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Adaptive Optics for GEO-Feeder Links: from Performance Analysis via Reciprocity Based Models to Experimental Demonstration

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ABSTRACT

High capacity GEO-Feeder optical links are very promising but constitute a real challenge for the whole transmission chain. The modeling and mitigation of turbulence effects is a particularly critical issue that drives the other subsystems design requirements. Building on SAOST, our reciprocity based performance evaluation tool, we study the GEO-Feeder link scenario: adaptive optics error budget and performance in terms of link availability threshold, for forward and return links, as a function of the number of corrected modes and of the ground telescope diameter. Adaptive optics correction is shown to be essential both for downlink and uplink. Choosing a large diameter is highly beneficial for downlink, point-ahead anisoplanatism is however shown to level uplink performance for diameters above a few tens of centimeters. The article also demonstrates that the reciprocity, beyond providing powerful numerical tools, is a key principle for an in-depth understanding of the physical effects impacting adaptive optics assisted ground-space optical links. These theoretical results are complemented by a brief presentation of FEEDELIO, the first experimental demonstration of uplink pre-compensation performed on a slant line of sight representative of a GEO-Feeder link.

Keywords: Ground-Space Optical Links, Satellite Feeder Link, Adaptive Optics, Reciprocity Principle, Anisoplanatism.

1. INTRODUCTION

The exponential growth of the needs in data transfer drives an increasing interest for high capacity free space optical links between the ground and telecommunication satellites. Currently the most appealing configuration relies on bidirectional ground / geostationary satellite optical links, so-called GEO-Feeder links, aiming at about one Terabit/s on uplink. The strong requirements in performance of such systems imply innovative developments on each segment of the chain. In particular, the mitigation of atmospheric turbulence effects is essential to reduce mean loss and deep fadings of the detected optical power. Adaptive Optics (AO) serves this purpose and is used on the ground side to sense and correct the incoming downlink beam, before injection in a single mode fiber, and to pre-compensate the emitted uplink beam.

AO pre-compensation has been considered for more than 40 years [1][2]. Point ahead, induced by the movement of the satellite during the light roundtrip, however limits pre-compensation efficiency [1] due to the effect of anisoplanatism [3][4]. Although this physical effect is well known, its impact on AO performance is often modeled [2][5] with simplified expressions [3] that do not account for system specificities such as the finite telescope aperture and the finite number of AO corrected modes. Regarding experimental validations in the context of GEO-Feeder link, one can cite the near ground demonstration of a high data rate telecom link but with only tip-tilt pre-compensation [6] as well as recent AO pre-compensation validations in the laboratory [7] and near ground [8][9] but in conditions that are not clearly representative of the GEO-Feeder case, and without comparison to link performance models.

The aim of this paper is to estimate the performance of AO assisted GEO-Feeder links with a refined AO modeling putting a particular emphasis on anisoplanatism effects. We use SAOST (Simplified Adaptive Optics Simulation Tool) a pseudo-analytical tool originally developed for downlink [10][11] and recently extended to uplink. SAOST is a unified tool that treats down and uplink with a consistent formalism [12] that exploits the reciprocity principle [13][14], a strategy inspired from our recent developments in the context of high precision frequency transfer [15]. We remind that we have also developed the tool WPLOT [16] which is an alternative model based on a more straightforward description of the uplink propagation of a truncated Gaussian beam. WPLOT is a computation efficient tool that provides time series of uplink detected flux. For now, it is however limited to ground apertures smaller than a few Fried parameters r_0 , and it only addresses tip-tilt pre-compensation.

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Preliminary results on performance of AO assisted GEO-Feeder links can be found in [12][17] but a more exhaustive analysis is presented in this article and addresses: evaluation of AO error budget and performance in terms of link availability threshold for up and down link as a function of the number of corrected modes and of the ground telescope diameter. Moreover this article demonstrates that the reciprocity, beyond providing powerful numerical tools, is a key principle for an in-depth understanding of the physical effects impacting adaptive optics assisted ground-space optical links. These theoretical results are complemented by a brief presentation of FEDELIO, the first experimental demonstration of uplink pre-compensation performed on a slant line of sight representative of a GEO-Feeder link.

