

Turbulence-Driven Design Constraints for Long-Range LEO–HAPS Optical Links

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ABSTRACT

Optical links between Low Earth Orbit (LEO) satellites and High-Altitude Pseudo Satellite (HAPS) are emerging as a promising solution for extending high-capacity connectivity beyond terrestrial networks. Unlike conventional inter-HAPS links, these links may operate at low elevation angles, forcing the optical beam to propagate through several hundred kilometers of stratospheric atmosphere and leading to the accumulation of turbulence-induced impairments. This study investigates the impact of atmospheric turbulence on LEO–HAPS optical communications using a realistic propagation geometry combined with the Hufnagel–Valley 5/7 turbulence model. Key turbulence and communication performance metrics are evaluated as a function of elevation angle. The results indicate that turbulence effects remain limited at high elevation angles but become increasingly significant as the elevation decreases. Noticeable performance degradation is observed below approximately 30°, where accumulated wavefront distortions generate increased scintillation, resulting in reduced link reliability and higher outage probability. The analysis identifies aperture size and turbulence mitigation capabilities as critical design parameters for maintaining link performance under challenging propagation conditions. These findings provide quantitative insight into the operational limits of LEO–HAPS optical links and support the development of turbulence-aware terminal architectures and system design strategies for future high-capacity airborne and spaceborne optical communication networks.

Keywords: HAPS, Optical Communication Terminal, Scintillation, Impairments mitigation solutions

1. INTRODUCTION

The emergence of high-throughput optical inter-satellite networks in Low Earth Orbit (LEO) is reshaping the architecture of future non-terrestrial communication systems. As part of this evolution, High-Altitude Pseudo Satellites (HAPS) are increasingly considered as flexible, persistent nodes capable of extending optical connectivity to the stratosphere. While optical inter-HAPS links over ranges of tens to hundreds of kilometers have been extensively studied and industrially demonstrated, the transition toward long-distance LEO–HAPS optical links exceeding 2000 km introduces a fundamentally different regime of constraints, particularly regarding terminal design, link geometry and atmospheric propagation.

At such distances and at data rates reaching several tens to hundreds of gigabits per second, the performance of the link becomes highly sensitive to atmospheric turbulence, even in the 18–40 km region normally considered weakly turbulent [1]. The long slant-path geometry significantly increases the effective turbulence-affected propagation distance, which may approach 500 km at low elevation angles [1]. As a result, turbulence-induced scintillation, wavefront distortion and reduced coupling efficiency become non-negligible contributors to link degradation [1]. Understanding the onset and magnitude of these impairments is therefore essential for determining feasible elevation angles, terminal apertures, and optical budgets.

Concurrently, HAPS terminals available today are optimized for lightweight, low-power operation, with apertures on the order of a few centimeters and SWaP budgets compatible with stratospheric aircraft or balloon platforms. Such terminals, although suitable for short inter-HAPS links at ~1 Gbps, are not directly scalable to the long-range, high-capacity LEO–HAPS scenario. Larger apertures, enhanced pointing stability and potentially adaptive optics would be required to mitigate turbulence effects and sustain high-SNR operation, driving significant mass and power increases. This raises new design challenges and trade-offs that have not yet been widely addressed in the literature.

This work presents, to our knowledge, one of the first quantitative assessments of the impact of turbulence on long-distance LEO–HAPS optical links. Using a realistic geometrical model combined with the HV 5/7 turbulence profile [2,9] and established laser propagation theory [1], we analyze the resulting scintillation, wavefront errors, BER performance and outage probability across a range of elevation angles and SNRs. These results form the basis for identifying the critical thresholds, design drivers and architectural constraints that must guide the development of next-generation high-capacity optical terminals for HAPS platforms.

It should be noted that the analysis presented in this paper does not include the effects of Adaptive Optics (AO) correction nor Forward Error Correction (FEC) coding. The objective is to quantify the intrinsic impact of atmospheric turbulence on LEO–HAPS optical links using an unmitigated propagation model. Consequently, the reported BER and outage probability results should be interpreted as conservative estimates of system performance

2. METHODOLOGY

Vertical turbulence model

The communication performance of the link is evaluated using the Hufnagel–Valley 5/7 (HV 5/7) turbulence model [2,9], as recommended by ITU-R P.1621-1 [2], the refractive-index structure parameter profile is given by

$$C_n^2(h) = 0.00594 \left(\frac{v}{27} \right)^2 (10^{-5}h)^{10} e^{-\frac{h}{1000}} + 2.7 \times 10^{-16} e^{-\frac{h}{1500}} + C_0 e^{-\frac{h}{100}} \quad (1)$$

Wavefront error model

The Fried coherence diameter is computed analytically based on the link topology following the methodology described in [1] and based on Fried's coherence theory [3].

$$r_0(\gamma) = \left[0.423 k^2 \sec(\gamma) \int_0^\infty C_n^2(h) dh \right]^{-\frac{3}{5}} \quad (1)$$

The corresponding wavefront error induced by atmospheric turbulence is derived from Kolmogorov turbulence statistics following Noll's formulation of phase aberrations [4].

$$\sigma_\phi^2 \approx 1.02 \left(\frac{D}{r_0} \right)^{\frac{5}{3}} \quad (3)$$

For the downlink, turbulence-induced degradation is quantified in terms of (i) coherence loss and (ii) intensity scintillation.

The coherence loss is quantified through the on-axis Strehl ratio using the Maréchal approximation [5].

$$S \approx \exp(\sigma_{\phi, total}^2) \quad (4)$$

We note that an additional 20% loss may be introduced to account for the mode mismatch between the diffracted point spread function (PSF) and the single-mode fiber fundamental mode. Nevertheless, this additional loss was not considered in the present analysis, as the objective of this paper is to provide a qualitative rather than a highly quantitative assessment. Furthermore, this effect can be addressed through design parameter optimization.

Scintillation model

Atmospheric turbulence induces random fluctuations in the received optical irradiance, commonly referred to as scintillation. The strength of these fluctuations is usually quantified through the Rytov variance, a fundamental parameter for characterizing optical wave propagation in random media [6]. The formulation follows the classical theory of wave propagation in turbulent media and its application to optical links reported in [1,6].

