International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

ICSO 2022
International Conference on Space Optics
3 – 7 October 2022 | Dubrovnik | Croatia

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International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 127775U · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2691100

Effects of Pointing Errors on Intensity Losses in the Optical LEO Uplink

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ABSTRACT

Different pointing errors from different sources cause an angular deviation in the uplink beam transmitted from an optical ground station (OGS) to a satellite. In optical link-budget calculations, the beam intensity loss due to pointing errors, "pointing loss", is usually given a constant value regardless of the satellite elevation. In this paper, elevation-dependent intensity losses are calculated, considering a transmitted uplink beam with a Gaussian profile. The elevation of the satellite and the divergence of the uplink beam are considered to assess the impact of the following sources of tracking and pointing errors: OGS static pointing misalignment, uncorrected or fixed-corrected point-ahead angle (PAA), satellite orbital data uncertainties (specifically the along-track error), and mechanical jitter at the OGS. Each source of error is first evaluated separately and then the combination of their effects on the intensity loss in the LEO uplink is determined. It is demonstrated that the elevation-dependent pointing errors analyzed in this work have a greater impact on the intensity loss for satellites at lower altitudes and higher elevations. Therefore, not considering that the value of the "pointing loss" varies with elevation -especially for LEO satellites-, would result in lower link performance. Values of intensity loss are provided for LEO satellites at different altitudes and elevations, and uplink beam divergences. The results provided can be used for link-budget calculations in the optical LEO uplink in the presence of elevation-dependent pointing errors, and for system improvements in the design of future ground and space optical terminals.

Keywords: Free-space optical communications, pointing loss, link budget, elevation-dependent, point-ahead angle, orbit uncertainties, mechanical jitter, divergence angle

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1. INTRODUCTION

Optical point-to-point links for space applications involve the data transmission by modulated laser beams, through agile optical terminal setups that are tracking each other.[1] Data exchange with free-space optical (FSO) communication can be performed with terminals having lower size, weight, and power (SWAP) compared to their radio frequency counterparts and has the potential of reaching much higher data rates. Further advantages include the physical-layer security stemming from the minimum signal spread[2] and the fact that, in contrast to radio frequency links, FSO communication does not require regulatory approval due to the signal's directivity and the huge available frequency spectrum. Technology for satellite FSO communication is becoming mature and is currently undergoing the first round of standardization in the Consultative Committee of Space Data Systems (CCSDS).[3,4] The high directivity of the laser beam entails, however, the technological challenge of maintaining ultra-stable pointing from transmitter to receiver during the entire communication, which proves much more challenging for the link to a low-Earth orbiting (LEO) satellite due to its fast angular movement seen from ground, the high orbit uncertainty, among others.[5] Pointing errors result in signal power loss compared to the ideal case of perfect alignment of the laser beam and their analysis is the scope of the current investigation.

Illustrations of FSO data links with a LEO satellite are presented in Figure 1, where closed-loop tracking of the signal is performed in order to maintain a stable communication. On the left a ground-to-satellite (G2S) data link scenario is shown and, on the right, a satellite-to-ground (S2G) data link scenario, also known as "uplink" and "downlink" respectively. In the data uplink case, the pointing, acquisition and tracking (PAT) procedure is performed as follows. The link acquisition begins when a beacon is sent from the satellite to the Optical Ground Station (OGS), typically when the satellite is still at low elevation above the horizon (①). Subsequently, the OGS tracks the beacon and points to the satellite to start the communication (②). The communication signal is transmitted from the OGS until the satellite has a too low elevation (③), before disappearing over the horizon. An analogous PAT procedure is performed in the data downlink case, with a reversal of the roles of the satellite and of the OGS; the use of bi-directional data links and beaconing is also a possibility, as well as beaconless communications in which ephemeris data is used to determine the OGS pointing and the satellite attitude (open-loop tracking). In the following, the effect of pointing errors will be considered only for the case of G2S laser beams; it is important to note that, in this paper, G2S beam refers indifferently to either the data signal (in a data uplink scenario) or to a beacon signal (in a data downlink scenario).

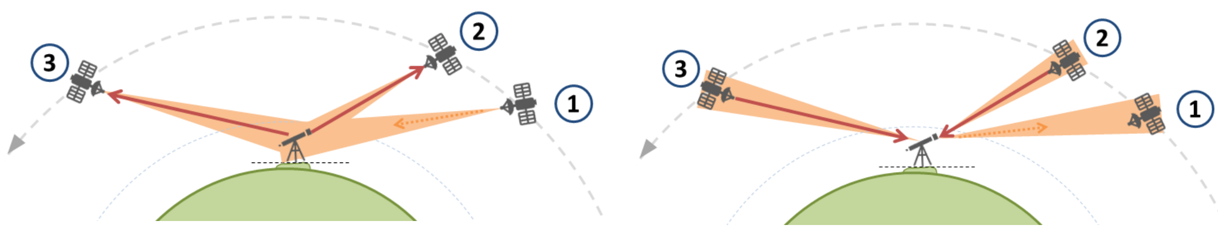

Figure 1. Data uplink (left) and data downlink (right). Data links are represented with red arrows, laser beacons are represented as orange cones.

In FSO G2S communications, the divergence of the transmitted beam can be chosen to be rather wide, in order to compensate for different types of uncertainties including: uncertainties in the ephemerides data, calibration errors, miss-pointing of the OGS, and effects of the atmospheric index-of-refraction turbulence. This is done in order to maintain the satellite within the uplink beam spot at all times during the communication and tracking. However, the beam intensity at the receiver quadratically decreases with the increase of the beam divergence angle, which could result in unacceptably low power at the receiver (negative link margin). Hence, it is necessary to compute and compensate all factors that contribute to pointing errors, in order to maximize the transmitter gain, while at the same time minimizing the pointing loss.

1.1 Pointing loss definition and assumptions

Pointing losses are defined as the ratio between the received optical power (including the effect of pointing misalignment, and the on-axis beam power) corresponding to the beam power that would be detected in the ideal case where the beam had no angular deviation due to pointing errors. The pointing loss will be expressed in decibels (dB) and the calculations are performed using the following set of assumptions.

A Gaussian beam with the lowest order of transverse mode (TEM_{00}) is considered. An uplink laser beam propagates through the atmosphere and is affected by turbulence, causing beam widening, beam wander and spatially-modulated beam scintillation.[6] Nonetheless, previous research has shown that by considering a temporally averaged beam intensity, the beam can still be regarded as having a Gaussian profile, even after propagation through the atmospheric channel.[7,8] Although the beam wander effect is another source of pointing error, it is not considered in this paper, as it has been studied extensively.[9]

A point-like receiver and transmitter are assumed. For point receivers, only the received signal intensity at one point has to be calculated, rather than needing to integrate the power over the receiver's aperture. This is always a valid approximation in satellite communications, since the long link distances result in a beam spot that is much larger than the receiver size. For point transmitters, the beam spot size can simply be approximated as the beam divergence angle multiplied with the link distance, corresponding to the far-field approximation (large distance compared to the Rayleigh range). The paraxial approximation is employed and hence small misalignment angles in different directions can be summed simply as two-dimensional vectors. Finally, the receiver is mounted on a satellite having a circular orbit around the Earth and Earth's shape is assumed to be spherical for simplicity.

1.2 Signal intensity loss due to pointing errors

Several physical sources of tracking and pointing errors are considered in this paper. For a transmitted beam having a Gaussian profile with a known divergence angle, the induced "pointing loss" in the received optical intensity (which can be translated into power) can be calculated.

