First results of ground to GEO optical links channel monitoring with FEELINGS

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ABSTRACT

In the coming decade, optical GEO feeder links should form the backbone of future spatialized high-data rate networks, provided that atmospheric propagation channel influence can be adequately mitigated. Currently foreseen mitigation strategies (interleaving and error correcting codes) rely on strong hypothesis on the statistics of the transmitted optical power, the latter being particularly dependent on the atmospheric channel models considered to tune them. Atmospheric transmission is affected by thin clouds (cirrus), aerosols and contrails, resulting in a several dB uncertainty in the link budget. Atmospheric turbulence causes fluctuations in the transmitted power, with properties highly dependent on the turbulence distribution along the line of sight and its temporal characteristics. Though well-documented in the favorable propagation environments of astronomical observatories, the compatibility of propagation channel properties with very high data rates still needs to be demonstrated for ground segments located closer to densely populated areas.

In order to characterize the relationship between challenging optical propagation and optical link performance, ONERA has built the FEELINGS ground station, a 600 mm based adaptive optics (AO) corrected demonstrator equipped with a 50 W optical booster. Located in the periphery of Toulouse, FEELINGS' primary objective is to address the scientific and technological uncertainties associated with optical links and their application in realistic environments. The aim is to pave the way for future operational Optical Ground Stations (OGS) systems.

The TELEO payload developed by Airbus, composed of a TOP-M laser terminal with a 260 mm diameter telescope, a 5W optical amplifier and a 10 Gbaud compatible data transceiver, enables both uplink and downlink 10 Gbaud data transmission. Recently put into orbit, it offers a unique opportunity to confront atmospheric propagation channel models to the challenges of regular high data rate operations.

This paper will present the first results of optical links between TELEO and ONERA's ground segment with a specific focus on the propagation channel analysis and modeling for the uplink.

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

1. INTRODUCTION

Driven by the tremendous expansion of global connectivity needs in the coming years, bidirectional optical feeder links might become the backbone of future space data highways[1]. Expected data rates, from 100 Gbps to the Tbps, will be

accessible at the expense of dense and/or sophisticated modulation formats that have already proven their efficiency on ground in a relevant environment [2]. However, the performance available remains dependent on propagation conditions, which are much more severely affected than in radio frequency. Atmospheric transmission is degraded by thin clouds (cirrus), aerosols and contrails, resulting in a several dB uncertainty in the link budget. Atmospheric turbulence causes fluctuations in the transmitted power, with properties highly dependent on the turbulence distribution along the line of sight and of its temporal characteristics. To achieve the expected reliability of a communication service, several mechanisms of protection against propagation channel impairments are used: error correction codes to limit the impact of noise during detection, interleaving to limit the influence of deep attenuations, adaptive optics to limit the depth of attenuations, and site diversity to counteract the effects of cloud masking. At each step, margins are added to the link budget to cope with the different sources of uncertainties generated by the randomness of certain phenomena. These margins are perspectives for increasing throughput if they can be reduced to what is strictly necessary.
TELEO demonstration, with the geostationary orbit commissioning at the end of 2023 of an optical payload dedicated to the demonstration of high data rate key technological building blocks is a unique opportunity in Europe to test and evaluate in real conditions some of these key technologies [3]. The FEELINGS ground station[4], built by ONERA as a research platform to develop, test and validate in real conditions the ground segment key technological building blocks, has been recently used to establish with the TELEO payload several adaptive optics precompensated optical links with its full 600 mm aperture. These links, being to the best of our knowledge the first AO precompensated links with a GEO satellite with such a diameter at a telecom compatible wavelength, were exploited to initiate a systematic investigation of the atmospheric channel impact thanks to the specific atmospheric monitoring capability natively incorporated in the instrument. Section 2 of this paper is dedicated to a short overview of the FEELINGS ground station with a stress put on atmospheric monitoring capability. Section 3 presents the first results of precompensated uplinks with TELEO and a comparison of the measured irradiance with the output of our model.

2. FEELINGS, ONERA’S OPTICAL GROUND STATION

2.1 General presentation

The Feeder Links Ground Station (FEELINGS) has been designed as a research platform to develop, test and validate the ground segment building blocks for the future of space-ground optical links. 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 and a high power amplifier designed and built at ONERA (BOOster for FEEder a.k.a BOOFEE) to bring 50 W of output power. The AO bench is equipped with a 17x17 Shack-Hartmann wavefront sensor, an Alpao DM292 deformable mirror and a real time computer provided by Shakti able to drive the loop at up to 4.7 kHz sampling frequency with a 2.3 frames delay and an integrator control law. The FEELINGS ground station 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). The AO bench is illustrated on the right of Figure 2. The AO bench provides both downlink correction for single mode fiber injection and uplink precompensation in a monostatic configuration. A beacon shares the same common path for pointing and tracking protocol. Commissioning of the ground station occurred in March 2024 slightly before the first links with the TELEO payload.