The outline is as follows. Section 2 recalls the theoretical background and presents SAOST. Section 3 presents the GEO-Feeder performance study. Section 4 then briefly describes the FEDELIO demonstrator.

2. RECIPROCITY BASED MODELING OF BIDIRECTIONAL GROUND-SPACE OPTICAL LINKS

This section gives the theoretical background and presents our modeling strategy. Section 2.a first presents the ground-space optical link scenario, recalls the metric of interest in the case of direct detection, and gives a metric expression that exploits the reciprocity principle. Section 2.b then presents SAOST, our reciprocity based performance evaluation tool that allows treating down and uplink with a consistent formalism.

2.1 Reciprocity and complex coupling

Figure 1 displays a sketch describing the optical propagation through turbulence for ground-space optical links. On the one hand, uplink corresponds to the upward propagation of a truncated Gaussian beam through the atmosphere. The satellite, located far beyond the upper atmosphere and the Rayleigh distance, sees the far field. On the other hand, downlink is well approximated by the downward propagation of a plane wave. For GEO satellites, due to the large round-trip time, downlink and uplink are separated by the so-called point-ahead angle. The turbulence volume can be described by discrete layers (perpendicular to the line of sight) introducing local phase perturbation on the optical beam that eventually lead to phase and amplitude effects after propagation.

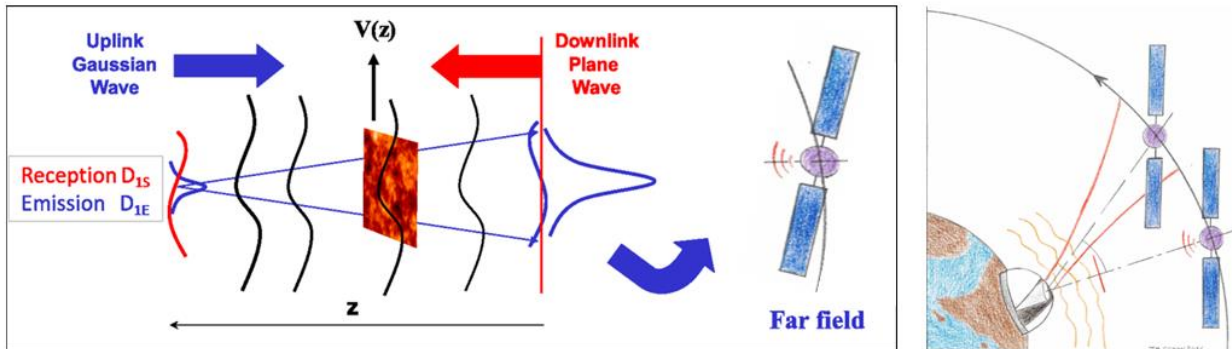


Fig. 1 Sketch describing the optical propagation through turbulence for ground-space optical links; [left]: illustration of up and downlink paths (point-ahead not represented); [right]: illustration of the point-ahead angle.

The key notion that optically characterizes such links is the “complex coupling” \mathcal{C} , that corresponds to the overlap integral between the received complex field $\mathcal{E}_R(\mathbf{r})$ and the complex conjugate of a local reference field $\mathcal{E}_L(\mathbf{r})$:

$$\mathcal{C} = \int \mathcal{E}_L^*(\mathbf{r}) \mathcal{E}_R(\mathbf{r}) d\mathbf{r} \quad (1)$$

where \mathbf{r} is the spatial coordinate in the terminal pupil. This complex coupling can of course be defined on both ends of the link, say \mathcal{C}_1 for terminal 1 on ground, and \mathcal{C}_2 for terminal 2 in space. In the case of coherent detection the local reference field is the complex field of the local oscillator, while for direct detection after injection in a single mode fiber (SMF) the local reference field is the pupil complex mode characterizing the fiber. We focus here on the latter case for which the parameter of interest is the detected flux proportional to $|\mathcal{C}|^2$. The reader interested in coherent detection can read [15][18][19] and references therein.

