

# Optimal transmitter beam size in FSO uplink from ground to LEO and GEO satellite

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## ABSTRACT

Realizing effective high speed Free Space Optics (FSO) system to/from satellites will be a key step toward the seamless integration of the terrestrial and the satellite optical networks. To this aim, FSO uplink is well known to require the most careful design, since the atmosphere induces impairments that are much more critical than in downlink. To design this class of links, we developed an effective numerical tool that simulates the propagation of various Gaussian beams having different beam waist, through a given set of phase screens: the tool is optimized to perform ten of thousand Monte Carlo iterations in few hours and thus allows to estimate the loss margins for scintillation and beam wander at the requested outage probability (e.g.,  $10^{-3}$ ). Our Monte Carlo simulations also indicate that the relevant additional losses produced by shape distortions in the medium and strong turbulence regimes. When combined with FSO losses, we show for the first time how all these statistical effects interplay: this allows to determine the achievable gains provided by the tip-and-tilt (T&T) correction. Most importantly, we can then identify the optimal beam waist as function of the turbulence regime.

**Keywords:** FSO systems, turbulence, optical propagation, satellite communications

## 1. INTRODUCTION

Free Space Optics (FSO) links are required to realize the seamless extension of fiber networks to include satellite nodes [1]–[4]. In this scenario, three wide classes of optical links should be deployed: intersatellite, satellite-to-ground (downlink) and ground-to-satellite (uplink). Today, intersatellite FSO links are known to operate in private constellations, with tens of Gbit/s speed [5]. The high-speed 100 Gbit/s FSO links from satellite to ground are currently investigated and successfully tested [6]: although they are not yet operational in real networks, these last types of links could be deployed for operation in the future. However, optical uplinks still lag behind, there are very few demonstrations and at much lower speed values. This was expected because any FSO uplink faces the most serious issues due to propagation through a random medium (atmosphere), these are indeed known to induced by far more serious impairments than in downlink [7]. The asymmetry is due to a leverage-like effect, since the wavefront perturbations appear at start/end of the link in the two cases: whilst in downlink this induces mostly phase variations, which can be compensated by aperture averaging and/or adaptive optics, in uplink the phase distortions are coupled with the free-space propagation, producing clear intensity variations and beam wander [8]. Therefore, the beam wander and the scintillation in uplink represent the most serious challenges towards the realization of the future satellite FSO networks [7].

Modelling of FSO uplinks can be realized by analytical means or by Monte Carlo numerical simulations. However, analytical approximations frequently rely upon small-perturbation assumptions, thus they can reliably work in the very-low turbulence regime. Moreover, they frequently assume either plane-wave or spherical wave approximations, which do not exactly match the Gaussian profile of real beams.

Therefore, numerical simulations are the only reliable solution to carefully design these links. To this aim, we developed an effective numerical tool that simulates beam propagation using the phase screen method combined with wave optics: we used this tool to investigate how the choice of the transmitter beam diameter  $w_0$  determines the final impact of the turbulence-induced impairments [8]. Namely, beams with narrow widths show larger beam wander, and

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beams with wider beam-waist exhibit higher intensity fluctuations. Here, the tool is optimized to obtain tens of thousands of Monte Carlo iterations in a reasonable time: this allows us to estimate the FSO system margins corresponding to very low values of outage probability (OP), namely  $10^{-3}$ . We first provide system estimates of margins for the separate effects, at different turbulence levels. Then we combine the effects with (ideal) tip-and-tilt (T&T) correction. This allows to determine how the achievable T&T gain varies when the beam waist and the turbulence conditions change. Finally, we combine this information with the total free-space loss and show that, in each condition, we can determine an optimal beam waist.

## 2. NUMERICAL MODEL

We consider the vertical propagation of Gaussian beams at 1550 nm wavelength, first through atmosphere and then over free space. The atmosphere is made of phase screens, each corresponding to 100 m length [9]. At each iteration, a set of phase screens is numerically generated, according to well-known techniques, and assuming the Hufnagel-Valley model:

$$C_n^2(h) = 0.00594(V/27)^2 (10^{-5}h)^{10} \exp(-h/1000) + 2.7 \times 10^{-16} \exp(-h/1500) + A \exp(-h/100) \quad (1)$$