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.

2.2 Atmospheric monitoring platform and software

Figure 2 : Atmospheric monitoring equipment installed on FEELINGS, from left to right : VAISALA's CL51 ceilometer, CIMEL CE318 Sun-Sky-Lunar spectral photometer, Miratlas Integrated Sky Monitor including a visible all-sky camera, ONERA's AO bench.

This section focuses on the atmospheric monitoring capability of the ground station.

Atmospheric transmission

To validate the hypothesis on the transmission of the link budget, 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 is the French Defence Procurement Agency (DGA) reference code for modeling atmospheric radiative transfer on a global scale [5]. It provides atmospheric radiance and transmission over the entire optical spectrum. It includes databases that can be used to fill in the input parameters: standard or climatological thermodynamic profiles, optical properties of aerosols and cloud types, reflectance of the ground, sea temperature, etc.

This assessment provides an initial estimate of the various contributors to transmission along the line of sight (molecules, cloud and aerosol transmission), with the temporal and spatial resolution of Météo-France forecasts, i.e. 5 km and 1 h respectively. Accuracy is limited to forecasts accuracy. As an example the forecasted transmission for 24/07/2024 and 25/07/2024 is shown in Figure 3-a.

FEELINGS ground station is equipped with instruments that provide, after data processing, precise information of the atmospheric transmission either spatially distributed or integrated along the line of sight in a time scale of a few minutes thanks to the microphysical and radiative aerosol properties measured. A visible all-sky camera and a LIDAR-like system, namely a ceilometer, allow for characterizing atmospheric aerosols and clouds. A radiative property such as the attenuated backscatter coefficient can be quantified from the ceilometer at 910 nm, as shown in Figure 3-b. Co-located, a CIMEL sun-sky-lunar photometer (CE318TL9) brings information about the column-integrated radiative properties of the aerosols. Hardware for transmission monitoring deployed on FEELINGS is illustrated Figure 2 from left to right: VAISALA's CL51 ceilometer, CIMEL CE318TL9 Sun-Sky-Lunar spectral photometer, Miratlas Integrated Sky Monitor (ISM).

The synergistic operation of a LiDAR (ideally bi- or multi-wavelengths), all Sky visible camera, and day/night sun photometer is an effective solution for characterizing the atmosphere since it allows the overcoming of particular sensor limitations, enhancing the diversification of the products and improving the quality of the retrievals—Figure 3 highlights complementarity. Figure 3c-d presents an example of aerosol Angström coefficient and aerosol optical depth time series measured on 24-25/07/2024.

The next stage is to develop a dedicated data processing automation chain to perform the local evaluation of transmission along the optical link at the wavelength of interest for the FEELINGS ground station. To do so, local atmospheric measurements are gathered to feed the atmospheric propagation model. This approach should be beneficial as i) it allows a local description of the atmosphere through measurements and ii) it also brings flexibility to the modeling, e.g., by selecting the spectral bands' calculation scenarios, among others. However, as the parameters returned by local measurements cannot always be directly fed into the code, an intermediate translation step is still necessary.