Wave propagation being a linear process, the principle of reciprocity applies to propagation through turbulence [13]. This principle has direct consequences on link reciprocity [13][14] and on the expression of the complex couplings [15]. For the sake of concision we directly give their expression in the particular case of ground-space propagation:

$$\mathcal{C}_1 \propto \int \mathcal{E}_{1L}^*(\mathbf{r}_1) h_0(\mathbf{r}_1) d\mathbf{r}_1 \quad \text{and} \quad \mathcal{C}_2 \propto \int \mathcal{E}_{1E}(\mathbf{r}_1) h_{pa}(\mathbf{r}_1) d\mathbf{r}_1 \quad (2)$$

where $h_0(\mathbf{r}_1)$ and $h_{pa}(\mathbf{r}_1)$ are the complex fields received in the ground terminal pupil corresponding to the downlink propagation of a plane wave, respectively from the on-axis and from the point ahead angle direction. Reciprocity leads to the remarkable property that the complex couplings of both ends of the link can be expressed in the ground-terminal pupil plane as the overlap integral between specific downlink plane waves and respectively the SMF mode $\mathcal{E}_{1L}(\mathbf{r})$ for down and the laser emission mode $\mathcal{E}_{1E}(\mathbf{r})$.

These equations remain valid in the presence of AO, used for either correction at reception, or for pre-compensation at emission [14][15]. AO simply adds correction phase terms to emission or local oscillator fields in the previous expressions. Phase correction can indeed be beneficial to the ground terminal to partly compensate the turbulent phase effects in $h_0(\mathbf{r}_1)$, respectively $h_{pa}(\mathbf{r}_1)$. In practice, one effectively receives the downlink beam $h_0(\mathbf{r}_1)$ from the satellite, which can be used for wavefront sensing, and be corrected by AO at reception. In contrast, there is unfortunately no off-axis beacon coming from point ahead. Pre-compensation of the uplink therefore has also to rely also on downlink wavefront sensing. This formalism clearly demonstrates that up and downlink can be studied with the same formalism by simply adding the anisoplanatism limitation for the uplink case. Impact of point ahead, and associated anisoplanatism effects, is the central issue addressed in the Section 3.

2.2 SAOST: reciprocity based performance evaluation tool

SAOST is a fast pseudo-analytical tool that provides detected flux statistics both for SMF coupling of the AO corrected downlink [10][11] and for detection on board the satellite of the AO pre-compensated uplink beam [17][12]. We remind that a standard AO loop is closed on the downlink pilot beam, the correction is therefore brought by a deformable mirror (DM) based on the pilot beam wavefront sensing (WFS). The uplink beam is simply reflected from the DM so as to benefit from a pre-compensation. Since pilot beam and uplink optical axes are separated by the point-ahead angle, anisoplanatism affects the uplink pre-compensation.

SAOST is a reciprocity based performance evaluation tool that allows addressing both links (down and up) with a simple and consistent formalism. Occurrences of detected flux are computed as the square modulus of the complex couplings, expressed in the ground-terminal pupil plane [12][15], while geometrical losses can be accounted for through standard formula [20]. These occurrences derive from the simulation of occurrences of AO corrected residual phases and occurrences of averaged scintillation over the pupil (flux variations in the pupil are neglected in the present study) [17]. Residual phase occurrences are based on an AO error budget modeling [21, 17], that is, a calculation with pseudo-analytical expressions of the residual phase variance expanded on the Zernike polynomials, assuming that correction is applied up to a given radial order [22]. This model accounts for the following standard AO limitations: limited number of correction modes (fitting error), limited WFS spatial sampling (aliasing error), limited sampling frequency of the loop (temporal error), and possibly point-ahead pointing (anisoplanatism error). With this formalism, modeling the uplink is therefore straightforward and simply consists of adding the point-ahead anisoplanatism error to the fitting, aliasing and temporal errors considered for downlink. SAOST uses a modal anisoplanatism model (on the Zernike basis) [4], accounting for the fact that only AO corrected modes are affected, since we have shown that the usual expression [3] often used in the literature (see for instance [2][5]) strongly overestimates the effective anisoplanatism error (see Sect. 2.3 for an illustration).