where  $h$  is in meters [m],  $V$  is the windspeed ( $V=7$  m/s in our case), and  $A$  is the nominal value of the structure constant at the ground [7]. In each Monte Carlo iteration, the phase screen structure is saved, so that, through the given set of phase screens, we numerically propagate seven Gaussian beams having different beam waist values at the transmitter ( $w_0$ ), namely  $w_0 = 20, 16, 13, 10, 7.5, 5$  and  $3$  cm. This is done to exactly consider the effect of  $w_0$  value. We do not include truncation effects due to common telescopes, for the sake of generality. The propagation through the atmosphere is modelled up to an altitude of 20 km, above that value, the atmospheric effects are neglected and the beam is propagated as in free space, assuming that it has to be received either on a LEO satellite (500 km altitude) or on a GEO satellite (36000 km altitude), in both cases assuming 90 degrees elevation.

We also note that, since the generated phase screens are exactly the same for seven different beams, the size and resolution of the numerical grid of the phase screens are chosen to allow the correct propagation of all beams (small and wide), this makes the procedure computing-intensive.

At the LEO/GEO altitude, for each beam we extract the following parameters: the intensity at the center of the beam (the origin), the distance of the beam centroid from the origin (instantaneous beam wander,  $\vec{\rho}$ ), the intensity at this centroid position, which corresponds to ideal T&T compensation. A first example of simulation results is presented in Figure 1, where we report the contour plots of two Gaussian beams propagating to 500 km altitude, starting from ground with  $w_0=3$  cm, and 20 cm, respectively. There is clearly a difference both in the beam wander, deformation and the scintillation effects.

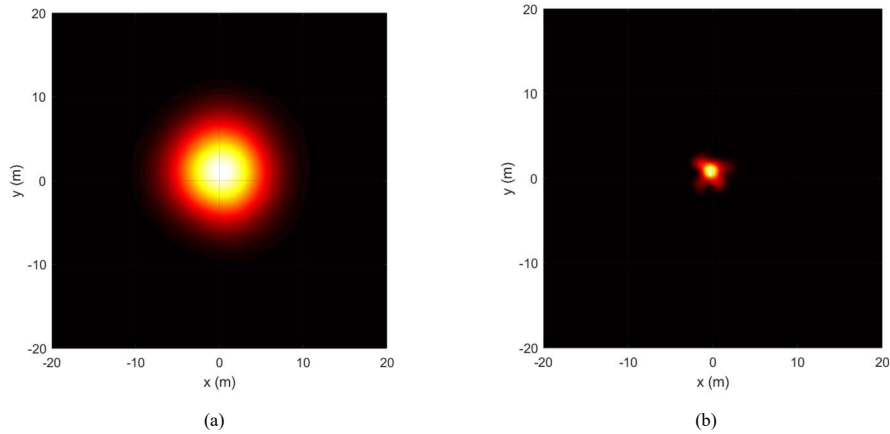


Figure 1. Contour plots of the simulated propagation of two Gaussian beams travelling to a LEO (500 km altitude) through the same statistical realization of phase screens; a:  $w_0=3$  cm, b:  $w_0=20$  cm.

### 3. RESULTS

#### 3.1 Estimating the impact of scintillation and beam wander

By iterating over  $10^4$  Monte Carlo realizations, we were able to estimate reliably the probability density function (pdf) and the corresponding cumulative distribution function (cdf) of the received intensity with and without T&T. We note that, as seen in [8], at given turbulence level, large beams can have a much wider pdf (even changing shape, showing asymmetries etc.) and can have an increased value for the equivalent loss at fixed OP value. Similar behaviors are observed at fixed beam waist and increasing turbulence.

As an example, we report in Figure 2 the estimated cdf's for untracked (blue) and tracked beam (black) beams, for  $w_0=5$  cm, and structure constant at ground level  $C_n^2=2\cdot 10^{-15} \text{ m}^{-2/3}$ , and  $C_n^2=1\cdot 10^{-14} \text{ m}^{-2/3}$ , respectively. In the figure, the values on the intensity axis are normalized to the corresponding average value for each statistical distribution, i.e., they do not include free space loss neither shape distortions. For the sake of clarity, two red circles are placed at the positions corresponding to the required OP value of  $10^{-3}$ . The X-values of the two red circles can be used to estimate the value of  $L_s$ , i.e. the equivalent loss to be added to the power budget, consistently with the OP value [10]. We note that this parameter directly affects the power budget of the link, and it can be also viewed as additional margin to be added to the power budget calculation to provide the expected OP value. In our case, as can be seen, the difference between the  $L_s$  values is apparent and it is due to T&T correction: this allows us to define a gain for T&T, as the difference in  $L_s$  values for tracked and untracked beam. In this first case (Figure 2 a), we get that the untracked beam has  $L_s^u=-3.7$  dB whilst the tracked has  $L_s^t=-0.9$  dB, which gives a gain of around 2.8 dB. In the second case (Figure 2 b), we obtain  $L_s^u=-10$  dB and  $L_s^t=-1.2$  dB, corresponding to a gain of 8.8 dB.