The values of the pointing error may vary depending on the space-terminal elevation above the horizon and, thus, the pointing loss is elevation dependent. For instance, the point-ahead angle (PAA) depends on the satellite position along its orbit and is elevation dependent. However, in link-budget calculations, the pointing loss is typically given a constant value regardless of the satellite elevation. In this paper, the assumption of a constant pointing loss is abandoned and elevation-dependent intensity losses are calculated. Table 1 shows a summary of the pointing errors that are analyzed hereafter: static errors (non-elevation dependent), dynamic errors (elevation-dependent but predictable) and stochastic errors (potentially elevation-dependent and unpredictable).

Table 1. Summary of the error mechanisms considered in this work.

Error type	Error cause description	Symbol	Section
Static pointing errors	OGS mechanical pointing misalignment	Δ_{OGS}	3.1
Dynamic pointing errors	Uncorrected PAA or fixed-correction PAA	Δ_{PAA}	3.2
	Uncertainties in satellite orbit determination (along-track orbital error)	Δ_{along}	3.3
Stochastic pointing errors	OGS mechanical pointing jitter	σ_{jit}	3.4

The approach followed to analyze the intensity loss due to the pointing errors discussed in this work is described in section 2. The angular deviation due to each pointing error is first analyzed in section 3, followed by the analysis of the intensity loss due to each pointing error in section 4. The effect of all pointing errors is then combined in section 5 to determine the total effect.

2. APPROACH

The intensity distribution $I(L,\theta)$ of a Gaussian beam in the far field is described by

$$I(L,\theta) = I_0(L)e^{-2\left(\frac{\theta}{\omega_0}\right)^2} \quad [\mathrm{W/m^2}] \tag{1}$$

where L is the link distance. As illustrated in Figure 2, $I_0(L)$ is the intensity at the center of the beam (peak intensity), ω_0 is the angular distance from the center where the intensity is $1/e^2$ (or ≈13.5%) of the peak intensity, and θ is the angular deviation from the center of the beam.

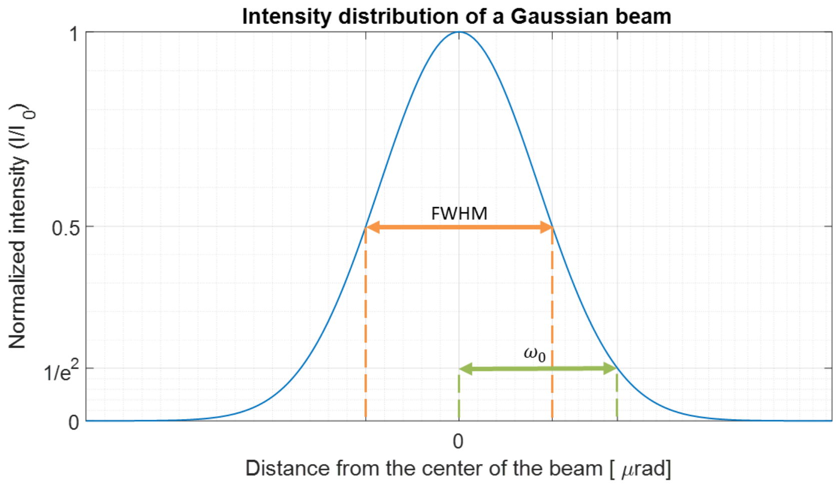

Figure 2. Intensity distribution of a Gaussian beam (TEM_{00}).

In link-budget calculations for FSO communication applications, the divergence angle of the transmitted Gaussian beam is often expressed as the full width at half maximum (FWHM) value. The FWHM value (ω_{FWHM}) is defined as twice the angular distance from the center of the beam to the point where the intensity drops to half the value of I_0. For Gaussian beams, ω_{FWHM} and ω_0 are related by

$$\omega_0 = \frac{\omega_{FWHM}}{\sqrt{2\ln 2}} \approx 0.849\ \omega_{FWHM} \quad \text{[rad]} \tag{2}$$

If an uplink beam transmitted from an OGS is centered on the satellite receiver, the receiver will detect the beam peak intensity. Pointing errors of various kinds can cause the beam to angularly deviate from the receiver, which causes the receiver to detect a lower beam intensity, as illustrated in Figure 3. If the angular deviation that is caused by a particular pointing error is known, the beam intensity at the receiver can be calculated by substituting that deviation with respect to the center of the beam as θ in equation (1). The resulting intensity can then be used to calculate the pointing loss in dB with

$$I_{loss}(L,\theta) = 10 \cdot \log\frac{I(L,\theta)}{I_0(L)} = -\frac{20\cdot\theta^2}{{\omega_0}^2\cdot\ln 10} \approx -8.686\frac{\theta^2}{{\omega_0}^2} \quad \text{[dB]} \tag{3}$$

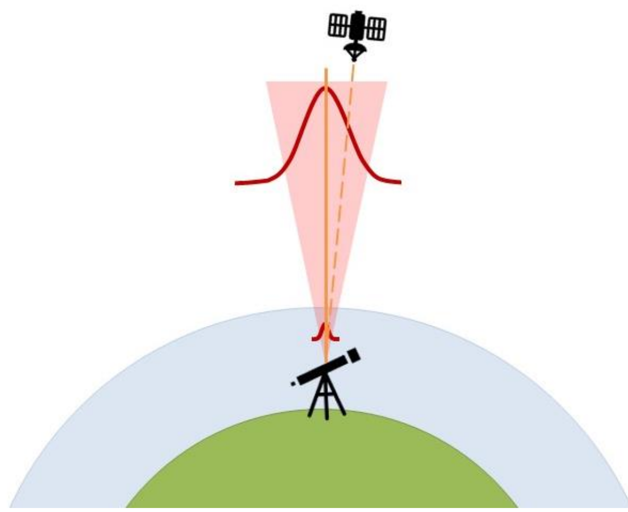

Figure 3. Deviation of uplink beam due to pointing errors.

For some of the pointing errors analyzed in this paper, it is required to know the link distance $L(\varepsilon)$ between an OGS at altitude H_{OGS} [m] above sea level and a satellite at altitude H_{sat} [m] with elevation ε [rad]. Taking into account the parameters shown in Figure 4 and by using the law of cosines, $L(\varepsilon)$ can be calculated as

$$L(\varepsilon) = \sqrt{(R_E + H_{OGS})^2 + (R_E + H_{sat})^2 - 2(R_E + H_{OGS})(R_E + H_{sat}) \cos\gamma} \quad [\text{m}] \tag{4}$$

where R_E [m] is the Earth radius, $\gamma = \pi/2 - \alpha(\varepsilon) - \varepsilon$ is the OGS-Earth center-satellite angle in radians, and the OGS-satellite-Earth center angle α is calculated by the law of sines as follows.

$$\alpha(\varepsilon) = \sin^{-1}\left[\left(\frac{R_E+H_{OGS}}{R_E+H_{sat}}\right)\cos\varepsilon\right] \quad [\text{rad}] \tag{5}$$

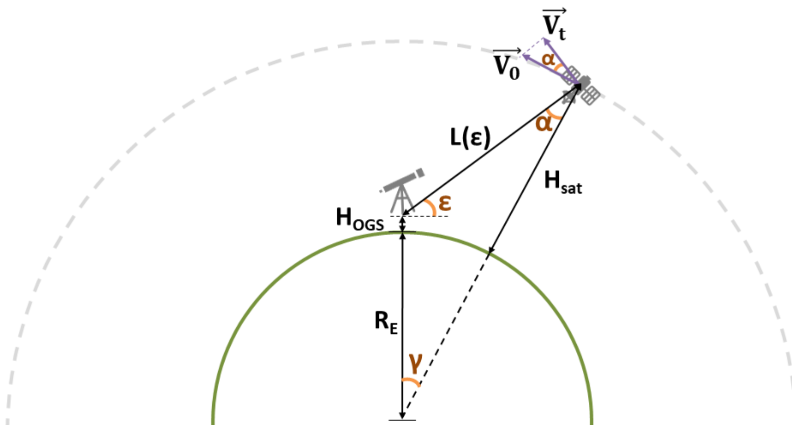

Figure 4. Parameters involved in the calculation of the link distance between an OGS and a satellite.