In summary, SAOST is a computation efficient unified reciprocity based tool that treats downlink and uplink with a consistent formalism and therefore allows computing efficient and accurate performance estimation for these two channels with AO correction/pre-compensation and without restriction on the turbulence strength provided one remains in the Rytov regime.

Despite several approximations (simplified expressions are used to derive the AO error budget, flux fluctuations inside the aperture are neglected...), SAOST has been shown to provide results that are consistent with those obtained by end-to-end modeling with TURANDOT+SAOST for the downlink [11].

3. GEO-FEEDER PERFORMANCE EVALUATION

3.1 Scenario

The observing conditions considered throughout this article for the quantitative analysis are the following: link at $1.55 \mu\text{m}$ between ground and a GEO satellite (distance $L_{\text{sat}} = 38614 \text{ km}$); Optical Ground Station (OGS) pupil diameter D_{OGS} varies from 10 to 50 cm while beam waist is always set to $w_0 = D_{\text{OGS}}/2.2$; collection pupil diameter on board the satellite is set to $D_{\text{sat}} = 30 \text{ cm}$ for geometrical loss calculations (approximated to : $[D_{\text{OGS}} D_{\text{sat}} / (\lambda L_{\text{sat}})]^2$); line of sight (LOS) with 30° elevation; point-ahead set to $18.5 \mu\text{rad}$; ITU-R P.1621 Hufnagel-Valley turbulence profile with $V_{\text{rms}} = 21 \text{ m/s}$ and a ground C_n^2 set to $5.4 \cdot 10^{-14} \text{ m}^{-2/3}$; Bufton wind profile with 5 m/s wind velocity at ground level and 30 m/s at the usual $12\,448 \text{ m}$ high altitude layer. This leads to a Fried parameter $r_0 \sim 3.0 \text{ cm}$ at zenith and at $0.55 \mu\text{m}$, which is typical of moderate turbulence by daytime in a rural environment. Along the LOS and at $1.55 \mu\text{m}$ one obtains $r_0 \sim 6.9 \text{ cm}$, an anisoplanatic angle $\theta_0 \sim 9.3 \mu\text{rad}$, a log-amplitude variance $\sigma_\chi^2 = 0.066$ (reduced to 0.013 et 0.0022 with pupil averaging respectively on 20 et de 50 cm apertures).

3.2 Adaptive optics performance and error budget

For clearer insights on AO performance and design rules in the GEO-Feeder context it is essential to first analyze the AO error budget as a function of the correction degree. We consider a two-frame delay control loop with a sampling frequency set to 1500 Hz . AO corrects up to a given radial order, ranging from order 1 (tip-tilt only) to order 12 (up to 91^{st} Zernike mode).

Figure 2 presents the AO error budget for uplink as a function of the number of corrected radial orders n_r for 2 emission pupil diameters (20 cm and 50 cm). One clearly sees that, with the considered assumptions, temporal error is negligible, and the dominant terms are fitting, aliasing and anisoplanatism (induced by point-ahead).

As expected, anisoplanatism error depends both on the emission pupil diameter and on the AO correction order. We stress the fact that the usual expression $(\theta_{\text{pa}}/\theta_0)^{5/3}$ given by [Fried-1982] is obviously too crude to account for such dependences and should be considered with much care. This formula gives a 3.2 rad^2 anisoplanatism error variance, hence a huge overestimation compared to the few 0.1 rad^2 observed in **Figure 2**.

Figure 2 also shows that tip-tilt anisoplanatism is a major contributor to anisoplanatism error even though this mode is highly correlated at point ahead (typically better than 90% correlation).