Using this methodology, we could obtain the numerical estimation of  $L_s^t$  and  $L_s^u$  values for different  $w_0$  values and different levels of turbulence. We indeed iterated the Monte Carlo procedure over a wide range of values of the structure constant at ground level  $C_n^2$  (from  $10^{-15} \text{ m}^{-2/3}$  to  $2\cdot 10^{-13} \text{ m}^{-2/3}$ ). This allowed us to obtain an accurate estimate of the T&T gain, in the various possible combinations of turbulence and beam waist.

We summarize these results in Figure 3, where the gain values in dB are reported as contour plots for LEO and GEO satellites. We see that, in both cases, three regions can be identified: towards the low-left corner, the gain is limited because beam wander effects are quite low due to the combination of small beam and low turbulence. On the other side, in the region close to the opposite corner, the effects are extremely strong because high turbulence is particularly affecting the beam shape of wider beams, and distortions are so large that T&T cannot compensate for them: in that case, the T&T correction does not provide a significant gain. We note that an intermediate and curved region is where the T&T benefits are the highest: in that region, the corresponding gain can exceed 20 dB. As far as we know this is the first evidence that the T&T benefits are related not only to the turbulence regime, but also to beam size.

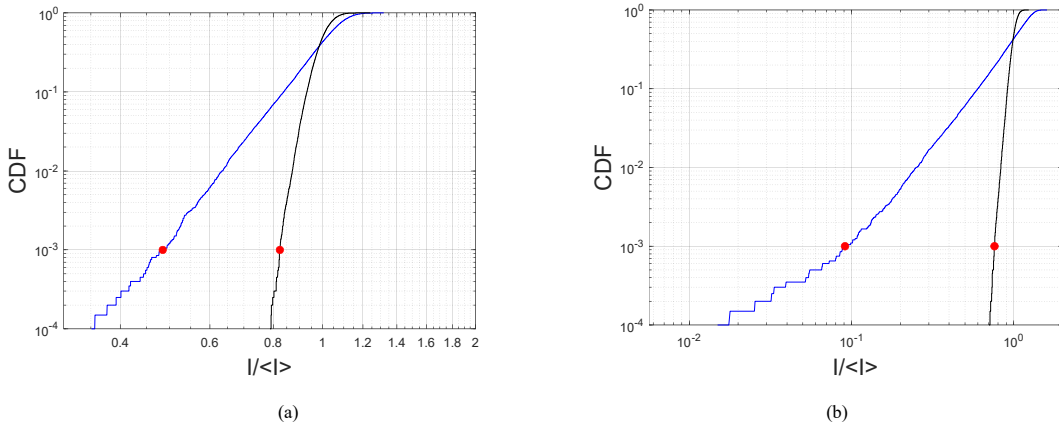


Figure 2. Estimated cdf's for untracked (blue) and tracked beam (black), for  $w_0=5$  cm, assuming  $C_n^2=2\cdot 10^{-15} \text{ m}^{-2/3}$  (a) and  $C_n^2=1\cdot 10^{-14} \text{ m}^{-2/3}$  (b) at 500 km altitude (LEO). As the red circles are used to estimate the value of statistical loss, we see that, in the two cases, the T&T gain is around 2.4 and 9 dB, respectively.