Table 2 presents values of link distances for satellites at different altitudes and elevations, with respect to an OGS at sea level. The values given to the constants for the analyses and the results presented in this paper are summarized in Table 3.

Table 2. Link distances for LEO satellites at different altitudes and elevations.

Elevation [deg]	Link distance [km]		
	Satellite at 410 km	Satellite at 500 km	Satellite at 1000 km
5	1833.066	2077.939	3194.454
15	1199.345	1407.514	2408.928
30	756.603	909.502	1702.392
60	468.754	570.517	1129.697
90	410	500	1000

Table 3. Constants used in this paper.

Symbol	Parameter	Value	Unit
R_E	Earth's radius	6378E+3	m
$G \cdot M$	Gravitational constant * Earth's mass	3.9858E+14	N·m^2/kg
ω_E	Earth's angular velocity	7.2921E-5	rad/s
c	Speed of light	299792458	m/s

The pointing loss depends on the intensity distribution of the uplink beam, which in turn depends on the beam divergence angle (ω_0). The peak intensity of the beam decreases quadratically with the beam divergence, that is, larger beam divergence results in lower received power even in an absence of pointing errors. However, there will be less intensity loss due to deviation of the uplink beam if the divergence of the beam is larger, as the intensity distribution of the beam will decay more slowly (i.e. larger effective beam spot size at the receiver) and consequently the received intensity will be closer to beam peak intensity. The intensity losses calculated in this paper can then be added as pointing losses to the other known losses involved (which are with respect to the beam that was transmitted by the OGS) in the calculation of a G2S link budget.

3. SOURCES OF POINTING ERRORS

Pointing errors are deviations from the line of sight between the OGS and the satellite and can depend on the satellite elevation. In FSO communications, there can be different pointing errors due to different causes.[1,10] This section introduces the four pointing errors discussed in this paper and the resulting angular deviations of the uplink beam in a G2S link.

3.1 OGS static pointing error

An OGS can have a constant angular deviation (Δ_{OGS}) from the line of sight with a satellite, or boresight, due to mechanical misalignments in the construction of the OGS optics. It can be considered that Δ_{OGS} is composed of a component in the direction of the satellite trajectory (along-track) and a transverse component (cross-track). If the static pointing error of the OGS is in the direction of the satellite trajectory (along-track direction), it can be taken as an additional deviation to the PAA (termed θ_{PAA_OGS} in section 3.2), which gets a positive value if the OGS points ahead of the satellite, or negative if the OGS points in the opposite direction to the satellite's direction of motion relative to the OGS.

3.2 Uncorrected point-ahead angle (PAA)

The PAA is the forward angle at which an OGS must be pointed for an uplink signal to be centered on the satellite, due to the relative motion of the satellite with respect to the OGS and the finiteness of the speed of light. The PAA is represented in Figure 4. At time $t = 0$ a satellite moving from point A to point B with orbital speed V_0 sends a downlink signal to an OGS (①). When the OGS receives the downlink signal at time $t_T = L/c$ -where c is the speed of light and L is the distance between the OGS and the satellite-, the satellite is already approximately halfway between point A and B (②). Finally, the OGS sends the uplink signal to the location where the satellite will be (at point B), taking into account that the beam will take t_T to reach the satellite (③).

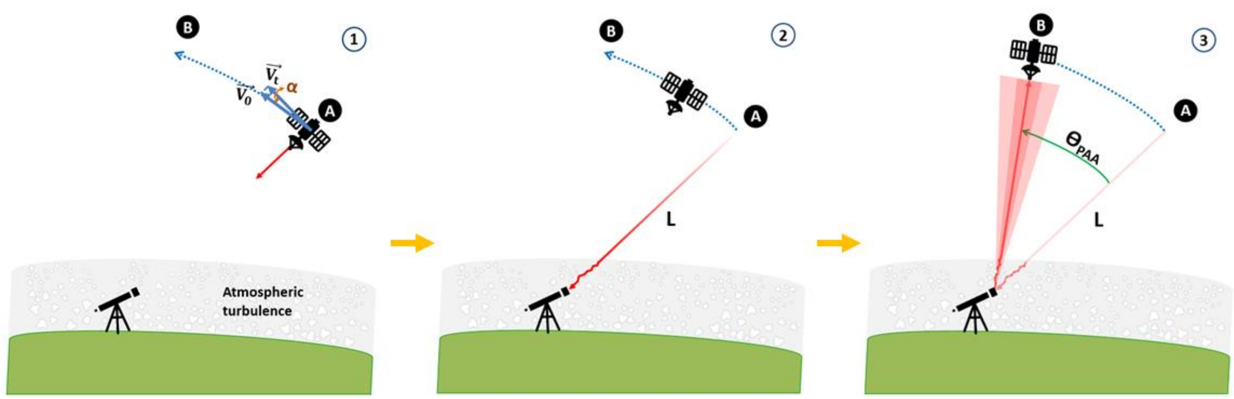

Figure 4. Representation of the PAA.

The calculation of the PAA can be approximated by assuming that L does not change between point A and B, and that there are no additional delay times at the receiver and transmitter that affect the total propagation time of the signals. Using the definition of arc length, it is possible to equal the half distance $V_{t\_sat} \cdot t_T$ between points A and B with $L \cdot \theta_{PAA}/2$, where V_{t_sat} is the speed of the satellite perpendicular to the line of sight with the OGS, t_T is the downlink or uplink signal propagation time, and $L = c \cdot t_T$. Consequently, the PAA [rad] without considering the Earth's rotation can be approximated as follows

$$\theta_{PAA\_stationaryOGS}(\varepsilon) = \frac{2 \cdot V_{t\_sat}}{c} = \frac{2 \cdot V_0 \cos \alpha(\varepsilon)}{c} \quad \text{[rad]} \tag{6}$$

where $\alpha(\varepsilon)$ can be calculated with equation (5), and the satellite orbital speed V_0 (constant for a circular orbit) can be calculated with equation (7), being G [N·m^2/kg^2] the gravitational constant and M [kg] the mass of the Earth.

$$V_0 = \sqrt{\frac{G \cdot M}{H_{sat} + R_E}} \quad \text{[m/s]} \tag{7}$$

To consider the effect of the Earth's rotation on the PAA, the rotational speed of the OGS at a given latitude of the Earth can be included in equation (6). The rotational speed of an OGS at latitude l is approximated by $(R_E + H_{OGS}) \cdot \omega_E \cdot \cos l$, where ω_E is the angular velocity of the Earth.

In this work, it is assumed that a satellite passes exactly over the OGS at some point during its pass, in order to have an analysis of the angular deviation due to pointing errors with the satellite elevation from 0 to 90°. For simplicity, a satellite with 0° orbital inclination, which transits over an OGS located on the equator (l = 0°) is considered. Just as for equation (6), where the perpendicular speed of the satellite to the line of sight with the OGS is considered, the perpendicular speed of the OGS to the line of sight with the satellite must be regarded. The perpendicular velocity of the OGS to the line of sight with the satellite depends on the satellite elevation ε. Hence, for an OGS located at the equator, the term $\sin\varepsilon$ is added. Thus, considering a satellite with a circular orbit of 0° inclination and an OGS at l = 0°, the equation (6) can be rewritten to account for the rotational speed of an OGS as

$$\theta_{PAA}(\varepsilon) = \frac{2\left(V_{t\_sat} - V_{t\_OGS}\right)}{c} = \frac{2(V_0 \cdot \cos\alpha(\varepsilon) - (R_E + H_{OGS}) \cdot \omega_E \cdot \sin\varepsilon)}{c}$$
$$\approx 0.1332 \cdot \frac{\cos\alpha(\varepsilon)}{\sqrt{H_{sat} + R_E}} - (3.1 \cdot 10^{-6} + 4.9 \cdot 10^{-13} \cdot H_{OGS})\, sin\, \varepsilon \quad \text{[rad]} \tag{8}$$

where the values given to ω_E and the constants involved in this analysis are shown in Table 3. While equation (8) was chosen, as it represents the worst-case scenario in which the PAA varies over a larger range during a satellite pass, the values of V_{t_sat} and V_{t_OGS} can be adapted if it is desired to either consider a satellite with a different orbital inclination or an OGS at a different geographic latitude.