For a spherical wave, the Rytov variance is given by

$$\sigma_R^2 = 2.25 k^{\frac{7}{6}} \sec^{\frac{11}{6}}(\zeta) \int_0^L C_n^2(z) z^{\frac{5}{6}} dz \quad (4)$$

Where:

$k=2\pi/\lambda$ is the optical wavenumber,

λ is the optical wavelength,

ζ is the zenith angle,

L is the propagation distance through the turbulent atmosphere.

The spherical-wave formulation is adopted because the optical field originates from a localized transmitter and propagates through the atmosphere with a finite wavefront curvature. In contrast, the plane-wave approximation assumes a source located at an infinite distance, resulting in an almost flat wavefront at the entrance of the turbulent medium. Therefore, the spherical-wave model is generally considered more appropriate for uplink optical links and, more broadly, for propagating beams emitted by a finite-aperture transmitter.

Once the spherical-wave Rytov variance has been evaluated, the parameters of the Gamma-Gamma distribution are obtained using the model proposed by Al-Habash et al. [7]. This approach separates the irradiance fluctuations into two statistically independent components:

- large-scale fluctuations, associated with refraction effects and turbulent eddies larger than the first Fresnel zone;
- small-scale fluctuations, associated with diffraction effects produced by smaller turbulent inhomogeneities.

The corresponding log-irradiance variances are expressed as

$$\sigma_x^2 = \frac{0.49 g \sigma_R^2}{\left(1 + 1.11 \sigma_R^{\frac{12}{5}}\right)^{7/6}} \quad (5)$$

and

$$\sigma_y^2 = \frac{0.51 g \sigma_R^2}{\left(1 + 0.69 \sigma_R^{\frac{12}{5}}\right)^{5/6}} \quad (6)$$

Using these quantities, the Gamma-Gamma shape parameters are computed as

$$\alpha = [\exp(\sigma_x^2) - 1]^{-1} \quad (7)$$

and

$$\beta = [\exp(\sigma_y^2) - 1]^{-1} \quad (8)$$

The parameter α characterizes the large-scale turbulence effects, while β describes the small-scale turbulence effects. Together, they fully define the Gamma-Gamma irradiance model and enable the representation of weak, moderate, and strong turbulence regimes within a unified statistical framework.

The resulting scintillation index can be written as

$$\sigma_I^2 = \frac{1}{\alpha} + \frac{1}{\beta} + \frac{1}{\alpha\beta} \quad (9)$$

After determining the Gamma-Gamma parameters α and β from the spherical-wave Rytov variance, the instantaneous received irradiance is generated using a Monte Carlo approach based on the multiplicative Gamma-Gamma model. In this model, the normalized irradiance III is represented as the product of two statistically independent Gamma-distributed random variables corresponding to large-scale and small-scale turbulence effects.

The instantaneous irradiance is therefore expressed as

$$I = XY, \quad (10)$$

where

$$X \sim \Gamma(\alpha, \alpha) \quad (11)$$

and

$$Y \sim \Gamma(\beta, \beta) \quad (12)$$

The Gamma distributions are parameterized such that

$$\mathbb{E}[X] = 1, \quad (13)$$

$$\mathbb{E}[Y] = 1, \quad (14)$$

Which ensures

$$\mathbb{E}[I] = 1. \quad (15)$$

Consequently, the generated irradiance fluctuations represent normalized turbulence-induced fading around the average received optical power.

For each elevation angle, the parameters α and β are first computed from the corresponding Rytov variance. A Monte Carlo simulation is then performed by generating N independent realizations of the two Gamma random variables. In the present implementation, the number of realizations is

$$N = 10^5 \quad (16)$$

which provides a statistically stable estimation of the irradiance distribution and its associated performance metrics.

The generated samples are obtained according to

$$X_i \sim \Gamma\left(\alpha, \frac{1}{\alpha}\right) \quad (17)$$

$$Y_i \sim \Gamma\left(\beta, \frac{1}{\beta}\right) \quad (19)$$

and

$$I_i = X_i Y_i, \quad i = 1, \dots, N. \quad (20)$$

The resulting set

$$\{I_1, I_2, \dots, I_N\}$$

constitutes a Monte Carlo realization of the Gamma-Gamma irradiance process for the considered turbulence conditions.

BER Estimation under Gamma-Gamma Turbulence

Once the Gamma-Gamma irradiance samples I have been generated, turbulence is incorporated into the communication model by assuming that the instantaneous electrical signal-to-noise ratio is proportional to the received optical irradiance. The instantaneous SNR is therefore expressed as

$$\gamma = \bar{\gamma}I, \quad (21)$$

where $\bar{\gamma}$ denotes the average SNR in the absence of turbulence and I is the normalized Gamma-Gamma irradiance random variable.

The average BER under turbulence is then obtained by averaging the conditional AWGN BER over the Gamma-Gamma irradiance statistics,

$$\bar{P}_b = \mathbb{E}_I[P_b(\gamma = \bar{\gamma}I)] \quad (22)$$

BER for DP-QPSK

Assuming coherent detection in an additive white Gaussian noise channel, the conditional BER of DP-QPSK is

$$P_b^{DP-QPSK}(\gamma = \bar{\gamma}I) = \frac{1}{2} \operatorname{erfc}(\sqrt{\bar{\gamma}I}). \quad (23)$$

The average BER is therefore

$$\bar{P}_b^{DP-QPSK} = \mathbb{E}_I \left[\frac{1}{2} \operatorname{erfc}(\sqrt{\bar{\gamma}I}) \right] \quad (24)$$

which is estimated numerically through Monte Carlo averaging.

BER for OOK

For OOK intensity modulation with threshold detection in AWGN, the conditional BER is expressed as

$$P_b^{OOK}(\gamma = \bar{\gamma}I) = \frac{1}{2} \operatorname{erfc} \left(\frac{\sqrt{\bar{\gamma}I}}{2} \right). \quad (25)$$

The turbulence-averaged BER is then

$$\bar{P}_b^{OOK} = \mathbb{E}_I \left[\frac{1}{2} \operatorname{erfc} \left(\frac{\sqrt{\bar{\gamma}I}}{2} \right) \right] \quad (26)$$

which is likewise evaluated numerically from the Monte Carlo realizations of the Gamma-Gamma irradiance.

The BER formulations used in this paper follow the standard digital communication expressions reported in [8].