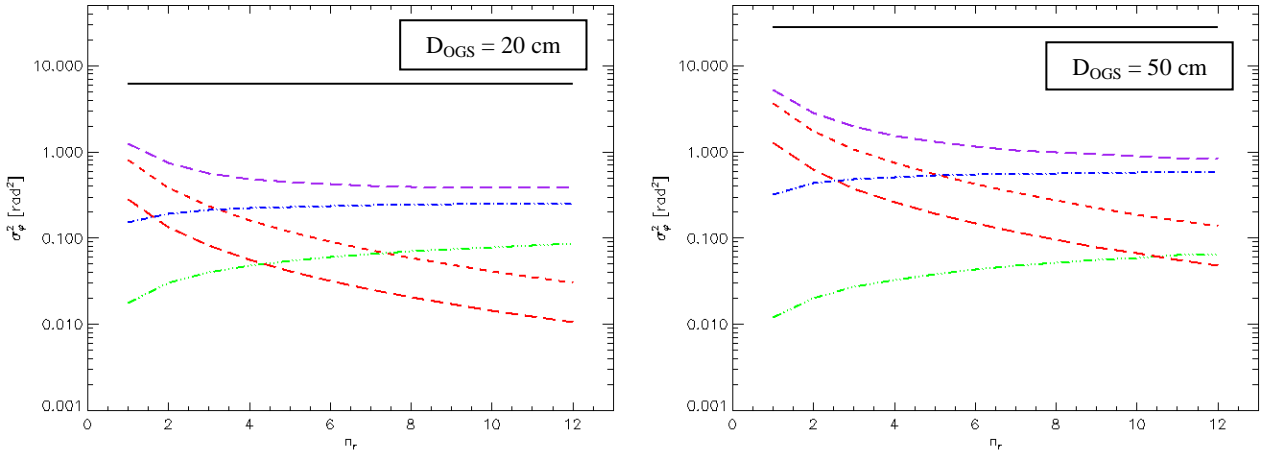


Fig. 2 Uplink AO residual error budget (phase variance in rad^2) versus number of corrected radial orders n_r for $D_{\text{OGS}} = 20 \text{ cm}$ [left] and 50 cm [right] for a 1500 Hz AO loop; fitting error (short dashed line in red), aliasing error (long dashed line in red), anisoplanatism error (dashed-dotted line in blue), temporal error (dashed-double-dotted line in green), total error (long dashed line in purple). Black solid line gives the turbulent variance without correction.

For low order corrections, see for instance the tip-tilt only case ($n_r = 1$), AO provides a huge variance reduction compared to the purely turbulent case and, as expected, anisoplanatism is not really an issue in this case; however, for higher orders correction, anisoplanatism becomes a clear limitation and levels performance beyond radial order ~ 4 for $D_{\text{OGS}} = 20 \text{ cm}$ and ~ 8 for $D_{\text{OGS}} = 50 \text{ cm}$. When going to larger diameters, turbulence effects are of course stronger, and all error terms increase. The difficulty is that correcting more modes is no longer a solution to obtain a small residual

phase variance (much smaller than 1 rad^2 to come near diffraction limit) because of the anisoplanatism error term. Performance relative to diffraction then becomes poor when aperture diameter increases, but in the meantime increasing diameter reduces the beam divergence hence reduces geometrical losses. The interest of using large diameters for uplink therefore remains an open question. This question is investigated in the following paragraph considering these two competing effects and their impact on detected flux statistics with a metric relevant to telecommunications.

3.3 Link availability threshold versus diameter and correction parameters

GEO-Feeder link budget, and eventually performance, is not only sensitive to the mean loss in detected flux but also to flux statistics. It is therefore common to characterize the link quality with the so-called link availability threshold (see for instance [17]), a notion sometimes also associated to the notion of link margin. This criterion is the threshold T (often expressed in dB) corresponding to $X\%$ on the complementary cumulated probability function (CCDF). We take here $X = 99.9\%$ for a 99.9% link availability. Values above T then capture 99.9% of the occurrences. Statistics are obtained on 30 000 independent occurrences generated with SAOST. Note that the results presented hereafter are mainly discussed from a reciprocal point of view: uplink performance is therefore interpreted based on “reciprocal effects” that would be observed on the ground emitting aperture.