Figure 5 shows the PAA calculated with equation (8) as a function of the satellite altitude and the satellite elevation. It can be observed that the lower the altitude of the satellite (in this case down to 1 km for illustrative purposes only), the greater the range of the PAA during a single satellite pass. While for a satellite in geostationary orbit (GEO) the PAA ranges from 20.3 µrad at low elevations to 17.4 µrad when the satellite is at the zenith of the OGS, the PAA of a satellite in LEO at 500 km altitude (indicated by a constant black line in the figure) can range from 19.18 µrad to 47.68 µrad. Table 4 shows values of PAAs for a satellite with a circular orbit and 0° inclination at different altitudes and elevations with respect to an OGS located at sea level at the equator.

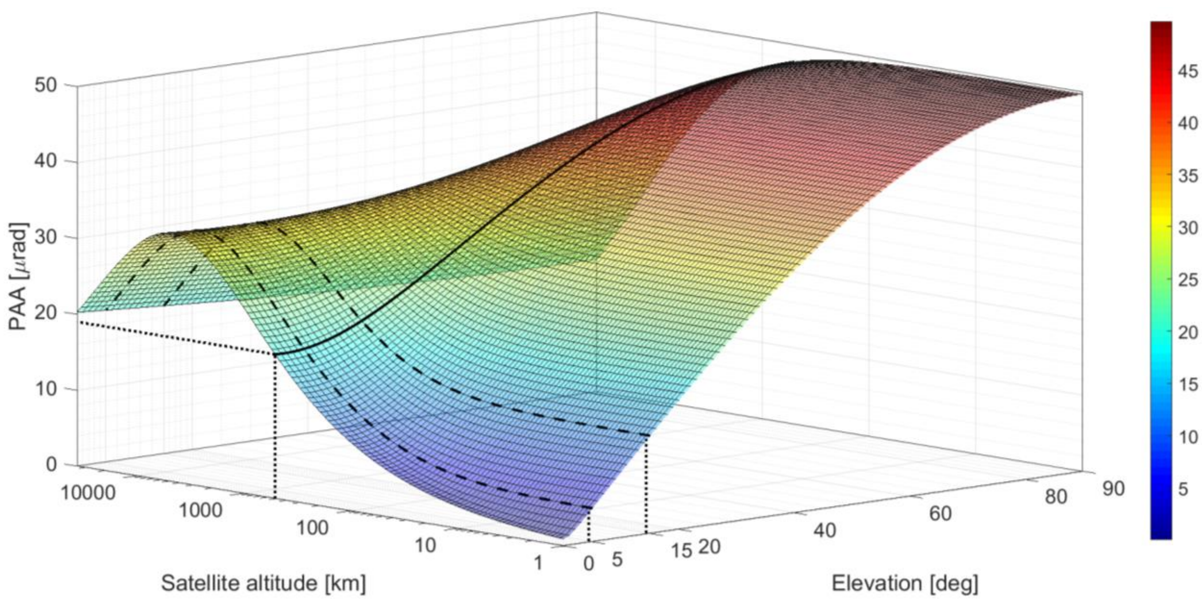

Figure 5. PAA between an OGS at sea level at the equator and a satellite with circular orbit and 0° inclination. The PAA for a LEO satellite at 500 km altitude is indicated by the constant black line.

Table 4. PAA values for LEO satellites at different altitudes and elevations.

Elevation [deg]	PAA [µrad]		
	Satellite at 410 km	Satellite at 500 km	Satellite at 1000 km
5	17.72	19.18	24.65
15	20.66	21.78	26.18
30	28.16	28.71	30.96
60	42.44	42.31	41.53
90	48.02	47.68	45.93

3.3 Orbit uncertainties (along-track error)

To analyze the pointing loss due to orbit uncertainties, an open-loop satellite tracking is considered in which an OGS uses the satellite orbit information to point to the satellite. When the orbit information is recent, the orbit uncertainties are low and the satellite can be targeted accurately with the OGS. For this reason, the satellite orbit must be determined frequently to reduce orbit uncertainties. In this paper only the along-track error is taken into account, as it is more significant than the cross and radial errors.[11] As an example, the mean along-track error can span from a few meters, when the two-line element set (TLE) is recent, to more than 5 km after a 3-day orbit propagation, and 24 km after 7 days of propagation period.[11]

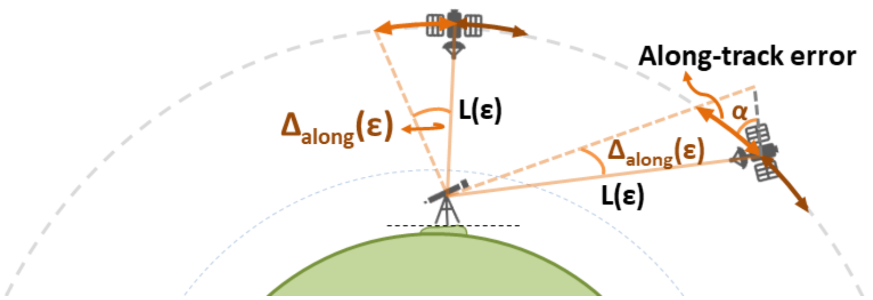

Figure 6. Representation of the elevation-dependent angular deviation observed by an OGS due to an along-track error.

The along-track error indicates how far the satellite can be from the predicted position along the orbit track (either in the direction of the satellite's trajectory or in the opposite direction). In this paper, the along-track error is translated as an angular deviation that covers the uncertainty of the satellite position with respect to the OGS, as illustrated in Figure 6. Since this angular deviation is relative to the OGS, it changes with the satellite elevation, and it can be calculated by assuming that the link distance does not change between the predicted position of the satellite and the position the satellite would be in if it deviated by the determined along-track error. Considering (for simplicity) the case of a satellite passing over the zenith of an OGS, the angular deviation ($\Delta_{along}(\varepsilon)$) as seen from an OGS considering a given along-track error δ [m] is approximated to

$$\Delta_{along}(\varepsilon) = \frac{\delta \cdot \cos\alpha(\varepsilon)}{L(\varepsilon)} \quad [\text{rad}] \tag{9}$$

where $L(\varepsilon)$ and $\alpha(\varepsilon)$ are calculated with equation (4) and equation (5) respectively. Figure 7 shows the angular deviation due to a given along-track error, as a function of the satellite altitude and elevation. It is observed that the angular deviation is greater at lower satellite altitudes and at higher elevations. While for a satellite at 500 km altitude (constant black line) the angular deviation can vary by 1.85461$\cdot\,\delta$ when the satellite has gone from 0 to 90° elevation during a pass, for a satellite in GEO the angular deviation only varies by $4.227 \cdot 10^{-3} \cdot \delta$. Table 5 presents values of the angular deviations for satellites at different altitudes and elevations.

