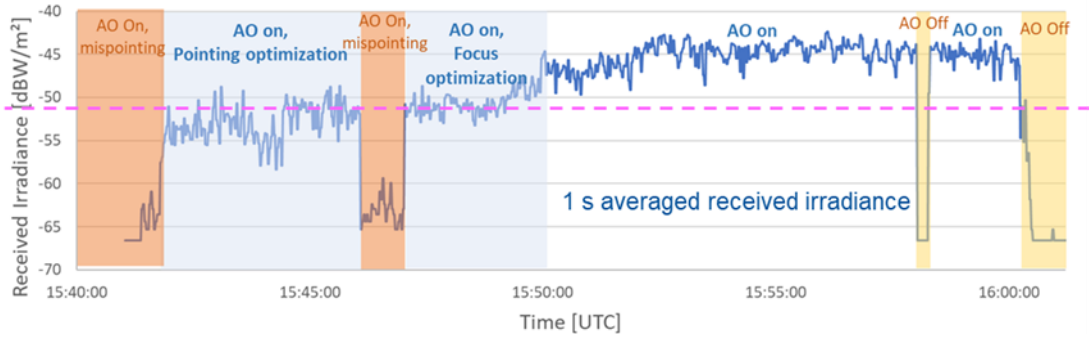


Figure 7 : Received irradiance in the aperture plane of the payload as estimated from TELEO focal plane measurements as a function of time, during session 2, 10/07/2024. Pink dashed line corresponds to the threshold expected for a 25 Gbps link assuming similar performance for the onboard modem system as on ground.

We focus on the same time slot as Sect. 3.2.2 and Figure 5, during session 3, on the 23/09/2024, identifying the same red boxes. We can observe on Figure 8 that the received irradiance in the aperture plane of the payload is stable and close to $-43dBW/m^2$ after optimization of the two time slots, with slight fluctuations due to anisoplanatism fluctuations. As for Figure 5, the fluctuations observed out of these two time-boxes are related to calibrations, tests and clouds.

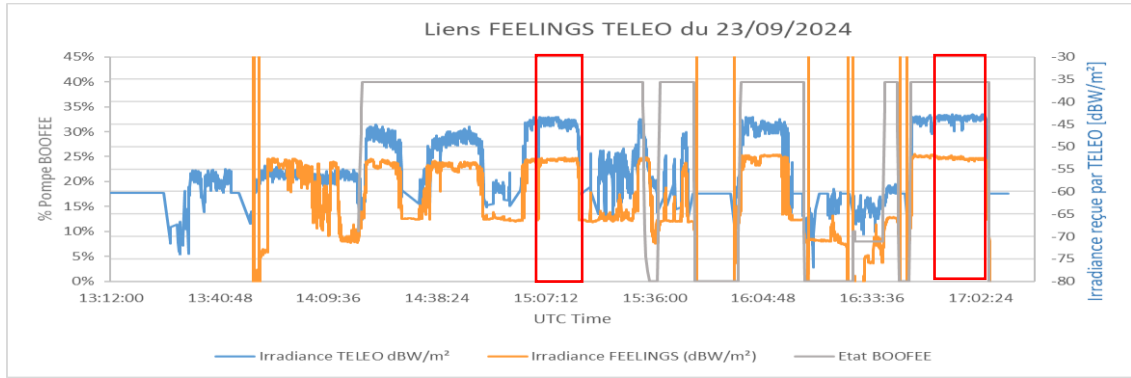


Figure 8: Received irradiance in the aperture plane of the payload (blue) as estimated from TELEO focal plane measurements and received irradiance at TELEO level (downlink) as a function of time, during session 3, 23/09/2024.

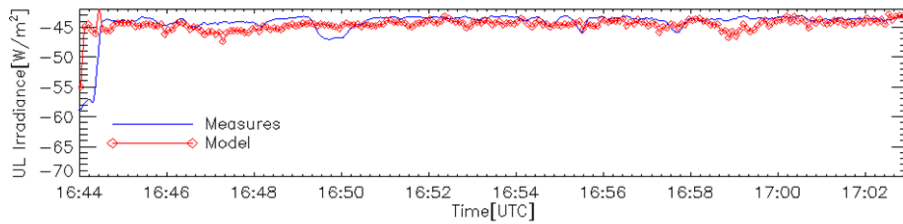


Figure 9: Received irradiance in dBW/m² in the aperture plane of the payload as estimated from TELEO focal plane measurements (blue) or computed using the SAOST tool (red) as a function of time, during session 3, 23/09/2024.