Examples of CCDFs and associated threshold T are displayed in **Figure 3** in the case of uplink (with point-ahead anisoplanatism) for $D_{\text{OGS}} = 20$ and 50 cm and for various AO correction degrees: correction up to radial order $n_r = 1$ (tip-tilt only), 4, 8 and 12. We add also an ideal case, stated “null-phase” hereafter, where the phase is fully canceled and for which we are left only with flux fluctuations due to pupil average scintillation multiplied by the diffraction limited coupling (~ 0.81 here). Geometrical losses are not included in these graphs. The fact that the null-phase link budget is better for the bigger aperture simply reveals the gain brought by the aperture averaging of the scintillation. As explained before, T captures the mean flux loss as well as fluctuations after AO correction. Higher order AO correction leads obviously to higher threshold T , as clearly seen in **Figure 3**. One can also note that CCDF curves are sharper for the smaller aperture since the impact of PAA anisoplanatism decreases with the aperture size.

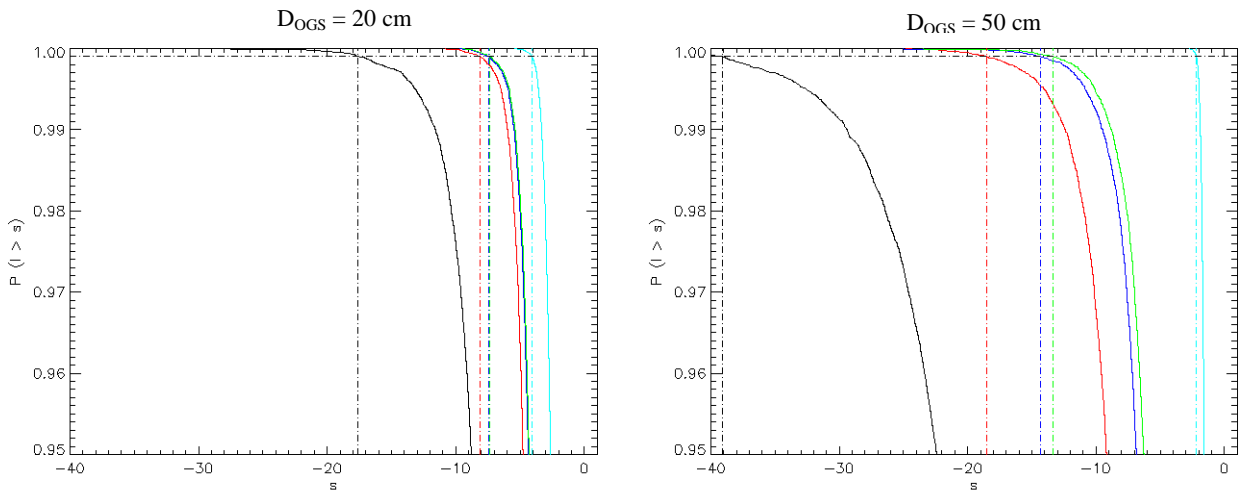


Fig. 3 Complementary Cumulated distribution function, probability of having flux values I above s , as a function of s in dB: case of uplink (with point-ahead anisoplanatism) for $D_{\text{OGS}} = 20$ cm [left] and 50 cm [right] and for various AO correction degrees: correction up to radial order 1 (tip-tilt only) [black], 4 [red], 8 [blue] and 12 [green], and ideal null-phase case (pupil average scintillation) [cyan]. Geometrical losses are not included in these graphs. The 99.9% level is indicated [dashed horizontal line] as well as associated thresholds T [dash dotted vertical lines] corresponding to the various correction degrees.

It is now possible to analyze the influence of aperture diameter on the link budget. As mentioned before, this requires quantifying an overall performance including both the threshold T and the geometrical losses. It is also interesting to compare uplink and downlink performance, respectively with and without anisoplanatism error. Results are shown in **Figure 4** for the various correction degrees. Note that when comparing downlink and uplink performance for a given aperture diameter one implicitly assumes that uplink and downlink share the same telescope aperture.