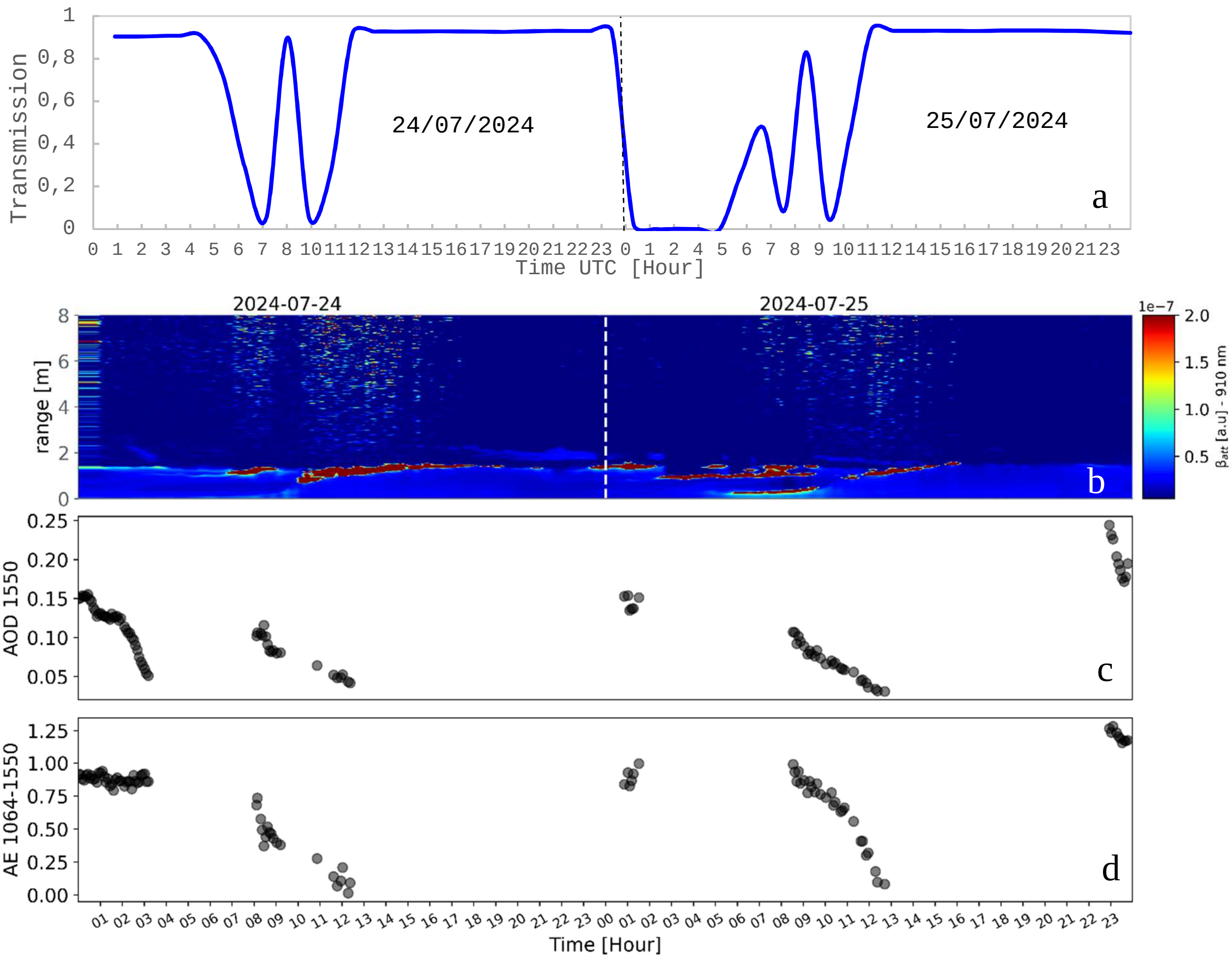

Figure 3 : (a) Transmission calculated with MATISSE-v3.6 from Météo-France forecast data ; (b) Ceilometer attenuated backscatter coefficient measured ; (c) Aerosol Angström coefficient times series; and (d) aerosol optical depth time series on 24-25/07/2024.

Atmospheric turbulence

Atmospheric turbulence monitoring on FEELINGS relies on the exploitation of complementary instruments to provide a 24h/24 coverage. Together with local meteorological parameters Miratlas's ISM provides integrated parameters of the turbulence (daytime and nighttime Fried parameter r_0, nighttime isoplanatic angle and scintillation index) that document turbulence conditions on a 24h basis. Due to the measurement principle, by daytime the exploitation of solar scintillation, by nighttime the differential motion of a bright star according to the DIMM principle, these measurements are performed in directions that can be different from the direction of the optical link, bringing uncertainties in the atmospheric channel assessment. To circumvent this drawback and reduce atmospheric turbulence contribution uncertainty in optical links performance assessment, the data of the Shack-Hartmann wavefront sensor gathered during the link are exploited to estimate high resolution turbulence profiles. The method, called SCO-SLIDAR [6][7] for Single Coupled SLopes And Intensities Detection And Ranging relies on the inversion of the direct problem describing the relationship between the C_n^2 profile and Shack-Hartmann data covariances (slopes and intensities) that exists in the small perturbations regime. The parameters of the method selected for FEELINGS are described in [8], please refer to the reference for their justifications. The method can be exploited on both open or close loop data. Close loop data are considered further.