The angular deviation due to a radial orbital error can be computed following the approach used to calculate the angular deviation due to an along-track error, by calculating the maximum link distance due to that radial error and then estimating the angular deviation with equation (9).

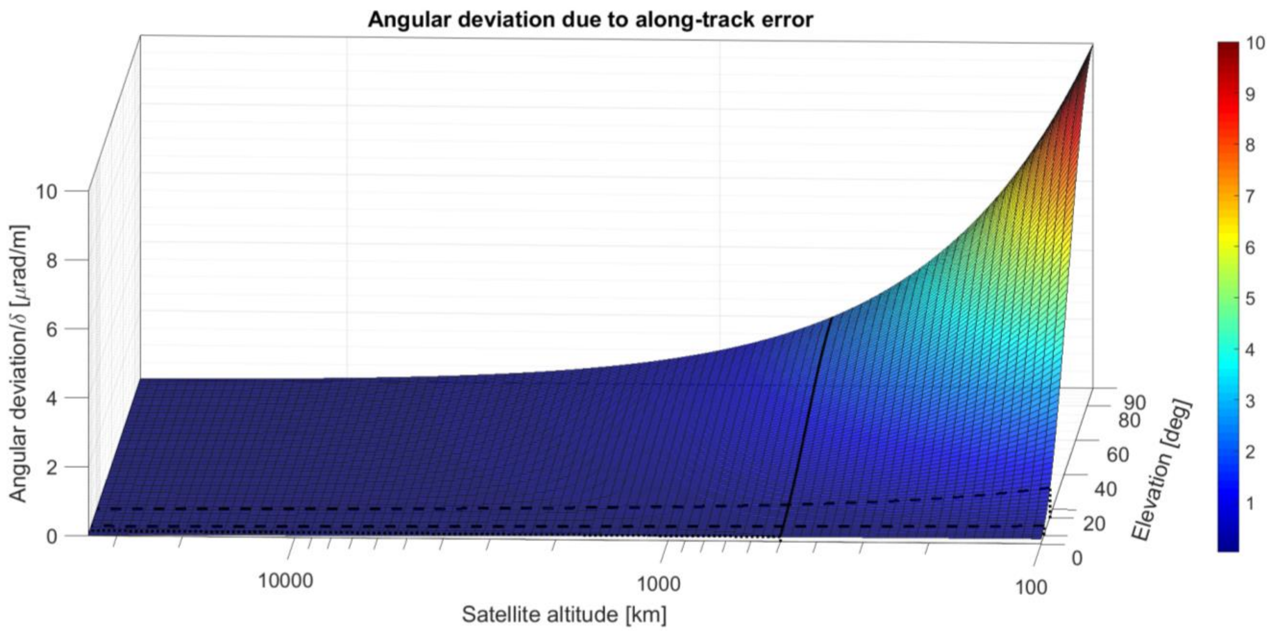

Figure 7. Angular deviation observed by an OGS due to a given along-track error. The constant black line indicates the corresponding angular deviation for a LEO satellite at 500 km altitude.

Table 5. Angular deviations of an uplink beam due to a given along-track error for LEO satellites at different altitudes and elevations.

Elevation [deg]	Angular deviation [μrad]		
	Satellite at 410 km	Satellite at 500 km	Satellite at 1000 km
5	$0.19199 \cdot \delta$	$0.18429 \cdot \delta$	$0.15912 \cdot \delta$
15	$0.35008 \cdot \delta$	$0.31591 \cdot \delta$	$0.22842 \cdot \delta$
30	$0.76825 \cdot \delta$	$0.65518 \cdot \delta$	$0.38943 \cdot \delta$
60	$1.8832 \cdot \delta$	$1.553 \cdot \delta$	$0.79823 \cdot \delta$
90	$2.439 \cdot \delta$	$2 \cdot \delta$	$1 \cdot \delta$

3.4 OGS mechanical jitter

Random mechanical vibrations (mechanical jitter) in the OGS's optical transmitter cause variations in the intensity of the uplink beam detected by a satellite. The mechanical jitter can be modelled as inducing a normally distributing pointing error, having circular symmetry around the beam axis and standard deviation σ_{jit}.

The pointing jitter could have several physical sources that contribute to it. For instance, both the coarse pointing assembly (CPA) and the fine steering mirrors (FSM) could introduce some jitter to the beam pointing, having associated standard deviations σ_{CPA} and σ_{FSM}. Since these sources of pointing errors are statistically independent, the corresponding standard deviations can be added in quadrature, resulting in a total pointing jitter of $\sigma_{jit} = \sqrt{\sigma_{CPA}^2 + \sigma_{FSM}^2}$.

4. INTENSITY LOSSES DUE TO POINTING ERRORS

If during a G2S link there are angular deviations of the uplink beam with respect to the line of sight between the OGS and the satellite, the satellite will observe beam intensity loss compared to the ideal case. The angular deviations due to pointing errors described in section 3 are used in this section to calculate the intensity detected by the satellite and, subsequently, the intensity loss.

4.1 Intensity loss due to OGS static pointing error

If only the static pointing error of an OGS (Δ_{OGS}) is considered for the calculation of the intensity loss due to pointing errors, the value of Δ_{OGS} in radians can directly be substituted into θ in equation (1) to then calculate the intensity loss due to this error with equation (3). Hence, the intensity loss due to a static pointing error at the OGS does not depend on the altitude or elevation of the satellite, and is approximated by

$$I_{loss\_OGS} = -\frac{20 \cdot \Delta_{OGS}^2}{\omega_0^2 \cdot \ln 10} \approx -8.686 \frac{\Delta_{OGS}^2}{\omega_0^2} \tag{10}$$

4.2 Intensity loss due to uncorrected point-ahead angle (PAA) or fixed-corrected PAA

If an OGS does not consider the PAA during a G2S link or relies on a constant PAA, there will be a deviation angle between the center of the uplink signal and the line of sight to the satellite, resulting in intensity loss. A constant PAA of 50 µrad (FWHM) is sometimes assumed during G2S links with LEO satellites. This approach results in more power loss at the satellite's receiver for lower satellite elevations. Conversely, when the PAA is not corrected, there would be more power loss at the receiver as the satellite approaches the zenith, because the theoretical PAA is more significant at higher satellite elevations (Figure 5).

Having calculated the theoretical PAA that an OGS must have to point towards a satellite at a given altitude and elevation using equation (8), and considering the PAA that an OGS uses in practice (θ_{PAA_OGS}), it is possible to calculate the deviation of the center of the uplink beam with respect to the line of sight to the satellite and, therefore, the intensity at the receiver by substituting the PAA for θ in equation (1). The intensity loss due to an uncorrected PAA or a fixed-corrected PAA, defined as

$$\Delta_{PAA} = \theta_{PAA} - \theta_{PAA\_OGS} \tag{11}$$

can be calculated in dB using equation (3).

$$I_{loss\_PAA} = -\frac{20 \cdot \Delta_{PAA}^2}{\omega_0^2 \cdot \ln 10} \approx -8.686 \frac{\Delta_{PAA}^2}{\omega_0^2} \tag{12}$$

Figure 8 shows the PAA and intensity loss in dB at the satellite when the OGS does not consider a PAA (θ_{PAA_OGS} = 0 radians) when pointing towards a LEO satellite at 500 km altitude with an uplink beam with divergence of 50 µrad (FWHM).