Outage Probability

The outage probability is defined as the probability that the instantaneous received irradiance falls below a predefined threshold I_{th} . In a Gamma-Gamma fading channel, the outage probability can be expressed as

$$P_{out} = \Pr(I < I_{th}), \quad (27)$$

where I_{th} denotes the minimum normalized irradiance required to maintain the desired communication quality.

Since the irradiance statistics are generated through Monte Carlo simulations, the outage probability is estimated from the set of N Gamma-Gamma realizations $\{I_i\}_{i=1}^N$ as

$$P_{out} \approx \frac{1}{N} \sum_{i=1}^N \mathbf{1}(I_i < I_{th}), \quad (28)$$

Where $\mathbf{1}(\cdot)$ denotes the indicator function, equal to one when the outage condition is satisfied and zero otherwise.

Several outage thresholds may be considered according to the required system margin. In this work, the thresholds are expressed in linear scale and correspond to normalized irradiance levels derived from predefined attenuation values.

Particularities of the Downlink Channel

In the downlink configuration, atmospheric turbulence is modeled through Gamma-Gamma irradiance fluctuations characterized by the parameters α and β derived from the spherical Rytov variance. The instantaneous received irradiance is represented by the Gamma-Gamma random variable I .

In addition to scintillation, the downlink model accounts for wavefront degradation through the Strehl ratio S , which represents the loss of optical power caused by turbulence-induced phase distortions. Consequently, the effective received irradiance is expressed as

$$I_{DL} = IS \quad (29)$$

where I denotes the Gamma-Gamma scintillation component and S is the turbulence-induced Strehl factor.

The instantaneous SNR used for BER evaluation then becomes

$$\gamma_{DL} = \bar{\gamma} I_{DL} = \bar{\gamma} IS. \quad (30)$$

Thus, the downlink channel combines irradiance fluctuations and turbulence-induced wavefront quality degradation.

Particularities of the Uplink Channel

In the uplink configuration, turbulence affects not only the irradiance fluctuations but also the transmitted beam geometry. Besides the Gamma-Gamma scintillation process, the model incorporates beam spreading and beam wander effects generated during propagation through the turbulent atmosphere.

The turbulence-induced spreading loss is represented by a long-term attenuation factor L_{turb} . The effective received irradiance is therefore written as

$$I_{UL} = IL_{turb}, \quad (31)$$

where I is the Gamma-Gamma irradiance and $L_{turb} \leq 1$ denotes the long-term turbulence transmission factor associated with beam spread and beam wander.

The instantaneous SNR becomes

$$\gamma_{UL} = \bar{\gamma} I_{UL} = \bar{\gamma} IL_{turb}. \quad (32)$$

Beam Wander

Beam wander arises from large-scale turbulent eddies that randomly tilt the optical wavefront and cause fluctuations in the beam centroid position at the receiver plane. The variance of the beam-centroid displacement following the turbulence propagation model reported in [1], can be expressed as

$$\sigma_{BW}^2 = 2.42k^2W_0^{-\frac{1}{3}} \int_0^L C_n^2(z)z^3 \left(1 - \frac{z}{L}\right)^2 dz, \quad (33)$$

where

- W_0 is the transmitter beam radius,
- $k = \frac{2\pi}{\lambda}$ is the optical wavenumber,
- L is the propagation distance,
- $C_n^2(z)$ is the refractive-index structure parameter.

The quantity σ_{BW} characterizes the random displacement of the beam centroid around its nominal position.

Beam Spreading

Small-scale turbulence additionally causes random phase distortions across the optical wavefront, leading to an increase of the long-term beam radius. The resulting turbulence-broadened beam radius can be written as

$$W_{LT} = \sqrt{W_{geo}^2 + \sigma_{BW}^2}, \quad (34)$$

where

- W_{geo} is the diffraction-limited beam radius,
- W_{LT} is the long-term beam radius including turbulent effects.

The long-term beam radius therefore incorporates both diffraction and beam-wander contributions.

The long-term beam broadening induced by turbulence is evaluated according to the propagation theory described in [1].

Collected Power Reduction

Assuming a circular receiver aperture of radius $a = \frac{D_{rx}}{2}$, the fraction of collected optical power for a Gaussian beam is approximated by

$$F = 1 - \exp\left(-\frac{2a^2}{W^2}\right). \quad (35)$$

The corresponding power-coupling factor is evaluated for both the diffraction-limited beam radius W_{geo} and the turbulence-broadened radius W_{LT} . The additional turbulence-induced loss is then expressed as

$$L_{turb} = \frac{F_{LT}}{F_{geo}}. \quad (36)$$

The effective uplink irradiance becomes

$$I_{UL} = IL_{turb}, \quad (37)$$

where I denotes the Gamma-Gamma irradiance fluctuation and L_{turb} represents the long-term loss associated with beam wander and beam spreading. This term is subsequently included in the BER and outage calculations.

3. LEO–HAPS LINK CONDITIONS

Before presenting the simulation results, a reference LEO–HAPS scenario is defined. The objective is not to represent a specific operational system but rather to establish a consistent set of link and atmospheric parameters allowing the quantification of turbulence-induced impairments as a function of elevation angle. Conservative values of the HV 5/7 model parameters, including a ground-level refractive-index structure parameter $C_n^2(0) = 10^{-13} \text{ m}^{-2/3}$ and a wind speed of 100 m/s, are adopted to investigate the upper bound of turbulence effects. The complete set of assumptions used throughout the analysis is reported in Table 1.

Table 1. Reference LEO–HAPS link parameters and environmental assumptions used throughout the turbulence analysis.

HAPS Altitude:	18 km
LEO Altitude	1220 km
Optical Path Distance:	Computed considering Earth curvature
Ground-Level Structure Parameter	$C_n^2(0) = 10^{-13}$ at $h = 0$ (worst case)
Wind Speed	$v = 100$ m/s (worst case)
Turbulence Layer:	• Starts at 18 km • Ends at 40 km • Almost negligible between 30 km and 40 km
Transmitter Aperture:	• $D_{tx} = 8$ cm
Receiver Aperture	• $D_{rx} = 8$ cm
Assumption / Conditions	• No additional pointing errors • Ideal optics without turbulence penalties in baseline scenario

Before analyzing turbulence metrics, it is useful to quantify the atmospheric propagation distance crossed by the optical beam within the turbulent layer. As the elevation angle decreases, the optical path through the atmosphere increases significantly due to Earth curvature and slant-path propagation geometry. This increase directly contributes to the accumulation of turbulence-induced impairments.