3. PROPAGATION CHANNEL ASSESSMENT AND PRELIMINARY RESULTS

3.1 Link sessions overview

Optical link experiments between FEELINGS and the TELEO payload have been ongoing since spring 2024. After an initial pointing validation phase held on 28 March, two link sessions between FEELINGS and TELEO took place, the first between 05/06 and 06/06 and the second between 10/07 and 11/07. The purpose of these test sessions was to validate the station/payload interfaces and assess the robustness of the protocols for pointing; acquisition and tracking (PAT) before switching to payload communication mode. During these test phases, FEELINGS first lit on its beacon, the signal is detected then locked by TELEO and the payload switches to tracking mode. The carrier of the communication beam (BOOFEE amplifier) is then switched on. The time evolution of the 1s averaged irradiance in the aperture plane of the satellite estimated from the focal plane received optical power (ROP) is shown on the right of Figure 4, at the top for the link session on 05/06/2024 and at the bottom for the link session on 10/07/2024. The conversion factor between focal plane measurements and estimated irradiance results from an as-built payload estimate.

On 05/06/2024 the test session was dedicated to adjusting the operating points of the point ahead mirror (PAM), AO and the booster. The irradiance received at the end of the session, around -65 dBW.m^{-2}, is well below the nominal irradiance, due to several instrumental limitations corrected before the second session: the PAM calibration had to be adjusted, as well as the focus of the uplink beam. During the second session, after a set of pointing and focus optimizations BOOFEE's power has been increased gradually to reach 20 W. The AO loop was operated at 2 kHz with a 0.25 fixed gain for each corrected mode. The consequent irradiance reaches -43.5 dBW.m^{-2} at 15:53 UTC and goes up to -42 dBW.m^{-2} when AO correction provides its best performance. Visible images of the all-sky camera are reported on the left of the figure to visualize the transparency of the sky in the visible during each session. The direction of the TELEO payload corresponds to the bottom right corner of the picture.

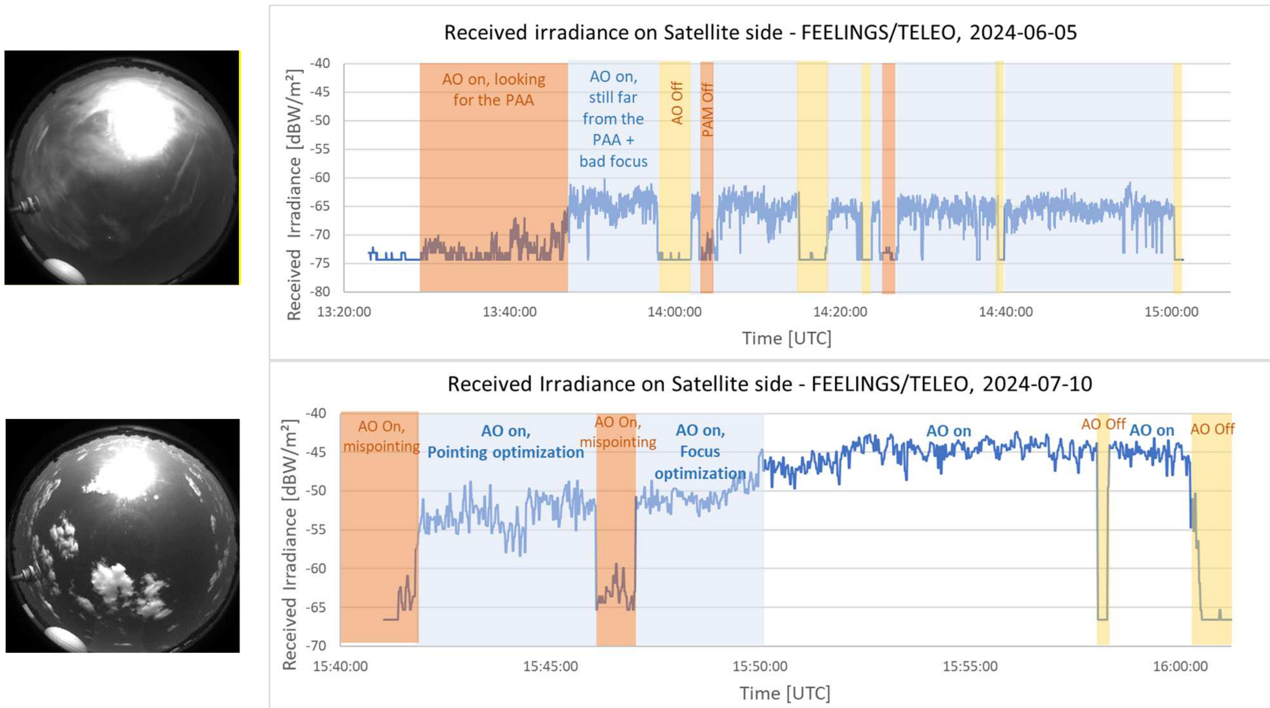

Figure 4 : Top Left: Allsky camera image on the 05/06/2024 at 15:00 UTC. TELEO payload direction corresponds to the bottom right of the illustration. Top right: Received irradiance in the aperture plane of the payload as estimated from TELEO focal plane measurements as a function of time for 05/06/2024. The status of the different subsystems is also reported on the figure. Bottom left: Allsky camera image on the 10/07/2024 at 15:50 UTC. TELEO payload direction corresponds to the bottom right of the picture. Bottom right: Received irradiance in the aperture plane of the payload as estimated from TELEO focal plane measurements as a function of time for 10/07/2024.