A similar analysis with SAOST can be made on the uplink signal as in Figure 6. This is shown in Figure 9. It shows a very good agreement with the experimental value. Once again, the finer simulation tool, AOSIM has also been investigated for higher precision and temporal resolution, showing very good coherence in terms of statistics [7].

3.2.4 Link budget

One of the key aspects in these bidirectional links is of course the link budget and its fine understanding. We first focus on the uplink error budget first. Considering the various values and parameters summarized in Table 2 an expected irradiance at TELEO level can be estimated at -46.23dBW/m² (2.1dB rms) during the fourth mission (16/10/2025, 15h20 to 15h29 UTC). This value includes estimation of AO correction residuals including anisoplanatism effects as provided by our SAOST tool. Impact of static aberrations still needs to be consolidated, leaving some indetermination. We can compare this estimated value to the measured irradiance on board estimated to -45.86dW/m² (1.46dB rms). We have observed a consistent experimental error budget over time (considering atmospheric conditions).

Table 2: summary of main contributors for the link budget

Contributors	Unit	value
Telescope transmission	dB	-1,77
Common path transmission	dB	-0,92
UL path transmission	dB	-1,49
UL static aberrations	dB	-0,41
DL path transmission	dB	-1,52
DL static aberrations	dB	-1,14
Atmospheric transmission (estimated based on instrumentation)	dB	-0,46
OGS antenna gain	dB	121,63
OGS Tx emitted power	dBW	13

Similarly, on the downlink the expected received optical power was -32.08dBm (including AO residuals, and scintillation derived from SAOST), while the measured value (measured on the focal detector and converted at SMF entrance thanks to optical calibrations), leads to a -31.82 dBm value (1dBm rms).

These experimental results are also fully in accordance with the expected values and show very good understanding of the link budget. Similar coherence between expected and measured values has been observed during session 4 and 5, though significant losses on the transmission of the telescope and AO optical path modified the budget error allocations (see Sect. 4.1).

3.2.5 Link duration/stability

While the first sessions were dedicated to optimization and suffered from various limitations and interruptions, we could evaluate during the last session the stability of the FEELINGS system and its AO. Figure 10 shows the TELEO received irradiance during the final acceptance of FEELINGS. This session, as underlined in Table 1, was of lower quality due on one side to strong wind, on the other side to loss of system transmission, as detailed in Sect. 4.1. Still, this plot shows a continuous and stable link during more than 4 hours, first part of the link was internal optimization, followed by a regular increase of irradiance level due to improving wind conditions (going from 40km/h in the first hour down to 5 to 10km/h in the last hour), at 16:00 the beacon is switched off, decreasing a bit the received irradiance. After 17:00 the link is severely degraded mostly due to clouds in the LoS. In total, more than 15 hours of cumulated data were obtained with continuous links of about 3 to 4 hours per day.