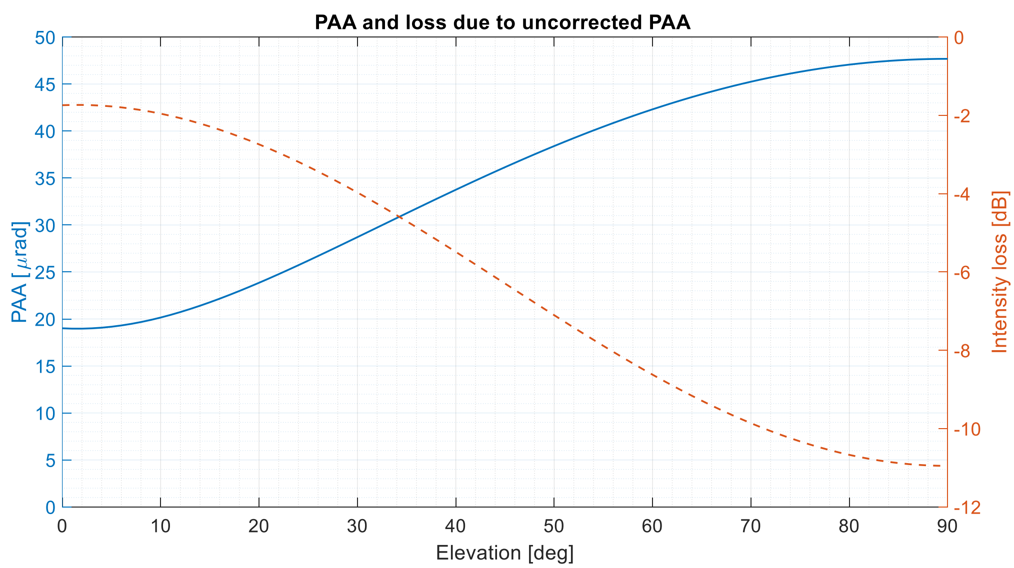

Figure 8. PAA and intensity loss due to uncorrected PAA (θ_{PAA_OGS} = 0 radians) when an OGS at sea level at the equator points an uplink beam with divergence of 50 µrad (FWHM) towards a LEO satellite at 500 km altitude with circular orbit of 0° inclination.

The loss of intensity at the receiver when selecting another uplink beam divergence and considering the same satellite at 500 km altitude is shown in Figure 9. It is observed that the narrower the divergence angle of the uplink beam and the higher the elevation of the satellite, the higher the intensity loss. This is because, as the PAA increases at higher satellite elevations (Figure 5), the satellite moves farther away from the point of the peak intensity of the uplink beam for a narrower beam.

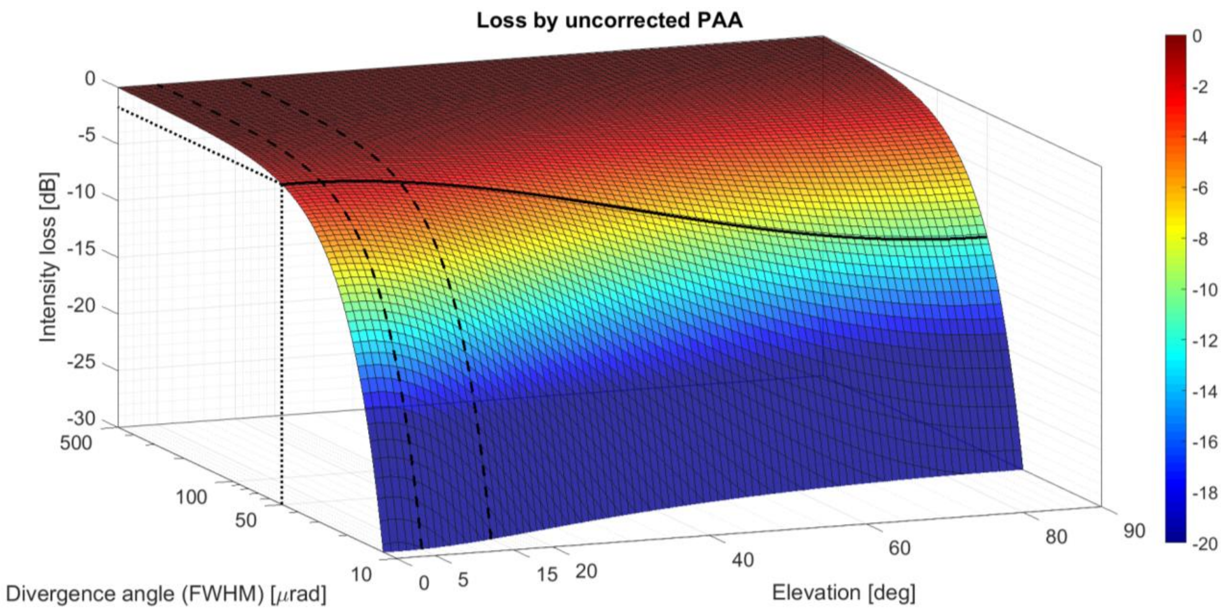

Figure 9. Intensity loss due to uncorrected PAA (θ_{PAA_OGS} = 0 radians) when an OGS at sea level at the equator points an uplink beam towards a LEO satellite at 500 km altitude with circular orbit of 0° inclination. The constant black line indicates the corresponding intensity loss when the uplink beam has a divergence of 50 μrad (FWHM).

Intensity losses for satellites at different altitudes and elevations, and with different divergences of the uplink beam are summarized in Table 6.

Table 6. Intensity loss due to an uncorrected PAA for LEO satellites at different altitudes and elevations, and different divergences of the uplink beam.

Divergence angle FWHM [μrad]	Elevation [deg]	Intensity loss [dB]		
		Sat. at 410 km	Sat. at 500 km	Sat. at 1000 km
50	5	-1.51	-1.77	-2.93
	15	-2.06	-2.28	-3.30
	30	-3.82	-3.97	-4.62
	60	-8.68	-8.62	-8.31
	90	-11.11	-10.95	-10.16
100	5	-0.38	-0.44	-0.73
	15	-0.51	-0.57	-0.83
	30	-0.96	-0.99	-1.15
	60	-2.17	-2.16	-2.08
	90	-2.78	-2.74	-2.54
500	5	-0.02	-0.02	-0.3
	15	-0.02	-0.02	-0.03
	30	-0.04	-0.04	-0.05
	60	-0.09	-0.09	-0.08
	90	-0.11	-0.11	-0.10

4.3 Intensity loss due to orbit uncertainties (along-track error)

After knowing the maximum pointing error of an OGS considering a given along-track error (δ) in the satellite orbital data, the loss of intensity can be calculated using equation (9) and (1), and substituting $\Delta_{along}(\varepsilon)$ for θ. The resulting intensity distribution can be further used to calculate the intensity loss due to an along-track error using equation (3) as

$$I_{loss\_along} = -\frac{20(\delta \cdot \cos\alpha(\varepsilon))^2}{(L \cdot \omega_0)^2 \cdot \ln 10} \approx -8.686\left(\frac{\delta \cdot \cos\alpha(\varepsilon)}{L \cdot \omega_0}\right)^2 \tag{13}$$

The intensity loss as a function of the uplink beam divergence angle and satellite elevation is represented in Figure 10. The intensity loss due to the along-track error in the orbital data is more significant for lower divergence angles and higher elevations. This is because at higher elevation, the angular deviation covering the uncertainty of the satellite position with respect to the OGS appears larger (as seen in Figure 7), and a wider uplink beam is required to cover it.