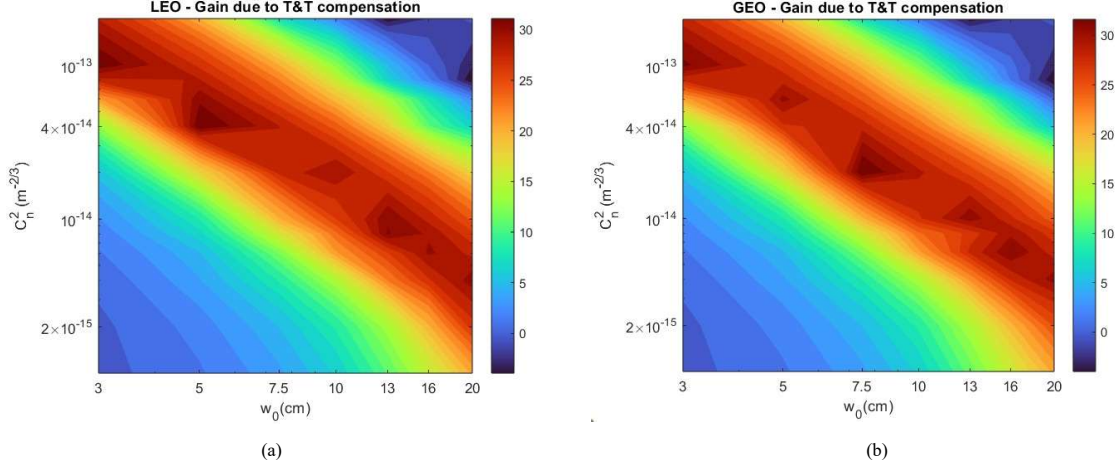


Figure 3. Contour plots of the estimated T&T gain (in dB), for a wide range of combinations of beam waist and turbulence at OGS level  $C_n^2$ , for uplink to a LEO (a) and to a GEO (b).

### 3.2 Estimating the total loss

The previous estimations only refer to beam wander and scintillation. They are summarized in Figure 4 a: here, we present the loss term, after ideal T&T compensation, as a function of the  $w_0$  value, for  $C_n^2 = 2 \cdot 10^{-15} \text{ m}^{-2/3}$  at ground level (low turbulence). The two reported curves refer to LEO (black) and GEO (blue). These curves show a very similar trend in the both cases; noteworthy, these should not be used to optimize the beam waist value: the lowest impact of atmospheric effect value is around  $w_0 = 5 \text{ cm}$ , it clearly indicates that turbulence effects (when beam wander is exactly compensated) would make preferable to adopt smaller beams. However, the complete power budget includes also a major term affecting the total loss that is also strongly depending on the beam waist, i.e. the contribution that is usually indicated as free space loss [10]. Furthermore, since we observe also significant shape deformations, we introduce a definition that also includes the effect of beam distortions. To account for both of these effects, here we define this term as

$$L_{FSO} = \frac{\langle I(\vec{\rho}, L) \rangle}{I_0} \quad (2)$$

where  $\langle I(\vec{\rho}, L) \rangle$  is the intensity at the centroid of the beam ( $\vec{\rho}$ ), calculated at altitude  $L$  in each run, and averaged over the Monte Carlo simulations, whilst  $I_0$  is the intensity of the beam at its center, at the transmitter. As we extract this term from the simulations and combine with  $L_s^t$ , we obtain a realistic estimation of all above effects. The loss curves obtained when considering all these terms become quite different. An example is shown in Figure 4 (b), where we report again the curves obtained for LEO and GEO, for the same low-turbulence conditions: obviously, when including the FSO loss, the two curves are largely separated. However, we can see that, once the FSO loss is included, the prevailing effect of these last losses would make preferable to use a quite larger beam.

However, this is not a general conclusion: as could be expected, when the turbulence is stronger, its effects are balancing the effects of diffraction, and we see that large beams are no longer preferable. Two examples are reported in Figure 5, which reports the estimated total loss as function of the beam waist at higher turbulence levels, i.e.,  $C_n^2 = 2 \cdot 10^{-14} \text{ m}^{-2/3}$  (a) and  $C_n^2 = 6 \cdot 10^{-14} \text{ m}^{-2/3}$  (b). Here, we see that the best loss condition is attained at quite a lower value of initial beam waist, namely the optimal value of  $w_0$  is around 16 cm and 10 cm, in the two cases.

We present all results obtained for many different turbulence levels and a set of various values of beam waist, in Figure 6: this reports the estimations obtained over a very wide number of Monte Carlo simulations, as contour plots. The plots indicate the total loss for LEO (a) and GEO (b) satellites, again assuming perfect T&T compensation. Although some segmentation effects are visible, we see clearly that, when the turbulence is low, wider beams can be preferred thanks to their low divergence; however, when the turbulence is stronger, a smaller beam gives the best power budget, because it suffers scintillation effects to a lower extent.