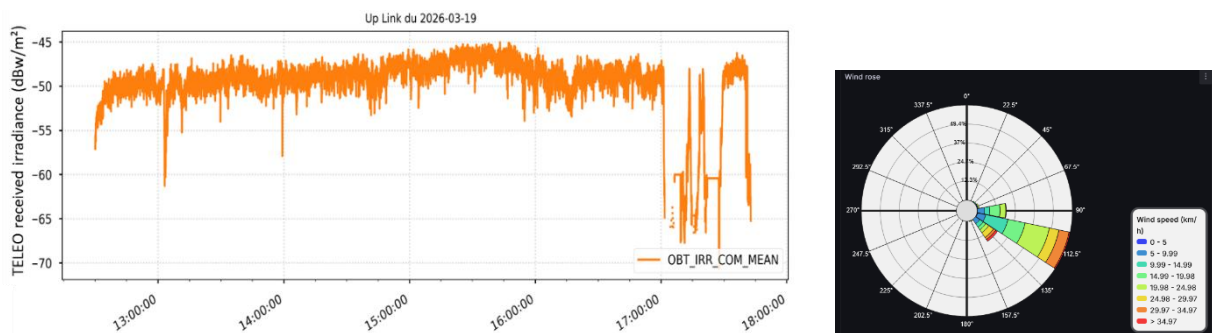


Figure 10: Left: received optical irradiance in the aperture of the payload along time during session 5, on the 19/03/2026. Strong winds dominate during the first hour. Last hour is strongly perturbed by clouds in the LoS. Right: wind compass rose during link beginning.

4. LESSONS LEARNED

These 2 years of regular testing with the OGS have allowed significant achievements. They also have underlined some limitations and robustness issues that we discuss in this section, and that may benefit for future systems.

4.1 Static losses

Static losses are mostly driven by transmission losses, static aberrations and polarization. They directly reduce the optimal performance and link budget of the system and need continuous monitoring and optimization.

During this 2-year testing, a significant evolution of the power budget has been observed, with a loss of detected power at the OGS level, and irradiance level on board. Fine analysis of the transmission of the OGS has shown that while the AO performance did not evolve, this loss was fully related to transmission losses, of about 1.7dB uplink and 3dB downlink on the AO bench. Various optics within the AO bench exhibit a reduced transmission that can be attributed to fast ageing related to humidity in spite of the cooling system within the shelter and possibly high-power laser. FEELINGS being a versatile research platform, standard gold and argentic coatings have been used that may explain this faster ageing, while dielectric coatings would have proved more robust. Replacement of optics and use of a dehumidifier is ongoing. The telescope transmission has also been reduced. Protected aluminum coating is used for the telescope mirrors. Still, measurement of the telescope transmission can be tedious. Due to the very narrow bandwidth of the AO bench, measurements on calibration stars proves to be difficult. Use of the uplink beam is also tricky. Cross validations between the various approaches still allowed us to estimate telescope transmission. Cleaning the optics resulted in a substantial

gain in transmission (1.7dB), without, however, restoring nominal transmission levels so that the current transmission is of -4.1dB (39%) instead of -1.8dB (66%). Recoating shall be performed. These results underline the impact of environment on the system performance on the long term and the need for high quality coatings and dust protection, in particular in non-astronomical environment. They also point out the need for fine and regular transmission monitoring, including of the telescope. Power monitoring through the bench has been developed. A dedicated set-up for telescope transmission monitoring is currently being considered. Evaluation of the input flux at telescope entrance could also be considered.

To conclude on transmission losses, and as discussed in section 2.3, atmospheric transmission is a key contributor. Proper estimation of atmospheric transmission combining in situ instrumentation as well as weather data and modelling proves to allow a fine assessment of transmission and thus of link budget, with more robustness. Further improvements are however needed, and monitoring and characterization of clouds play a significant role, that can be addressed with further instrumentation (use of all sky camera combined with ceilometer, new generation of ceilometer with depolarization measurement, cloud radar ...).

Static aberrations, and more specifically non-common path aberrations, may represent a significant contributor to static losses. It is quite usual to compensate static aberrations through AO loop setpoint adjustment. Our monostatic design reduces alignment issues but as a single AO system is used both for the uplink and downlink, it is not possible to optimize the static aberrations compensation for all paths (uplink and downlink) simultaneously. The downlink path is prioritized with optimization of Non-Common Path Aberrations (NCPA) (except Tip-Tilt) at the AO level, as the uplink performance will be mostly driven by turbulence residuals. FEELINGS performance could be further improved on the downlink with respect to NCPA, as some high order residual static aberrations on the downlink path have been identified on a specific component, to be replaced. As for the uplink, some specific aberrations have to be considered. First, the use of the 28W uplink beam leads to an additional thermally induced defocus. It is however stable once the uplink beam is on. It leads to some refocusing on target to optimize the Received Optical Power (ROP). An adjustable focus shall still be considered to be able to optimize the bench with or without the uplink beam, or in case of uplink power evolution. Second, some residual aberrations do exist on the uplink path (astigmatism mostly) that could be optimized optically in the long term.