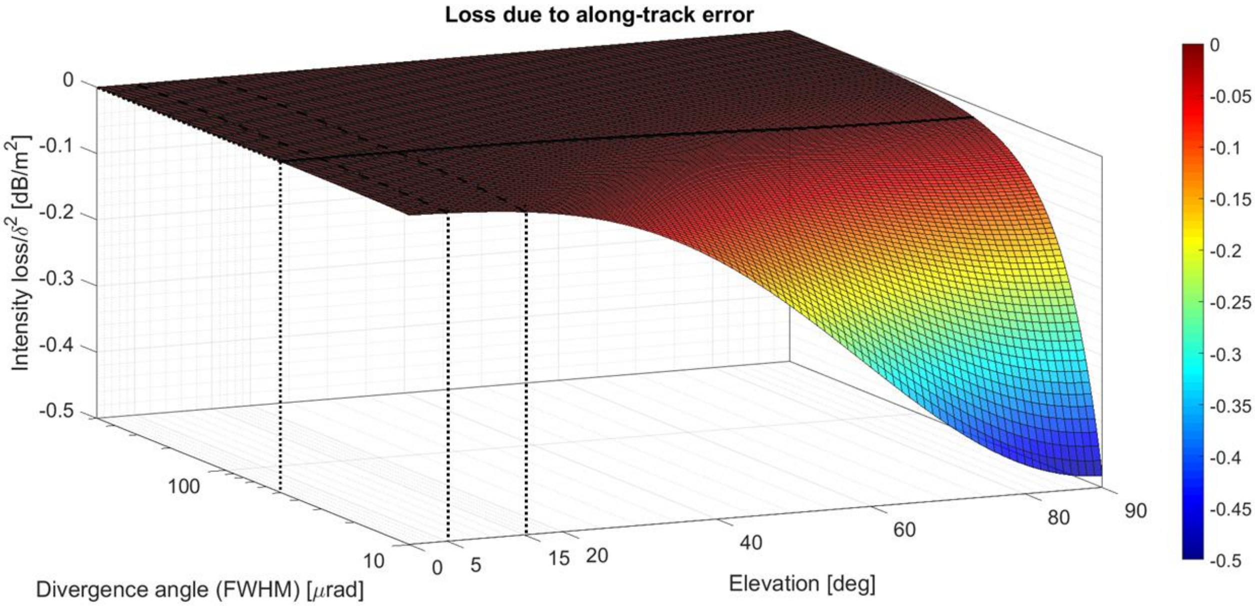

Figure 10. Intensity loss caused by angular deviations observed by an OGS due to a given along-track error. The constant black line indicates the corresponding intensity loss when an OGS at sea level at the equator points an uplink beam with divergence of 50 µrad (FWHM) towards a LEO satellite at 500 km altitude.

Table 7 shows intensity loss values of an uplink beam detected in satellites at different altitudes and elevations. It is important to note that the values given in the table are multiplied by the square of a given along-track error to obtain the corresponding loss of intensity.

Table 7. Intensity loss caused by angular deviations of an uplink beam due to a given along-track error.

Divergence angle FWHM [µrad]	**Elevation [deg]**	**Intensity loss [dB]**		
		Sat. at 410 km	**Sat. at 500 km**	**Sat. at 1000 km**
50	5	$-0.00017754 \cdot \delta^2$	$-0.00016357 \cdot \delta^2$	$-0.00012196 \cdot \delta^2$
	15	$-0.00059031 \cdot \delta^2$	$-0.00048067 \cdot \delta^2$	$-0.0002513 \cdot \delta^2$
	30	$-0.0028428 \cdot \delta^2$	$-0.0020675 \cdot \delta^2$	$-0.00073047 \cdot \delta^2$
	60	$-0.017082 \cdot \delta^2$	$-0.011617 \cdot \delta^2$	$-0.003069 \cdot \delta^2$
	90	$-0.028653 \cdot \delta^2$	$-0.019266 \cdot \delta^2$	$-0.0048165 \cdot \delta^2$
100	5	$-4.4386 \cdot 10^{-5} \cdot \delta^2$	$-4.0894 \cdot 10^{-5} \cdot \delta^2$	$-3.0489 \cdot 10^{-5} \cdot \delta^2$
	15	$-0.00014758 \cdot \delta^2$	$-0.00012017 \cdot \delta^2$	$-6.2825 \cdot 10^{-5} \cdot \delta^2$
	30	$-0.00071069 \cdot \delta^2$	$-0.00051688 \cdot \delta^2$	$-0.00018262 \cdot \delta^2$
	60	$-0.0042706 \cdot \delta^2$	$-0.0029042 \cdot \delta^2$	$-0.00076725 \cdot \delta^2$
	90	$-0.0071632 \cdot \delta^2$	$-0.0048165 \cdot \delta^2$	$-0.0012041 \cdot \delta^2$
500	5	$-1.7754 \cdot 10^{-6} \cdot \delta^2$	$-1.6357 \cdot 10^{-6} \cdot \delta^2$	$-1.2196 \cdot 10^{-6} \cdot \delta^2$
	15	$-5.9031 \cdot 10^{-6} \cdot \delta^2$	$-4.8068 \cdot 10^{-6} \cdot \delta^2$	$-2.513 \cdot 10^{-6} \cdot \delta^2$
	30	$-2.8428 \cdot 10^{-5} \cdot \delta^2$	$-2.0675 \cdot 10^{-5} \cdot \delta^2$	$-7.3047 \cdot 10^{-6} \cdot \delta^2$
	60	$-0.00017082 \cdot \delta^2$	$-0.00011617 \cdot \delta^2$	$-3.069 \cdot 10^{-5} \cdot \delta^2$
	90	$-0.00028653 \cdot \delta^2$	$-0.00019266 \cdot \delta^2$	$-4.8165 \cdot 10^{-5} \cdot \delta^2$

4.4 Intensity loss due to OGS mechanical jitter

The average intensity detected at the receiver due to random jitter σ_{jit} can be approximated to[12,13]

$$I_{jit} = \frac{\omega_0^2}{\omega_0^2 + 4\sigma_{jit}{}^2} \quad (14)$$

The average intensity loss at the satellite can be calculated by substituting the average intensity I_{jit} in equation (3), resulting

$$I_{loss\_jit} = 10 \cdot log\left(\frac{\omega_0^2}{\omega_0^2 + 4\sigma_{jit}{}^2}\right) = 10 \cdot log\left(\frac{\beta}{\beta+1}\right) \quad (15)$$

where $\beta = \omega_0^2/4\sigma_{jit}{}^2$.

4.5 Total intensity loss due to all pointing errors

The effect of all pointing errors considered in this paper are now combined. Two classes of errors can broadly be considered: deterministic errors and stochastic errors. In our analysis, the PAA-fixed correction, the along-track and radial orbital errors, and a static pointing error of the OGS, have been considered as sources of pointing bias; these can be summed together (as two-dimensional vectors, in the small angle approximation) to find the total pointing bias (Δ_{tot}). For the stochastic errors, only the OGS mechanical vibration has been considered, but another effect that may be taken into account is jitter induced by atmospheric turbulence (beam wander, having standard deviation σ_{bw}). It is assumed that these stochastic errors are independent and normally distributed, so that the combination of these effects results in a normally distributed total pointing jitter with standard deviation σ_{tot}, which can include the mechanical jitter and beam wander:

$$\sigma_{tot}{}^2 = \sigma_{jit}{}^2 + \sigma_{bw}{}^2 \quad (16)$$

The probability density function of the modulus of the pointing error (rather then considering a two-dimensional distribution for the x and y component of the pointing error) is then given by the Rice distribution:

$$P_{tot}(\theta) = \frac{\theta}{\sigma_{tot}^2} exp\left(\frac{-\theta^2 - \Delta_{tot}^2}{2\sigma_{tot}^2}\right) Bessel_0\left(\frac{\theta \Delta_{tot}}{\sigma_{tot}^2}\right) \quad (17)$$

where $Bessel_0$ is the modified Bessel function of the first kind of order zero. As a result of this jitter, the beam intensity as seen by the receiver also fluctuates. Assuming a Gaussian beam having waist ω_0, this results in a normalized probability distribution for the normalized intensity $i = I/I_0$

$$P_{loss\_tot}(i) = \beta i^{\beta-1} e^{-\gamma} Bessel_0\left(\frac{\omega_0 \Delta_{tot}\sqrt{0.5\, ln\, i^{-1}}}{\sigma_{tot}^2}\right) \quad (18)$$

where $\beta = \omega_0^2/(4\sigma_{tot}^2)$ and $\gamma = \Delta_{tot}^2/2\sigma_{tot}^2$. The average loss is obtained in this model by computing the expectation value of the normalized intensity, which yields to

$$\langle I \rangle = I_0 \int_0^1 i\, P_{loss\_tot}(i)\, di = I_0 \frac{\omega_0^2}{\omega_0^2 + 4\sigma_{tot}^2} exp\left(-2\frac{\Delta_{tot}^2}{\omega_0^2 + 4\sigma_{tot}^2}\right) \quad (19)$$