3.2 Turbulence channel characterization

The results of the turbulence profile estimation along the line of sight using the SCO-SLIDAR method for a period of 10 min are shown in Figure 5. The profile is sampled over 12 equidistant layers distributed between the ground and the maximum distance of 36 km, corresponding to the output of the considered atmosphere for the line of sight (TELEO elevation is 31°). Sets of 10,000 frames acquired at 2 kHz were used to extract a C_n^2 profile every 5 s. Around 15:58 three outliers are present, corresponding to a temporary interruption of the link. Integrated turbulence parameters are estimated from these profiles. The Fried parameter, Rytov log-amplitude variance, isoplanatic angle, mean wind speed are reported Figure 6. For the evaluation of the mean wind speed, we use a Bufton wind profile with a 30 $m.s^{-1}$ high altitude layer, a typical value for Bufton wind profiles referenced in the literature [10]. The ground velocity parameter is provided by the weather station. For this very preliminary analysis the choice of a fixed value for the high altitude layer is imposed by the lack of more relevant data to feed the model. The implementation of a wind profile estimation from the data is part of the perspectives of this work. The first moment of the time series of the integrated parameters are provided Table 1. These integrated parameters correspond to typical operating conditions for which FEELINGS has been designed.

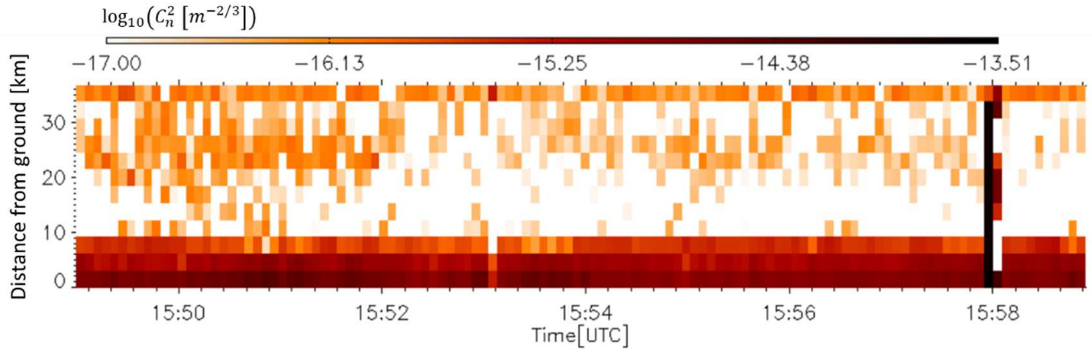

Figure 5 : C_n^2 profiles along the line of sight as a function of time for the 15:49 to 15:59 UTC time slot on 10/07/2024

	r_0 [cm]	σ_χ^2	θ_0[µrad]	$\bar{v}$[m/s]
Average	7,1	0,22	3,8	12,0
Std Dev.	1,3	0,05	0,6	2,4

Table 1 : Integrated parameters of the turbulence computed from the estimated C_n^2 profiles

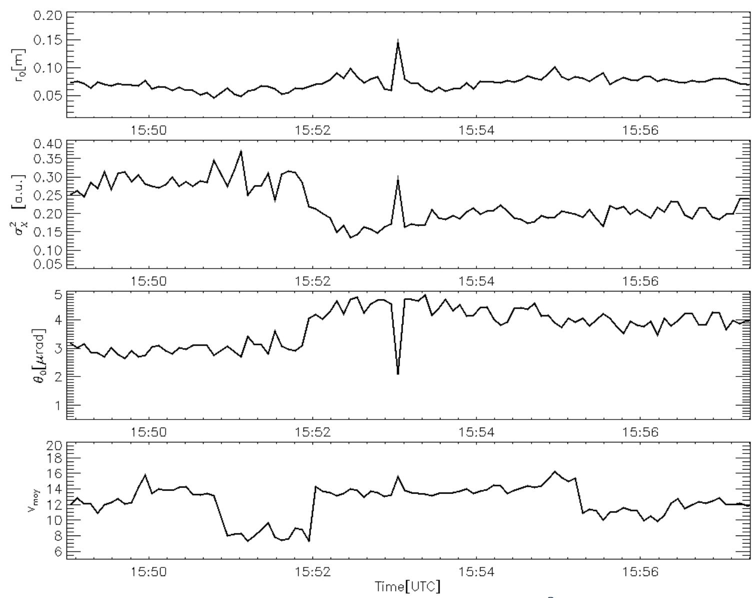

Figure 6 : Turbulence integrated parameters as computed from the reconstructed C_n^2 profiles as a function of time. Top : Fried parameter [m], second line: Rytov log-amplitude variance, third line : isoplanatic angle [µrad], bottom : average wind parameter [$m.s^{-1}$].