The overall link budget is improved when increasing the ground aperture (reception for downlink, emission for uplink). Regarding geometrical losses, obviously the downlink collecting area is increased and, reciprocally, the uplink beam divergence is reduced. As expected, large diameters also benefit to the aperture averaging of scintillation (null-phase

curve gets closer to geometrical loss curve for large diameters). Besides, these results prove that AO correction/pre-compensation is required for down/up-link: for diameters greater than 20 cm, gains of more than 10 dB are expected compared to plain pointing correction. Performance versus diameter is however very different for the two link directions. For downlink, increasing the reception diameter leads to huge gains provided the number of corrected modes is adapted accordingly: about 10 dB gain between $\{D_{\text{OGS}} = 20 \text{ cm}; n_r = 4\}$ and $\{D_{\text{OGS}} = 50 \text{ cm}; n_r = 8\}$. It can also be noticed that for small diameters (10 cm for instance) increasing the number of modes does not allow to reach the ideal null-phase case since the temporal error becomes the limitation.

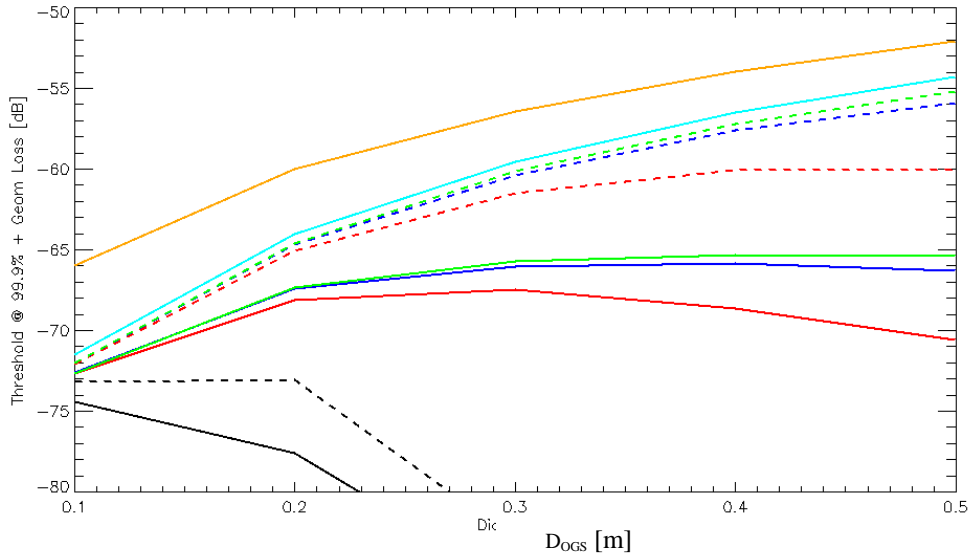


Fig. 4 Link availability threshold versus diameter for downlink [dashed lines] and for uplink [solid lines] for the various AO correction degrees: correction up to radial order 1 (tip-tilt only) [black], 4 [red], 8 [blue] and 12 [green], and ideal null-phase case, that is, pupil average scintillation only (common to up and down case) [cyan]. Geometrical losses [orange line] are always added.

However, for uplink, anisoplanatism levels performance beyond $D_{\text{OGS}} = 20 \text{ cm}$ and increasing the number of corrected modes cannot prevent it. Performance loss compared to downlink is of the order of 10 dB for a 50 cm diameter.

Note also that for a similar link budget level (for instance, about -67 dB for uplink with $\{D_{\text{OGS}} = 20 \text{ cm}; n_r = 8\}$ and $\{D_{\text{OGS}} = 50 \text{ cm}; n_r = 8\}$), CDFs may have a different structure (as observed in **Figure 3**) which may have an incidence on coding/interleaving strategies and eventually on the link capacity for a given laser power. Such an analysis of the whole telecom chain, based on ONERA time series, can be found in [23].