Finally, polarization has proved to be easily handled with proper calibration methods. Still, instrumentation for polarization characterization and monitoring proves to be necessary to reduce the uncertainties and calibration overheads.

4.2 Thermomechanical stability

We have only discussed so far of static (or quasi-) aberrations. Still, such kind of system is subject to multiple sources of thermomechanical drifts. First issue is related to daytime operation and strong evolution of temperature and sky illumination leading to possible evolution of telescope and of fore optics. Systems designed for full-time operation can provide more stability thanks to carbon composite components and bafflings for instance, though this was not the intent of FEELINGS that focuses on research. Still, these thermomechanical drifts have not led to sensitive limitations of FEELINGS operation.

A second issue arises within the AO bench and shelter. In spite of the cooling system, some thermomechanical drift has been observed in particular at the DL injection level. This leads to regular drifts, over time horizons of few minutes or more, of the coupling efficiency, that shall not be mixed with loss of AO performance or turbulence conditions evolution, as described in [8]. Stability of injection thus plays a critical role. While use of more stable materials could be considered, the stringent requirements on injection stability [18] lead to considering a dedicated optimization process that continuously maximizes the coupled signal in the fiber with a characteristic time of less than few minutes. An automatized procedure has been developed using iterative approaches such as SPGD [19][20][21] to simplify the operation and ensure continuous optimization of injection. Tests are ongoing.

4.3 Pointing accuracy and stability

Not surprisingly, we have observed that use of ephemerids for target pointing leads to far better accuracy than TLE, reducing significantly the PAT duration. Of course, this result depends on the age of the information. It also appears that the beacon does not provide enough flux, coupled with a small divergence. This is particularly true with the loss of optical transmission and leads to more difficult PAT procedures. Still, use of ephemerids, and optimization of procedures and calibrations has allowed us to reduce PAT duration from tens of minutes down to less than 5 minutes with a manual operation.

The PAA pointing, once calibrated proves to be rather stable, though some adjustments can be necessary due to thermomechanical drifts within the AO bench along time. The procedure, still manual, shall be automatized in the near future using the onboard feedback in a spiral type procedure for instance.

4.4 Optical isolation

The monostatic design of FEELINGS leads to strong requirements on uplink and downlink isolation, considering that differential flux reaches some 10 orders of magnitude. Still, FEELINGS has shown that such conditions can be efficiently handled. Our strategy relies on a spectral and spatial filtering: use of a dichroic and of interferometric filters for paths spectral separation and use of mask and field stop to spatially filter the residual parasitic light on the downlink path. While some residual background can still be observed on the WFS, it remains quite low compared to the useful signal. A dynamic follow-up and subtraction of the background allows to suppress it, even in case of fluctuations. No impact on the downlink performance has been observed so far. Still, baffling of critical parts of the optical bench is necessary.

4.5 System operation

System operation has of course gained in efficiency from first to last session, the system becoming more and more stable and optimized. In parallel, we have developed a remote-control process, so that all elements can be controlled from a distant location (Onera's site in Châtillon close to Paris). Physical and manual switching (on or off) of the various instrument is still necessary on site, as well as an operator for safety issues (telescope control, high power laser ...). Now the system operation thus requires only one operator on site and one or two distant operators.

Operation can be maintained day long, except for the sun exclusion period, that can represent 3h in fall. This gap could be reduced, as the sun exclusion zone is 15° , but this has not been investigated so far.

Operation in a peri-urban environment allowed us to test the system in representative conditions, in particular of turbulence, transmission and dust. We also faced heat wave, storms, hail, heavy rains with strong winds. As pointed out in Sect. 4.1, humidity and dust clearly play a significant role in long-term transmission of the system and should be considered with care.

5. TOWARDS PAA MITIGATION

One of the main goals of FEELINGS is also to investigate new concepts, and first of all point ahead mitigation adaptive optics (PAMAO) concepts. The goal is to assess mitigation strategies, using the downlink measurements to optimize the uplink pre-compensation and thus the energy deposited on the payload, in spite of anisoplanatism.