3.3 Comparison to model

The establishment of a high data rate optical link depends on the compatibility of the instantaneous link budget with the sensitivity limit of the detection and demodulation chain. TELEO provides a unique opportunity to consolidate theoretical uplink propagation channel assessment by an experimental validation. We assess here the key parameters of the link budget, evaluate its slowly variable contributors due to atmospheric turbulence mitigation and compare them to the irradiance measurements gathered by the payload. We focus on the link established on 10/07/2024 and more specifically on the time slot when the best performance in terms of uplink power was reached, that is during the time slot between 15:49 and 15:58. Irradiance estimated focal plane measurement, denoted further as "measured irradiance", are plotted in blue on Figure 7. The 1 s sampled time series recorded by the payload has been convoluted by a constant 5 s sliding window in order to ease the comparison with the simulation results presented later.

Adjustments of the AO loop gain were performed up to 15:50. The link is briefly interrupted just before 15:58. Between these two events the average measured irradiance is -45 $dBW.m^{-2}$ and its standard deviation is 1.2 $dBW.m^{-2}$. The measured irradiance reaches -42.8 $dBW.m^{-2}$ as a maximum at 15:56.

Two major trends can be identified in the irradiance time evolution within these 10 min slot. From 15:50:47 to 15:52:30 the irradiance shows a progressive increase to reach -43 $dBW.m^{-2}$ (highlighted in grey on the figure). Then in the [15:52:30, 15:58:00] timeslot, highlighted in light orange in the different figures, the average irradiance goes to -45 $dBW.m^{-2}$. It shows several periodic oscillations (approximate period 30 s) before the interruption of 15:58.

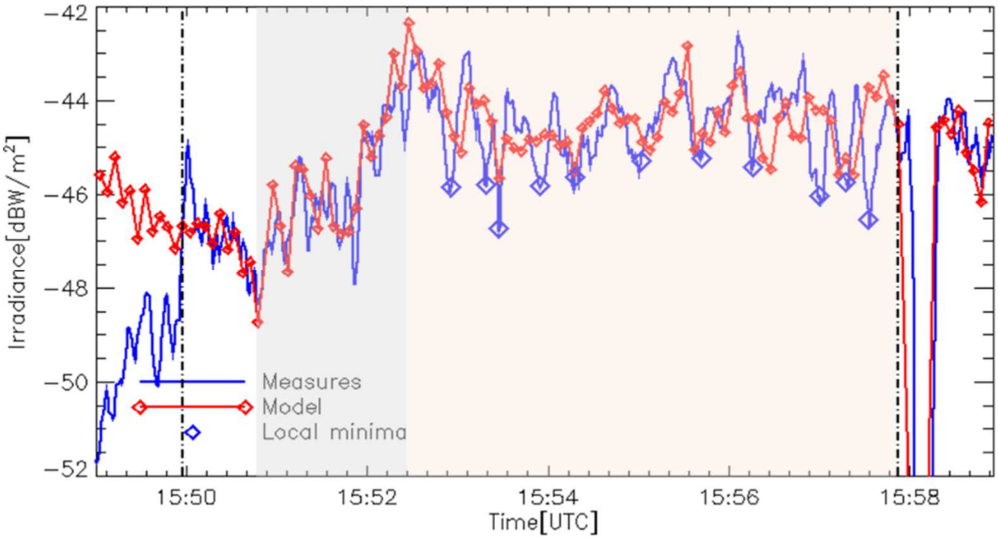

Figure 7 : Focus on received optical power onboard for the 15:49 to 16:00 on 10/07/2024. The grey highlight area corresponds to an overall increase of the received optical power, the orange one shows periodic oscillations into the ROP temporal evolution.