It is still worth mentioning that the link budget values and the diameter for which anisoplanatism becomes a limiting factor are strongly dependent of the hypothesis made on the turbulent conditions, which are known to be highly variable [24]. The link budget assessed here is also only restricted to turbulence effects and geometrical losses.

4. FEEDELIO EXPERIMENTAL DEMONSTRATION

The previous section demonstrates the need for AO pre-compensation for uplink and gives a clear insight on the expected performance and on the limitations induced by point-ahead anisoplanatism. At this stage it was essential to proceed with an experimental validation of the AO pre-compensation in conditions that are representative of the GEO-Feeder link scenario. Such an experiment is essential to demonstrate that we are able to operate an AO assisted optical link, to obtain the performance predicted and to quantify the effect of point-ahead in real turbulence conditions and despite inherent experimental difficulties (calibration issues, non-common path aberrations, hardware limitations...). Since GEO links are not easily available, ESA suggested performing this demonstration near ground on a slant line of sight.

The ground experiment (called hereafter FEEDELIO for FEEDER-LInk adaptive Optics) has been developed by ONERA under ESA contract and the experimental run took place in April 2019 on Tenerife Island (Spain). FEEDELIO (see **Figure 5**) consists in a Ground Terminal Breadboard (GTB) hosted in the ESA-OGS dome (altitude 2400 m) and a Space Terminal Breadboard (STB) located below mount Teide summit (at an altitude of 3500 m) at a distance of 13 km from GTB. STB emulates the on-axis pilot beam and off-axis detection at variable angles representing point-ahead. The GTB includes a 35 cm telescope, an AO system (8x8 Shack-Hartmann sensor, ALPAO 97 actuator DM, 1.5 kHz loop),

an SMF injection module, an uplink emission path equipped with a dedicated fast steering mirror for off-axis pointing. A particular care has been taken on calibration of non-common path aberrations, as well as pointing accuracy (better than 1 μ rad to truly benefit from the nearly diffraction limited uplink beam provided by AO pre-compensation).



Fig. 5 FEEDELIO slant path demonstration of AO pre-compensation for GEO Feeder links.

The representativeness of this 13 km line of sight for GEO-Feeder links is discussed in [17]. Details on the experiment set-up can be found in [25]. Experimental demonstration has been successful, data reduction is ongoing and preliminary results can be found in [26][27][28][29].

5. CONCLUSION

High capacity GEO-Feeder optical links are very promising but constitute a real challenge for the whole transmission chain. The modeling and mitigation of turbulence effects is a particularly critical issue that drives the other subsystem requirements. Building on SAOST, our reciprocity based performance evaluation tool, we have studied the GEO-Feeder scenario. We have derived the AO error budget and have quantified the performance in terms of link availability threshold for up and down link as a function of the number of corrected modes and of the ground telescope diameter. The article also demonstrates that the reciprocity, beyond providing powerful numerical tools, is a key principle for an in-depth understanding of the physical effects impacting adaptive optics assisted ground-space optical links.

AO correction is shown to be essential both for downlink and uplink: for diameters greater than 20 cm, link budget gains of more than 10 dB are expected compared to plain pointing correction. An emphasis is given on the quantification of the impact of point-ahead anisoplanatism on uplink. It is shown that anisoplanatism levels uplink performance beyond $D_{OGS} = 20$ cm, leading to a performance loss, compared to downlink, of the order of 10 dB for a 50 cm diameter. Exact performance of course will depend on turbulence conditions that are known to be highly variable. Note that recently published simulation results confirm the trends discussed here [30].

In parallel we have launched FEEDELIO, an experimental demonstration of AO pre-compensation performed on a slant line of sight representative of a GEO-Feeder link. FEEDELIO, developed under ESA contract, is briefly presented. A successful experimental run took place on Tenerife Island (Spain) in April 2019 and preliminary results can be found in [26][27][28][29]. This experimental effort is now pursued through the development of a dedicated ONERA ground station equipped with AO, and through further near ground experimental demonstrations in the framework the H2020 VERTIGO project [31].

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