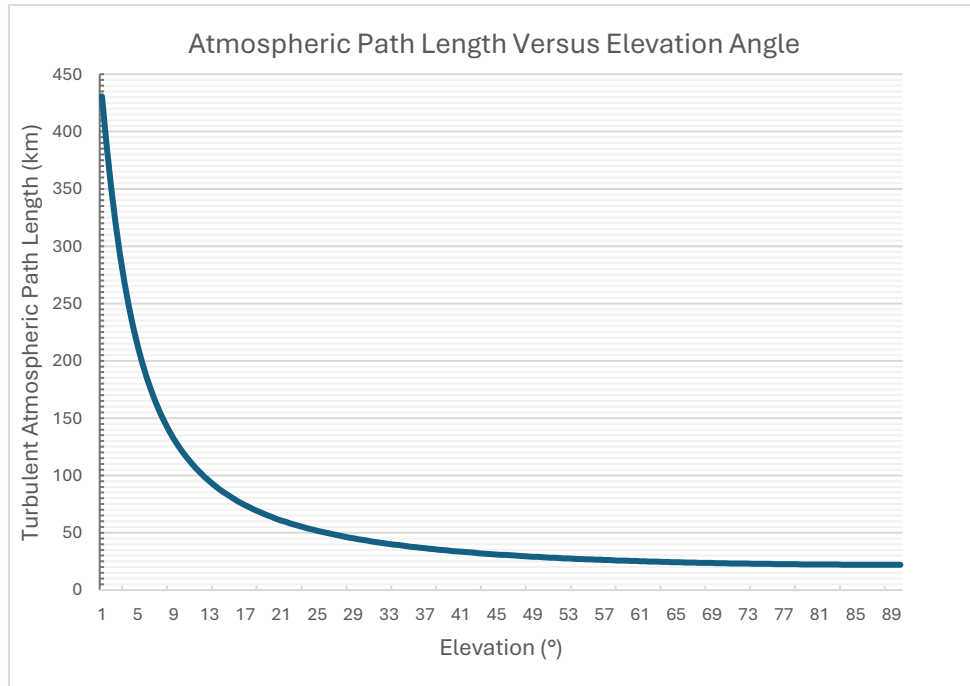


Figure 1. Length of the turbulent propagation path between 18 km and 40 km altitude as a function of elevation angle for the considered LEO–HAPS geometry. The distance is computed using a spherical-Earth model and represents only the atmospheric portion of the optical path. The atmospheric path length increases rapidly at low elevation angles, leading to stronger accumulation of turbulence-induced effects.

Using the link and atmospheric parameters listed in Table 1, Figure 2 presents the evolution of the Fried parameter r_0 with elevation angle.

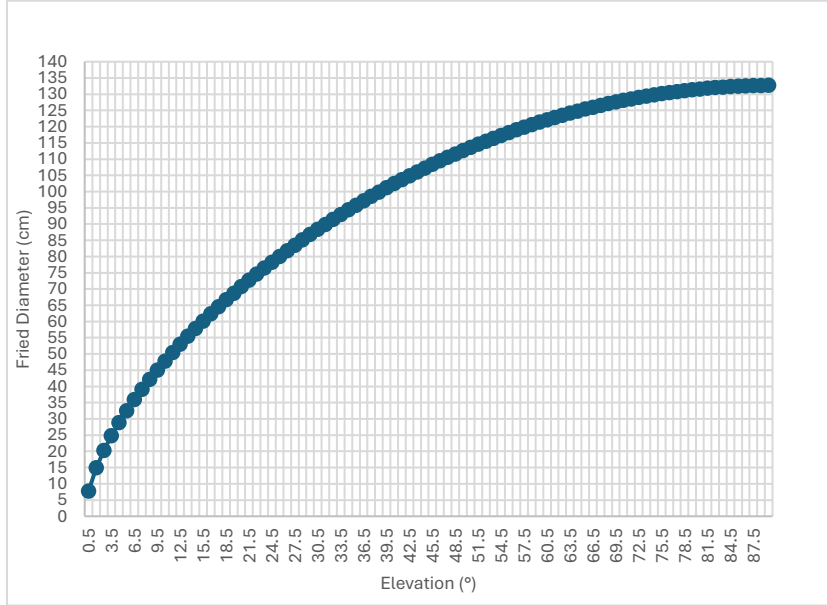


Figure 2. Fried parameter r_0 as a function of elevation angle for the reference LEO–HAPS scenario and atmospheric conditions defined in Table 1.

As expected, r_0 increases with elevation, reflecting the reduction of the turbulence-integrated path length at higher line-of-sight angles. The minimum value of r_0 is about 7 cm, obtained at the lowest elevation angle. Since this value remains close to the receiver aperture diameter ($D=8$ cm), the ratio $\frac{D}{r_0}$ remains close to unity, indicating that turbulence-induced wavefront aberrations are relatively weak. Therefore, only limited coherence loss and fiber-coupling degradation are expected, even under these conservative atmospheric conditions.

This behavior is consistent with the integrated turbulence strength predicted by the HV profile and conventional atmospheric propagation theory [1,2,9].

While the Fried parameter provides insight into the spatial coherence degradation induced by atmospheric turbulence, the impact on received power fluctuations is more conveniently described through the intensity variance. Using the Gamma-Gamma model of (Eq. 9) and the same LEO–HAPS reference scenario considered previously, Figure 3 shows the corresponding scintillation index as a function of elevation angle. The results allow the assessment of turbulence-induced fading effects under the conservative atmospheric conditions defined in Table 1.