We analyze the reasons for such trends in the light of simulation results. The simulation tool, called SAOST for Simplified Adaptive Optics Simulation Tool relies on a Monte Carlo process where random draws of 2D phase and amplitude maps are used to calculate intensity far field patterns in the satellite plane. A complete description of the principle of SAOST can be found in[11]. A set of 5000 draws for each profile is used to assess the average attenuation on the uplink due to turbulence for the timeframe corresponding to the calculation of the C_n^2 profile (5 seconds for each average attenuation estimation). The time evolution of the expected irradiance is plotted in red together with the measurements on Figure 7. The key static contributors to the simulated uplink link budget are provided in Table 2. Their evaluation were obtained through a careful calibration process conducted both by ONERA for FEELINGS and by Airbus for the TELEO payload. The atmospheric transmission contribution is obtained thanks to the forecasting process described in section 2.2.

Contribution	Unit	Uplink
Tx power	dBW	13,0
Tx antenna gain	dB	119,3
Tx optical loss	dB	-4,2
Tx static aberrations	dB	-0,4
Tx mispointing and residual defocus	dB	-1,2
Geometrical loss	dB	-289,8
Atmospheric transmission	dB	-0,5
Rx antenna gain (1 m²)	dB	127,2
Static irradiance	dBW/m²	-36,5

Table 2 : Main contributors to the link budget for the FEELINGS-TELEO session of 10/07/2024.

The temporal evolution of the measured irradiance is well reproduced by the simulation. The difference between the irradiance measurements and the model output is almost centred as it reaches -0.1 dB in average. It shows a 0.8 dB standard deviation. This illustrates the relevance of the C_n^2 profile estimation.

The analysis of the error budget, that is used to feed the simulation, provides clues to investigate the origin of the trends identified in the irradiance temporal evolution. The AO error budget for the downlink is plotted Figure 8. It is decomposed into four main contributions: fitting error, aliasing error, temporal error and anisoplanatism error. See [12] for a description of the three first error terms and [13] for the last one. The AO error budget analysis triggers several observations:

- The error budget is dominated by the anisoplanatism error. This is expected considering the very limited isoplanatic patch encountered during the link, the second major contribution appears to be the temporal error, with a residual error ten times smaller than the anisoplanatism error term,
- The increase of the measured irradiance observed between 15:50:47 and 15:52:30 in Figure 7 corresponds to a progressive decrease of the anisoplanatism error. It is highlighted in light grey in Figure 8 and Figure 9. Simultaneously, as expected, the isoplanatic patch increases (see the corresponding timeslot of Figure 6 for θ_0). On the overall timeslot the irradiance increases of + 6 dB.
- Considering the estimation of the static contribution to the link budget reported Table 2 and the measurements plotted Figure 7, atmospheric turbulence contribution on the uplink fluctuates between a 5.5 dB power penalty and a 12 dB power penalty for 5 s averaged measurements in the 15:49 to 15:58 timeslot.
- Quasi-periodic irradiance oscillations identified in the measurements are also visible in the simulation results. A careful analysis of local minima of the measured irradiance in the [15:52:30,15:58:00] timeslot, whose abscissa is identified in Figure 7 by blue diamonds, shows that for 8 local minima out of a total of 11 the considered minimum corresponds to a local maximum in the anisoplanatism error term. Note that the abscissa of local minima in the irradiance measurements is identified Figure 9 by blue diamonds reported in the anisoplanatism error term. These maxima also correspond to local minima in the temporal evolution of the isoplanatic patch (see the corresponding timeslot of Figure 6 for θ_0). Despite the fact that this observation supports the hypothesis of a phenomenon related to half a minute scale fluctuations of atmospheric turbulence, further investigations must be conducted to confirm this hypothesis as other potential origins may have comparable effects. The C_n^2 estimation method relies on the exploitation of spatial covariances of slopes and intensities recorded by the Shack-Hartmann. Any effect that would modify the spatial statistics of these quantities might lead to misleading estimations.

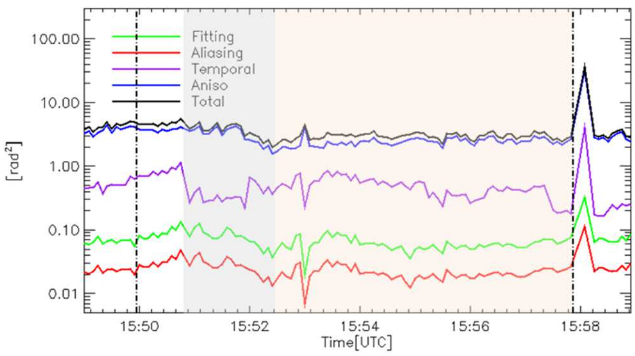

Figure 8 : Main contributors to the AO error budget for the uplink as a function of time for the 10/07/2024 session, between 15:49 and 15:59.