Such concept has been proposed in a static framework by P. Lognoné in [22]. In this scheme, the uplink pre-compensation phase can be estimated using the downlink phase and log-amplitude measurements and statistical priors. So far, only static estimation has been considered, using Minimum Mean Square Error estimation (MMSE) and first results were proposed for FEELINGS in [7] in a simplified configuration, showing significant potential gain. We go a bit further here, considering real-time compensation in a dynamic control approach. The MMSE reconstructor is embedded within a Pseudo-Open Loop Control (POLC) [23], which represents a potential candidate for real-time AO control precompensation dedicated to uplink. These numerical results are obtained with full end-to-end simulation of the FEELINGS ground station, including phase propagation and scintillation effects through the use of the TURANDOT simulation tool [24]. The Shack-Hartmann WFS and DM are representative of FEELINGS. High signal to noise ratio (SNR) is considered, and fully linear measurements (no saturation of detector). Only central obscuration is not accounted so far. Simulation is performed at an equivalent 2kHz frame rate over 1 second. We compare the PAMAO/POLC solution with classic integrator control correcting the downlink beam and suffering from anisoplanatism on the uplink precompensation. We also compare with a so-called "optimal" solution that stands for an ideal but not possible configuration where the uplink turbulence is measured and directly corrected through an integrator control law. Two turbulence profiles are considered here: P1 ($r_0 = 5.3cm$, $\theta_0 = 3.86\mu rad$, $\sigma_\chi^2 = 0.2$) and RT3030 ($r_0 = 9.8cm$, $\theta_0 = 7.8\mu rad$, $\sigma_\chi^2 = 0.07$). P1 profile represents a worst case, while RT3030 is more favorable and closer to conditions obtained on FEELINGS. These profiles are discretized on 24 layers and illustrated in Figure 11. They are described in details respectively in [25] and [26].

Results of PAMAO/POLC correction are presented in Figure 12. While the time average coupled flux is not significantly modified, a clear gain on the Cumulated Distribution Function (CDF) of the coupled flux is observed, with some 15dB on both profiles at a 10^{-3} level. This points out a significant gain in fading statistics, visible on the temporal series, offering potentially a big link margin gain. Of course, the PAMAO approach is not magic and the ultimate performance, symbolized by the "optimal" correction directly obtained in the PAA direction, would prove more efficient though not feasible, except through the use of an active slave companion satellite placed at the PAA position. These results now need to be further investigated, introducing lower SNR, and limited dynamics on the WFS, leading to extinction and saturation in the presence

of scintillation. In lab validation are ongoing on the PICOLO/LISA bench developed at ONERA [27], initially for LEO downlinks and now modified to emulate GEO feeder configurations. Still, these results are very encouraging. More details and complementary work can be found in [29].

To go further, an optimal control solution has been derived based on the seminal work of [22], using Linear Quadratic Gaussian (LQG) control. This work derives from an initial work dedicated to predictive control in LEO downlinks [28], now extended to the GEO feeder case. This approach provides a more general framework, with optimal solution, that could even extend to LEO feeder configurations. This LQG approach shows promising results in simulation and in lab validations as described in [29]. Now the goal is to extend these results for on sky validation with FEELINGS so as to assess in representative conditions the gain brought by PAMAO to GEO feeder links.