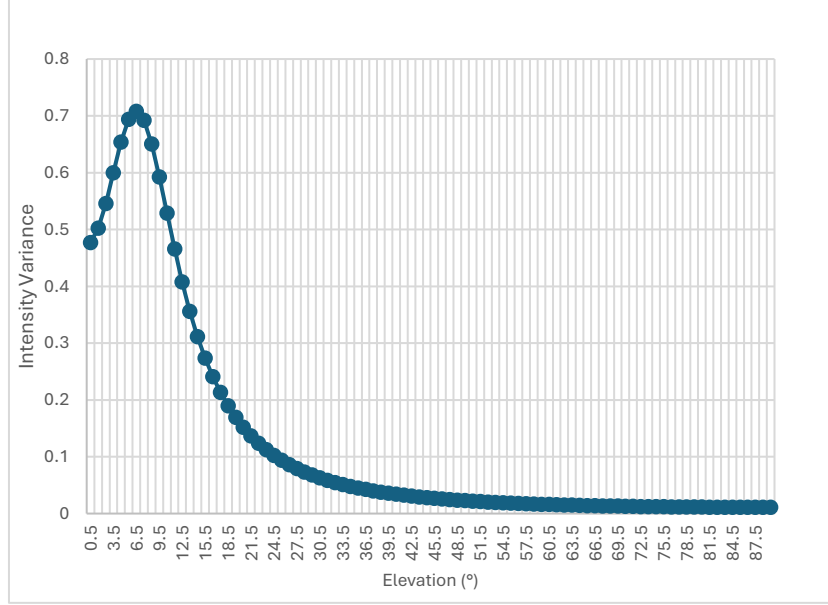


Figure 3. Evolution of the scintillation index with elevation angle for the reference LEO–HAPS link. Results are obtained using the Gamma-Gamma turbulence model of (Eq. 9) and the atmospheric parameters listed in Table 1.

As shown in Figure 3, the intensity variance remains relatively limited at high elevation angles but starts to increase progressively for elevation angles below approximately 30°. This trend is consistent with the longer atmospheric path length and the stronger turbulence effects encountered at low elevations.

In contrast to the wavefront distortions discussed previously, scintillation effects cannot be considered negligible under the assumed atmospheric conditions. While the minimum Fried parameter remains comparable to the receiver aperture diameter ($r_0 \approx 7\text{cm}$ versus $D=8\text{cm}$), resulting in only moderate coherence degradation, the predicted intensity fluctuations are more significant and therefore deserve a more quantitative assessment.

It should also be emphasized that the results presented here assume an aperture diameter of 8cm at the HAPS terminal. In practice, HAPS optical terminals are often subject to stringent size, weight, and power (SWaP) constraints, potentially leading to even smaller aperture diameters. In such cases, aperture averaging becomes less effective, resulting in stronger received-power fluctuations and increased sensitivity to scintillation.

The reduction of scintillation achieved by finite receiver apertures is commonly attributed to aperture averaging effects predicted by propagation theory [1].

Therefore, although turbulence-induced wavefront aberrations appear to have a limited impact for the considered scenario, scintillation may represent a more critical impairment mechanism. Its impact on link performance, and in particular on link availability and received-power statistics, is investigated in the next section.

This trend is consistent with the increase of Rytov variance for long atmospheric slant paths predicted by turbulence theory [1,6].

4. MAIN RESULTS

Based on the methodology described in the previous section 2 and the reference LEO–HAPS scenario summarized in Table 1, the impact of atmospheric turbulence on optical communication performance is evaluated for both downlink and uplink transmissions. The analysis is performed as a function of the elevation angle, which directly determines the propagation distance through the turbulent atmospheric layer and therefore the severity of turbulence-induced impairments.

For each propagation direction, the communication performance is assessed using two complementary metrics: the bit error rate (BER) and the outage probability. The BER analysis is carried out for two representative modulation and detection schemes, namely On-Off Keying (OOK) with direct detection and coherent DP-QPSK reception. These results provide insight into the sensitivity of different receiver architectures to turbulence-induced fading. The outage probability is then evaluated to quantify the likelihood of deep irradiance fluctuations leading to a temporary loss of communication performance.

The results are organized into two main parts. The first part focuses on the downlink channel, where atmospheric turbulence primarily affects the received wavefront quality and the corresponding optical coupling efficiency. The second part addresses the uplink channel, where turbulence additionally impacts the transmitted beam through beam wander and beam spreading mechanisms. For both transmission directions, BER performance is first presented, followed by the corresponding outage probability analysis.

Downlink

The downlink results investigate the propagation of the optical signal from the LEO satellite toward the HAPS terminal. In this configuration, turbulence-induced scintillation and wavefront distortions progressively increase as the elevation angle decreases and the atmospheric path length becomes larger. The analysis first examines the BER degradation for OOK and coherent DP-QPSK systems before evaluating the associated outage probability.

DL BER

Figure 4 presents the BER performance obtained for OOK detection as a function of elevation angle and average SNR. Figure 5 then reports the corresponding results for coherent DP-QPSK reception. The comparison between both modulation formats highlights the benefit of coherent detection in the presence of turbulence-induced intensity fluctuations and wavefront degradation.

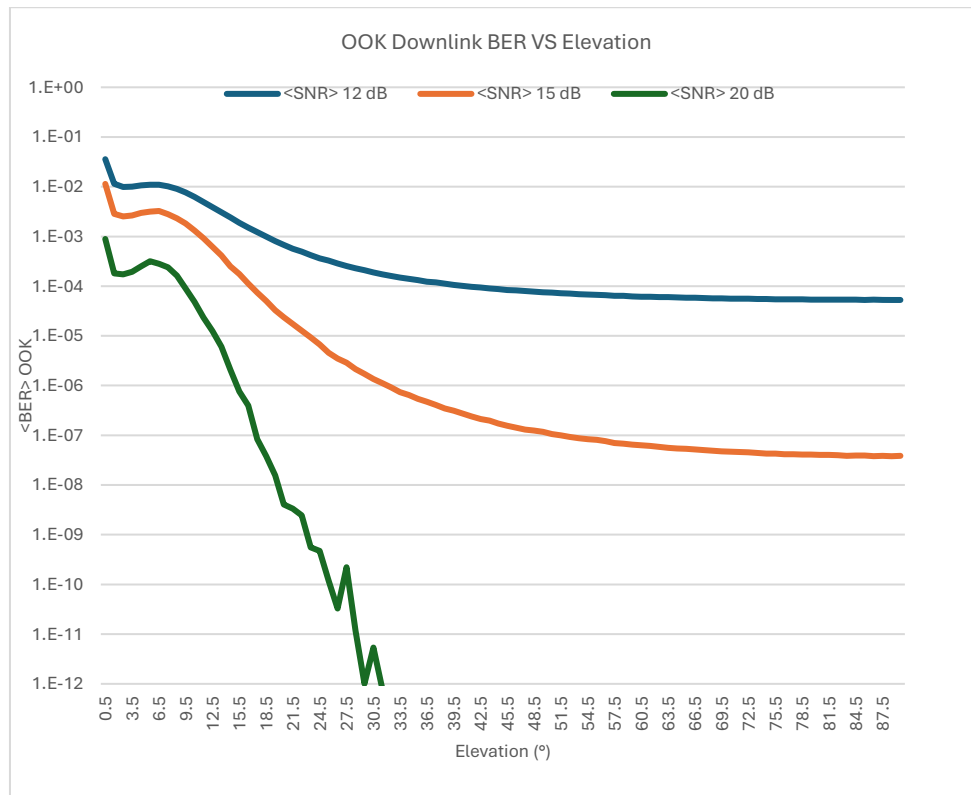


Figure 4. Average BER performance of OOK modulation under downlink Gamma-Gamma turbulence as a function of elevation angle for different average SNR values.