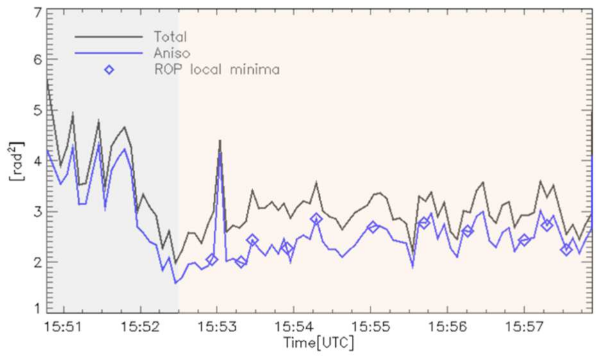

Figure 9 : Total residual wavefront error and anisoplanatism error term for the [15:50:47, 15:58:00] timeslot.

4. CONCLUSION

In order to fulfil the ambition of reducing link budget margins to the minimum and devote the maximum number of useful photons to the data transmission for GEO feeder links ONERA has recently built the optical ground station FEELINGS. FEELINGS is a research platform dedicated to the development and test of key technological building blocks in documented propagation conditions to understand technical limitations of existing technologies and prepare future game changing solutions. Reaping the benefits of the TELEO demonstration that started end of 2023, FEELINGS performed its two first optical links sessions in June and July 2024. June session was dedicated to validate interfaces and pointing acquisition and tracking with the payload. July session was dedicated to the adjustments of key subsystems that are of tremendous importance for the performance of the link: point ahead mirror, overall focus of the uplink path and AO loop. These two first sessions brought very encouraging results as in July the 1 second averaged measured irradiance reaches -42.8 dBW.m^{-2} with a booster setpoint below a half of its nominal power. These results need to be put into perspective of the very favourable atmospheric transmission encountered for this session (atmospheric attenuation of -0.5 dB) yet being very reinsuring. Atmospheric channel characterization performed with the wavefront sensor data and the use of a Monte Carlo model fed with an uplink error budget enables to assess the link budget with a precision better than 0.8 dB rms on the 8 min duration considered. The analysis confirms the predominance of the anisoplanatism error. It revealed the presence of quasi-periodic oscillations of the irradiance that are also present in the model. The correspondence of local minima with maxima in the anisoplanatism error tends to incriminate a physical phenomenon related to atmospheric turbulence temporal evolution, with a half a minute typical time scale. Further investigations still need to be conducted to consolidate this analysis. The predominance of the anisoplanatism error, confirmed here, strengthen the necessity to develop specific mitigation strategies to overcome the identified limitations. Among others, considering alternatives to the basic application of the downlink measured phase as the correction for the uplink would be highly beneficial[14].

For the considered experimental session the strategy developed to assess atmospheric transmission from weather forecast data proves to be sufficient.

Results presented here put the stress on the uplink, meanwhile equivalently rich data have been gathered at the focal plane of the downlink optical train. Analysis of these data is currently being conducted with a comparable approach. Given the contribution of the temporal error exhibited here on the uplink, temporal variations of the downlink coupling efficiency is highly probable.

Despite the limited number of link sessions carried out so far, the results obtained with FEELINGS are particularly encouraging. At the time this proceeding is submitted, a new session of bidirectional optical links has made it possible, thanks to the exploitation of the communication equipment provided by ADS, to digitize the uplink received power signal and to send it back to Earth thanks to the optical telemetry. Additional link sessions are planned with the goal to demonstrate bidirectional high-throughput optical links in a perspective to document and analyse the channel impact with an analogous approach as illustrated in this paper.

When it comes to the perspectives offered by the estimation of atmospheric turbulence profiles from Shack-Hartmann data, the characterisation of C_n^2 profiles shall be completed by a wind profile estimation to reap the benefits of the joint estimation of both quantities in the process to fit the spatio-temporal covariances of Shack-Hartmann data. FEELINGS participation to TELEO demonstration, if pursued, would enable the building of atmospheric turbulence profiles databases, associated to both experimental and simulated performance measurements simultaneously for uplink and downlink. These data could be of crucial importance to develop optical links performance prediction models, for both short and long term horizons if key questions about the primary (meteorological) parameters influencing link performance, the necessity to consider vertical turbulence profiles (altitude-dependent) rather than integrated parameters, and how to integrate weather forecast models or artificial intelligence into predictions can be at least partially answered. As a very first step these data could be exploited, following the methodology described in [15], to validate experimentally a Machine Learning based performance model that would be fed with integrated parameters only and investigate experimentally to what extent the use of high resolution atmospheric profiles can be avoided.

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