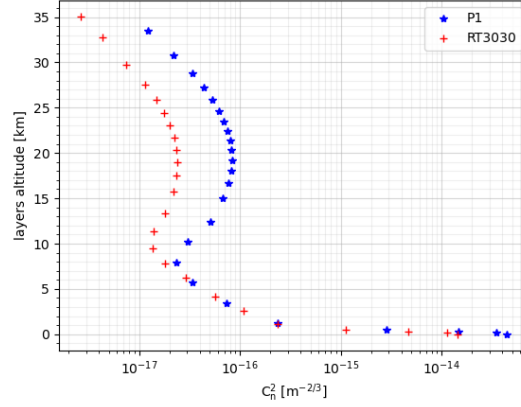


Figure 11: P1 (blue) and RT3030 (red) C_n^2 profiles along the LoS

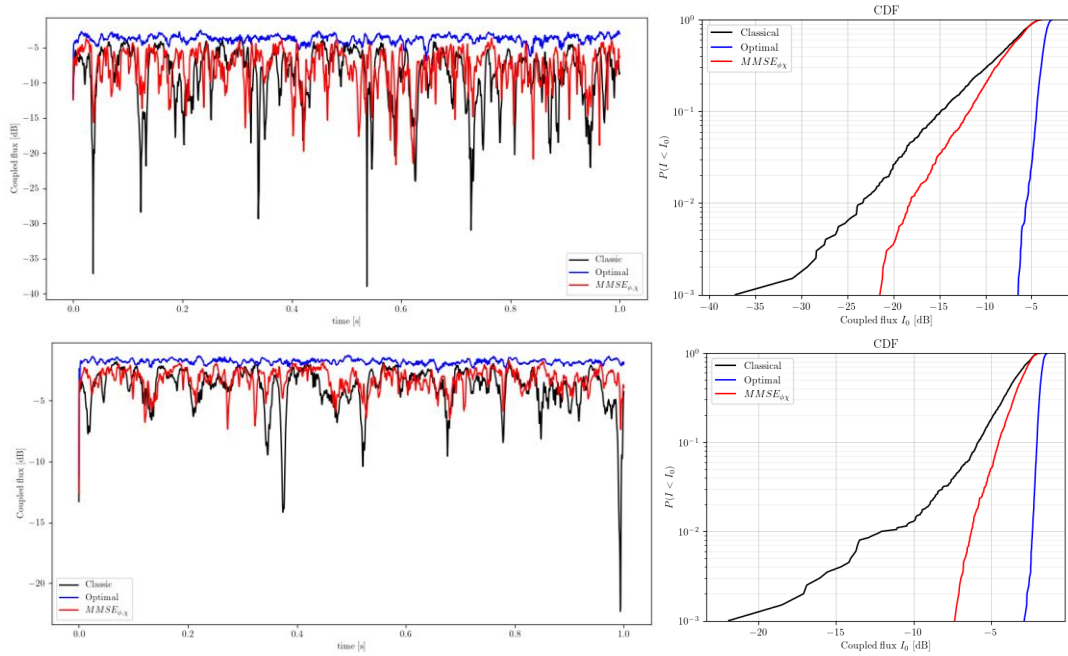


Figure 12: PAMAO performance simulation. Top to down: Performance of PAMAO in POLC implementation (red – noted MMSE) compared to integrator (black – noted classic) and optimal correction, time series (left) and CDF (right), for P1 profile (top) and RT3030 profile (down).

6. CONCLUSION

The work presented here provides a global view of the achievements of the FEELINGS OGS in the TELEO framework. The commissioning of the FEELINGS ground station and the stability of the adaptive optics performance validates a mastered platform, providing a solid foundation for future developments. To consolidate these achievements, immediate efforts will focus on controlling static losses (transmission losses and static aberrations), automating injection optimization, and reducing the processing time for atmospheric attenuation data.

Still FEELINGS is a research platform. As such, medium-term prospects aim to investigate further scientific issues. First goal is to leverage the turbulence profiles measured at FEELINGS to validate C_n^2 profile models, such as those included in MATISSE. Improvement of transmission estimation, through combined use of local measurement and numerical simulation shall also be further investigated.

Finally - and most importantly - the station is now ready to test innovative adaptive optics concepts. First of all, optimized precompensation at PAA is considered. Preliminary numerical analysis shows significant gain brought by the PMAO approach, in a dynamic control scheme involving POLC. This solution shall be extended to optimal control through LQG. Lab tests are currently on-going involving LQG or POLC [29] [31] and implementation in FEELINGS is considered at short-term. Robust handling of scintillation is also a key challenge. Preliminary work on robust wavefront sensing has been initiated [30] and shall be continued considering the coupled impact of scintillation on wavefront sensing and control. Deploying next-generation AO systems will require detailed analysis of current data and, above all, access to satellite opportunities (GEO and LEO) in order to fully leverage the platform's testing potential.

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