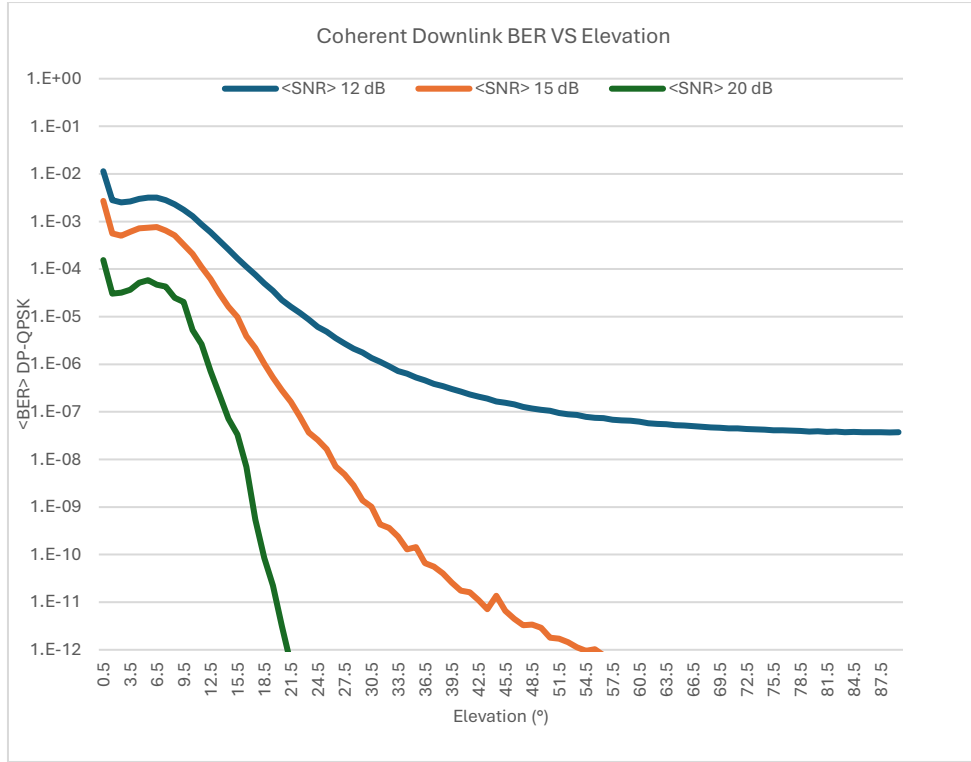


Figure 5. Average BER performance of coherent DP-QPSK under downlink Gamma-Gamma turbulence as a function of elevation angle for different average SNR values

The results highlight that achieving an acceptable BER primarily depends on maintaining a sufficiently high average SNR and minimizing the impact of atmospheric turbulence, which is naturally reduced at higher elevation angles. Among the modulation formats investigated, coherent DP-QPSK reception demonstrates greater robustness to channel impairments than OOK, enabling the target BER to be achieved with a lower SNR margin. These findings suggest that combining coherent detection with an adequate link margin is an effective strategy for ensuring reliable space optical communications under turbulent downlink conditions.

DL Outage Probability

To complement the BER analysis, Figure 6 shows the outage probability as a function of elevation angle. This metric quantifies the probability that the instantaneous received irradiance falls below the specified threshold due to turbulence-induced fading. The results provide an additional assessment of link availability under degraded atmospheric conditions.

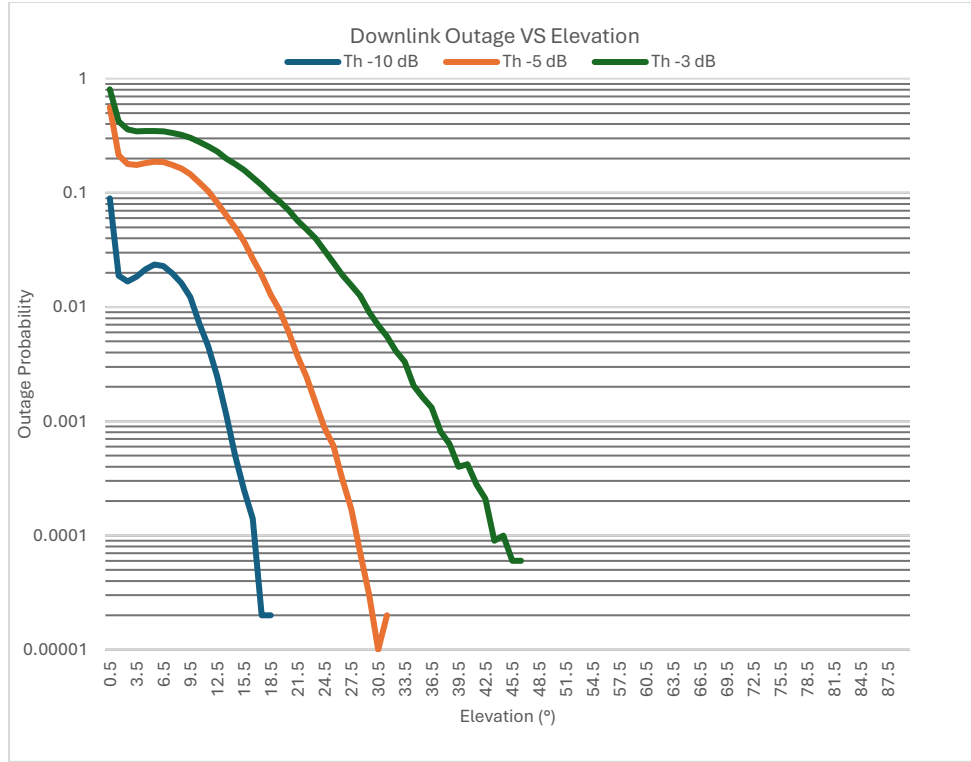


Figure 6. Downlink outage probability versus elevation angle for different irradiance outage thresholds under Gamma-Gamma turbulence conditions.