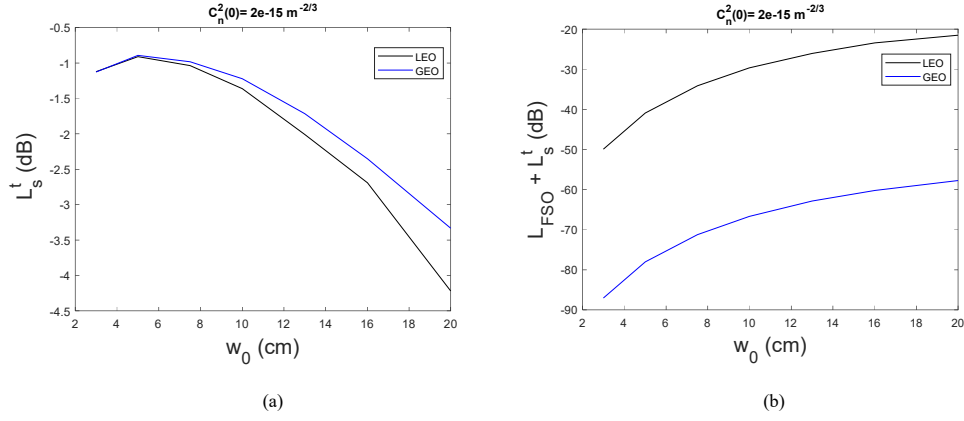


Figure 4. Estimated loss coefficient due to scintillation after T&T correction ( $L_s^t$ ) for different  $w_0$  values, according to  $OP=10^{-3}$  (left) and corresponding combined loss, including FSO propagation (right)

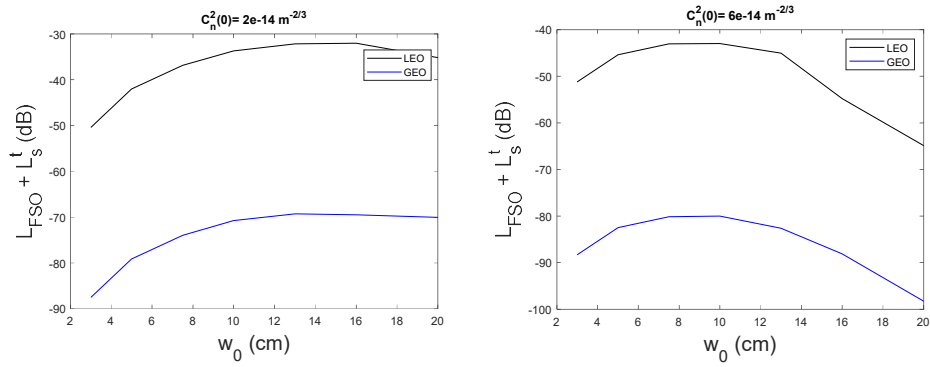


Figure 5. Estimated total loss due to scintillation and free-space propagation ( $L_s^t + L_{FSO}$ ) for different  $w_0$  values, for two values of the structure constant  $C_n^2 = 2 \cdot 10^{-14} m^{-2/3}$  (left) and  $C_n^2 = 6 \cdot 10^{-14} m^{-2/3}$  (right) at ground level, with ideal T&T compensation. The optimal value of  $w_0$  is around 16 cm and 10 cm, in the two cases.