By computing $10\log_{10}(\langle I \rangle / I_0)$, an expression for the average dB loss is obtained, including all contributing pointing error mechanisms

$$I_{loss\_tot} = -\frac{20\, \Delta_{tot}^2}{(\omega_0^2 + 4\sigma_{tot}^2)\, ln\, 10} + 10\, log\left(\frac{\omega_0^2}{\omega_0^2 + 4\sigma_{tot}^2}\right) \quad (20)$$

As an example, it is assumed that there are pointing errors during a G2S link due to an uncorrected PAA, and mechanical random jitter of 3.80 µrad (this value is taken from an example of link-budget design[1]). In this case, the OGS is located at the equator and points an uplink beam of 50 µrad (FWHM) to a LEO satellite at 500 km altitude with orbital inclination 0°. In this example, Δ_{tot}^2 is equal to $\Delta_{PAA}{}^2$. Using equation (20), and taking values for Δ_{PAA} from Table 4, the average pointing loss due to uncorrected PAA and mechanical jitter is -1.85 dB when the satellite is at 5° elevation, and -10.75 dB when it is at 90° elevation. Since the mechanical jitter considered in this example is much smaller than the corresponding PAA, the calculated intensity loss remains close to the value of loss due to uncorrected PAA (shown in Table 6).

5. CONCLUSION

Elevation-dependent intensity losses due to different pointing and tracking errors have been calculated for an optical LEO uplink, by considering the angular displacement of an uplink beam with a Gaussian profile with respect to the line of sight between an OGS and a satellite. The intensity losses were calculated with respect to the beam intensity that would be detected by a satellite's point receiver if the uplink beam had no angular deviation due to pointing errors. Therefore, a known intensity loss with respect to the beam originally transmitted by an OGS can be added to the intensity losses calculated here in link-budget calculations for a G2S link. Although the approach and results presented in this paper are applicable to satellites of any altitude, more emphasis is placed on the case of LEO satellites, since maintaining stable pointing to the satellite represents a more significant challenge due to the faster angular motion of the satellite with respect to the OGS.

The elevation of the satellite and the divergence of the transmitted uplink beam were considered to first assess the individual impact on the intensity loss of each source of pointing error: OGS static pointing misalignment, uncorrected PAA or fixed-corrected PAA, along-track orbital error, and mechanical jitter at the OGS. Subsequently, all errors were combined considering the Rice distribution to determine their cumulative effect on the intensity losses in the LEO uplink.

It has been demonstrated that the elevation-dependent pointing errors analyzed in this paper have a greater impact on the intensity loss when: (1) the satellite is at lower altitude, (2) the satellite is closer to the zenith, and (3) the uplink beam transmitted from the OGS is narrower. Therefore, not considering that the "pointing loss" varies with elevation during an OGS-satellite link -especially when the satellite is in LEO- would result in higher losses and, consequently, lower FSO communication performance. While these pointing errors cause greater intensity loss for higher satellite elevations, there are other parameters involved in link-budget calculations that lead to more loss for lower satellite elevations. The main contributing factor is the free-space loss, which results in a quadratic decrease of the signal intensity with the link distance. Another example is the atmospheric attenuation, which depends on the satellite elevation. In addition, beam propagation through the turbulent atmosphere also reduces the peak intensity due to beam broadening, and the effect is more prominent at lower elevations.

Intensity loss values are provided for different satellite altitudes, satellite elevations and uplink beam divergences. The results presented in this paper can be used for link-budget calculations in the optical LEO uplink in the presence of elevation-dependent pointing errors and for subsequent optimization of the optical uplink beam divergence. This analysis on the intensity loss due to elevation-dependent pointing errors in the G2S optical link is aiming at system improvements in the design of future ground and space optical terminals, where elevation-dependent solutions (such as improved pointing and coding, and data rate, modulation, and power adaptation) could be implemented to optimized data transmission during a G2S link. A plan to experimentally verify the findings is under consideration.

REFERENCES

[1] H. Hemmati, *Near-Earth Laser Communications*, 2nd ed. Rochester, New York: CRC Press, 2020.
[2] F. J. Lopez-Martinez, G. Gomez and J. M. Garrido-Balsells, "Physical-Layer Security in Free-Space Optical Communications," *IEEE Photonics Journal*, vol. 7, no. 2, pp. 1-14, April 2015, Art no. 7901014, doi: 10.1109/JPHOT.2015.2402158.
[3] B. L. Edwards, "Latest Status of the CCSDS Optical Communications Working Group, " *2022 IEEE International Conference on Space Optical Systems and Applications (ICSOS)*, Kyoto, Japan, 2022, pp. 1-6, doi: 10.1109/ICSOS53063.2022.9749734
[4] The Consultative Committee for Space Data Systems. (2020, July). "Optical communications physical layer – draft recommended standard," CCSDS 141.0-P-1.1.
[5] M. T. Knopp, A. Spoerl, M. Gnat, G. Rossmanith, F. Huber, C. Fuchs, D. Giggenbach, "Towards the utilization of optical ground-to-space links for low earth orbiting spacecraft," *Acta Astronautica*, vol. 166, pp. 147-155, 2020.
[6] L. C. Andrews, R. L. Phillips and P. T. Yu, "Optical scintillations and fade statistics for a satellite-communication system," *Appl. Opt*. vol 34, no. 33, pp. 7742-7751, 1995. Errata in: *Appl. Opt*. vol. 36, pp. 6068-6069, 1997.
[7] A. M. Prokhorov, F. V. Bunkin, K. S. Gochelashvily and V. I. Shishov, "Laser irradiance propagation in turbulent media," in *Proceedings of the IEEE*, vol. 63, no. 5, pp. 790-811, May 1975, doi: 10.1109/PROC.1975.9828.

[8] P. A. Lightsey, "Scintillation in ground-to-space and retroreflected laser beams," *Optical Engineering*, vol. 33, no. 8, pp. 2535–2543, 1994, doi: https://doi.org/10.1117/12.173566.
[9] L. C. Andrews and R. L. Phillips, *Laser beam propagation through random media*, 2nd ed. Bellingham, Washington: SPIE Press, 2005.
[10] *ESA pointing error engineering handbook*, European Space Agency. 2011.
[11] S. Aida and M. Kirschner, "Accuracy Assessment of SGP4 Orbit Information Conversion into Osculating Elements," in *Proc. 6th European Conference on Space Debris*, Darmstadt, Germany, 2013, vol. 723.
[12] P. J. Titterton, "Power Reduction and Fluctuations Caused by Narrow Laser Beam Motion in the Far Field," *Appl. Opt*., vol. 12, no. 2, pp. 423-425, 1973.
[13] M. Toyoshima, T. Jono, K. Nakagawa and A. Yamamoto, "Optimum divergence angle of a Gaussian beam wave in the presence of random jitter in free-space laser communication systems," *J. Opt. Soc. Am.*, vol. 19, no. 3, pp. 567-571, 2002.