The outage probability results show a strong dependence on the elevation angle and the selected irradiance threshold. Lower elevation angles lead to increased turbulence-induced fading, resulting in a higher probability of link outage and reduced link availability. Conversely, higher elevation angles significantly improve link reliability by reducing atmospheric impairments. These findings indicate that maintaining sufficient received power margins and operating under favorable elevation conditions are key to minimizing outage events. Overall, the outage analysis confirms the importance of robust link design and adequate system margins to ensure high availability in space optical communication links affected by atmospheric turbulence.

Uplink

The uplink results consider transmission from the HAPS optical terminal toward the LEO satellite. Unlike the downlink case, turbulence affects not only irradiance fluctuations but also the propagation geometry of the transmitted beam through beam wander and beam spreading effects. The performance evaluation follows the same structure as for the downlink, beginning with BER analysis and subsequently examining outage probability.

UL BER

Figure 7 presents the OOK BER performance for the uplink scenario, while Figure 8 shows the corresponding BER obtained with coherent DP-QPSK reception. These results quantify the combined impact of scintillation, beam spreading, and beam wander on communication performance as the atmospheric propagation path increases.

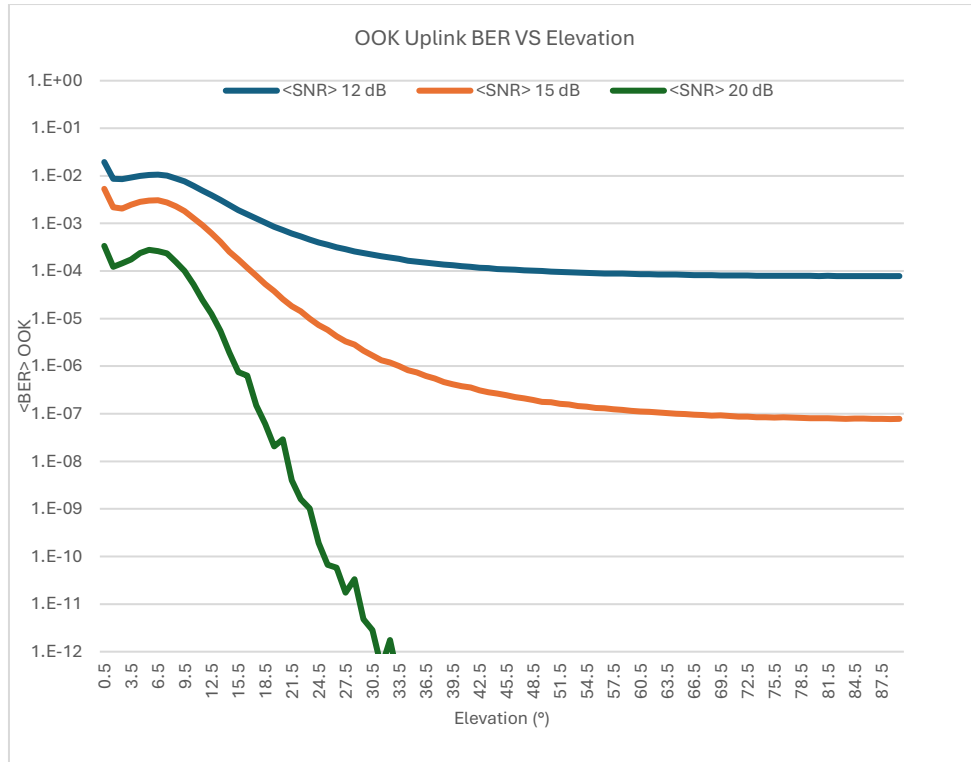


Figure 7. Average BER performance of OOK modulation under uplink turbulence including scintillation, beam wander, and beam spreading effects as a function of elevation angle for different average SNR values.

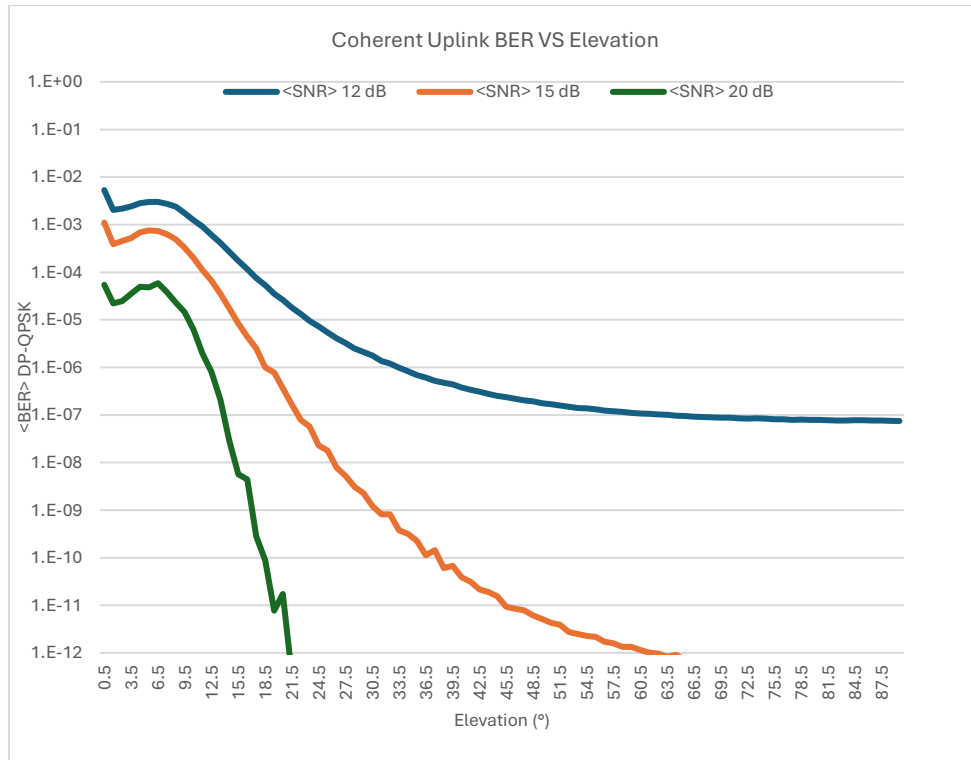


Figure 8. Average BER performance of coherent DP-QPSK under uplink turbulence including scintillation, beam wander, and beam spreading effects as a function of elevation angle for different average SNR values.