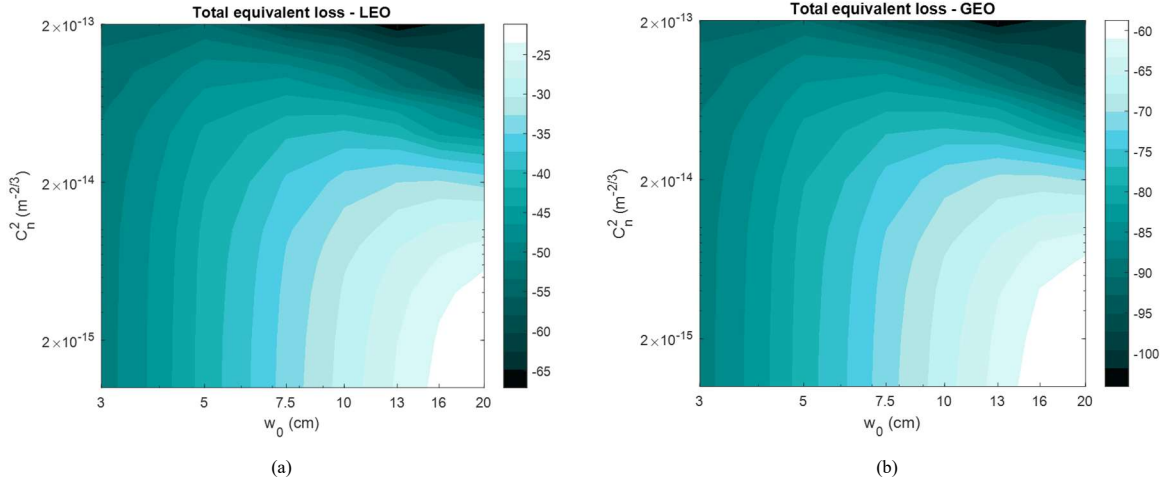


Figure 6. Contour plots of combined scintillation and free-space propagation loss ( $L_s^t + L_{FSO}$ ) for different  $w_0$  values, and turbulence constant structure  $C_n^2$ , with ideal T&T compensation for LEO (a) and GEO (b) satellites.

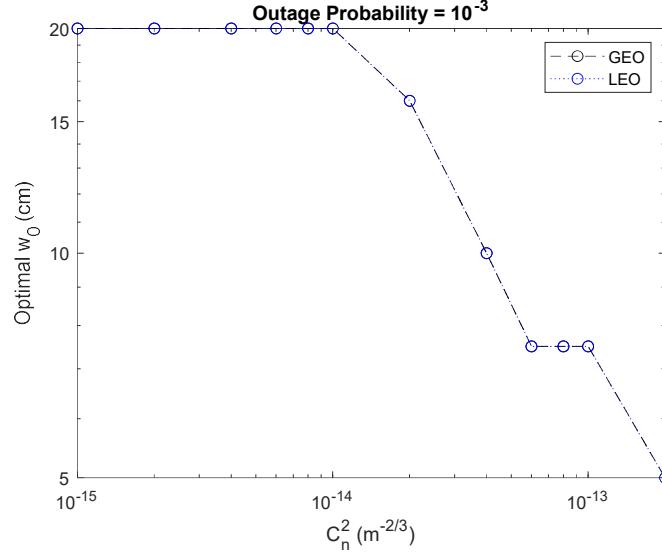


Figure 7. Estimated optimal  $w_0$  values versus turbulence constant structure  $C_n^2$ , at transmitter level for GEO and LEO satellites: the two curves are actually superimposed.

From these figures, we derive that, at each turbulence level, we could obtain an optimal value of  $w_0$ . This trend is summarized in Figure 7, where we present the estimated best values of  $w_0$  as a function of the structure constant. Again, some segmentation is apparent, because we used a set of discrete  $w_0$  values; however, we can clearly see that the best  $w_0$  monotonically decreases when turbulence increases. We also note that, for extremely low turbulence levels, the best  $w_0$  might be even greater than 20 cm, which is the greatest assumed value in our simulations.

Furthermore, we see that the best values are the same in the two cases of satellite altitude, at least with the assumed resolution of beam waist values.

#### 4. CONCLUSION

We used extensive Monte Carlo simulations to determine, for the first time, how all atmospheric effects combine together and with the (large) diffraction loss in a wide range of turbulence conditions, in a vertical uplink to a LEO or GEO satellite. This enables defining some key system parameters: first, the maximum gain due to tip-tilt compensation and, most importantly, the optimal beam waist value for LEO and GEO satellites as a function of turbulence strength. On average, when implementing perfect T&T compensation of the beam wander, we found that the optimal beam waist clearly depends on the assumed turbulence regime. These results also indicate that large beams may not be always preferable. Finally, we note that in our model, the losses due to pointing errors are not yet included: when included, they are expected to further shift the optimal values towards smaller beams, which could benefit from their higher divergence.

These findings indicate clearly that some intrinsic effects can strongly limit the design choices, thus having a major impact on the power budget. To this aim, we highlight that the use of massive Monte Carlo simulations can represent a novel approach for FSO system design in satellite links and could stimulate further studies.

#### ACKNOWLEDGEMENTS

This work was partially supported by the European Union -Next Generation EU under the Italian National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.3, CUP J53C22003120001, partnership on “Telecommunications of the Future” (PE00000001 - program “RESTART”).

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