The uplink results confirm the benefit of coherent DP-QPSK reception over OOK across the considered operating conditions. Although atmospheric effects such as scintillation, beam wander, and beam spreading still impact performance at low elevation angles, the BER degradation remains less pronounced than in the downlink case. This behavior is attributed to the reduced influence of turbulence-induced wavefront distortions at the transmitter side. Overall, the uplink configuration demonstrates improved resilience to atmospheric impairments, enabling reliable communication performance over a wider range of elevation angles.

UL Outage Probability

Figure 9 presents the uplink outage probability as a function of elevation angle. The obtained results characterize the probability of severe turbulence-induced fading events and provide insight into the operational limits of the considered LEO–HAPS optical link under challenging propagation conditions.

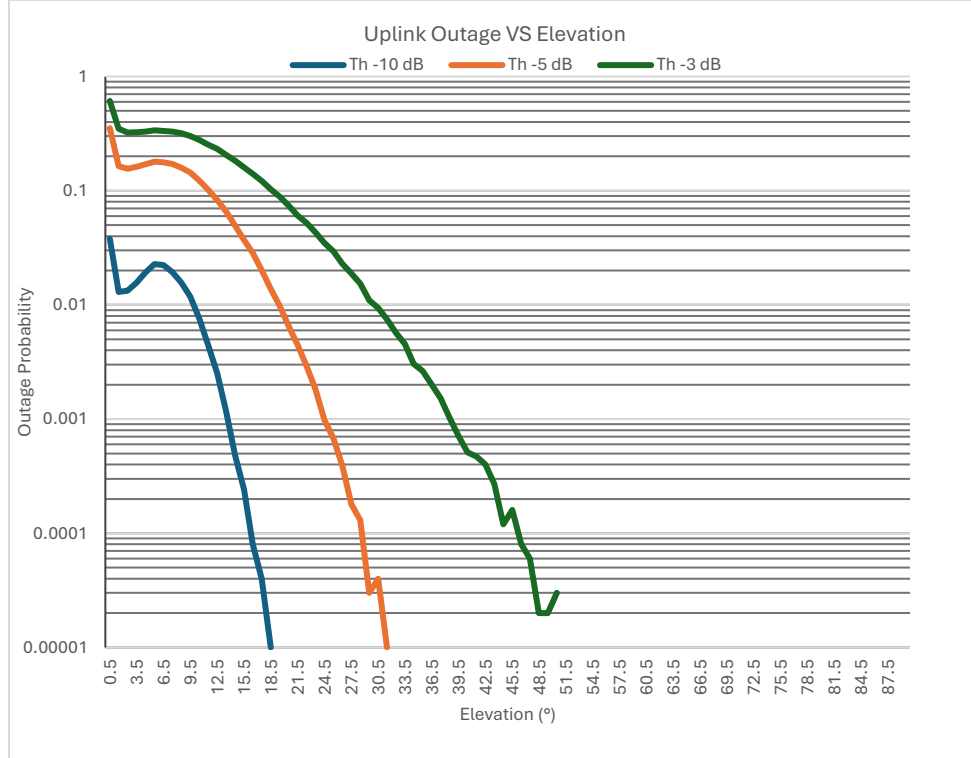


Figure 9. Uplink outage probability versus elevation angle for different irradiance outage thresholds under combined turbulence-induced fading and beam propagation impairments.

The uplink outage probability remains strongly influenced by the elevation angle and the selected irradiance threshold. Despite the additional impairments associated with beam propagation, the outage levels are slightly lower than those observed in the downlink scenario, particularly at low elevation angles. This result can be explained by the reduced impact of turbulence-induced wavefront distortions on the received signal in the uplink case. Consequently, the considered uplink configuration offers improved link availability and greater tolerance to fading events over the range of operating conditions investigated.

5. CONCLUSION

This work evaluated the impact of atmospheric turbulence on long-range LEO–HAPS optical links for both uplink and downlink configurations. The results show that turbulence-induced impairments remain limited at high elevation angles

but increase rapidly below approximately 30° , where the longer atmospheric slant path generates significant scintillation and performance degradation.

For the considered 8-cm apertures, aperture averaging remains effective at moderate and high elevation angles. However, below approximately 30° , the increasing turbulence accumulation progressively reduces its benefit and scintillation becomes a more significant contributor to link degradation. In the downlink, turbulence-induced wavefront distortions remain moderate but the optical coupling efficiency of single-mode-fiber receivers becomes increasingly sensitive to tip-tilt errors at low elevation angles. Below approximately 30° , adaptive tip-tilt correction is therefore expected to become beneficial to maintain stable receiver performance. In the uplink, the received power becomes increasingly affected by beam wander and beam spreading as the elevation decreases. While these effects remain manageable above approximately 30° , lower elevation operations are likely to require adaptive beam pre-compensation techniques to maintain link availability.

Overall, the results indicate that long-range LEO–HAPS optical links are feasible over a large fraction of a satellite pass, but that turbulence becomes a key design driver below approximately 30° elevation. These results suggest that adaptive optics techniques may become necessary below approximately 30° elevation to maintain optical coupling efficiency and mitigate turbulence-induced wavefront distortions [10]. In particular, adaptive optics solutions implemented on the HAPS terminal could be investigated in future work to assess their ability to reduce turbulence-induced wavefront errors and improve link performance. The potential benefit of adaptive optics implemented on both terminals could also be evaluated.

Future work will focus on optimizing terminal SWaP trade-offs, particularly regarding aperture size, transmit power, and phase-noise performance. The impact of Forward Error Correction (FEC) schemes on link availability and effective communication performance will also be investigated, especially under low-elevation turbulence conditions. Additional investigations will incorporate representative supplier terminal characteristics and higher-fidelity wave-optics simulations based on phase-screen propagation methods.

ACKNOWLEDGEMENTS

We thank the Eutelsat optical communications and non-terrestrial networks teams for their valuable discussions and technical insights. Their contributions helped shape the system assumptions and performance analyses presented in this work.

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