

Emulation of turbulence-induced fading of ground-to-space optical beacons

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ABSTRACT

Accurate pointing, acquisition, and tracking (PAT) remains one of the central challenges in ground-to-space free-space optical communication. In uplink configurations, spacecraft typically rely on one or more beacon signals transmitted from an optical ground station (OGS) to establish and maintain precise line-of-sight alignment. However, atmospheric turbulence introduces irradiance fluctuations that distort the received beacon signal. These fluctuations include fast scintillation, slow fading, and occasional surges, all of which can degrade the robustness, responsiveness, and reliability of the on-board tracking system. Such impairments are especially relevant for fine-pointing stages and closed-loop PAT systems, where beacon stability directly influences tracking accuracy and communication performance.

This work presents an end-to-end methodology to simulate and experimentally emulate turbulence-induced irradiance scintillation for single- and multi-beacon uplink configurations. The objective is to provide a controlled and reproducible means of evaluating PAT subsystems and, more broadly, optical communication terminals and payloads under realistic turbulence-affected conditions. The methodology has been developed in support of the performance testing and verification of the OPS-SAT VOLT pointing and tracking system, a spacecraft mission within the ESA ScyLight programme designed to offer OPS-SAT Space Lab services to European industry and research institutions. The approach consolidates established models of atmospheric turbulence and wind profiles and applies them to a wide range of ground-to-satellite optical link scenarios, including static GEO links and time-varying LEO passes. These models are used to predict both the statistical behaviour and temporal characteristics of turbulence-induced irradiance fluctuations at the satellite receiver. Based on these atmospheric inputs, we generate synthetic irradiance time series that reproduce the expected scintillation levels, fading statistics, and temporal dynamics associated with representative turbulence conditions, elevation angles, and atmospheric states. We compare the simulated irradiance time series across multiple turbulence and link scenarios and assess their statistical and temporal properties. Furthermore, we validate the performance of a laboratory-based irradiance emulator capable of reproducing these time series with controlled dynamic range and repeatability. The combined numerical-and-experimental framework provides a traceable link between turbulence theory, simulation, and hardware-in-the-loop testing, enabling more realistic qualification of fine-pointing subsystems and optical communication terminals subject to atmospheric turbulence effects.

Keywords: Atmospheric turbulence, irradiance fluctuations emulation, scintillation, uplink beacon, free-space optical communication, pointing acquisition and tracking (PAT), OPS-SAT VOLT, hardware-in-the-loop testing, optical ground station (OGS), LEO/GEO optical links

1. INTRODUCTION

Ground-to-space free-space optical communication (FSOC) and quantum key distribution (QKD) are emerging technologies for future space communication systems, offering high data rates, efficient spectrum utilization, and enhanced communication security. Both technologies rely on establishing and maintaining highly directional optical links between ground and space terminals. Consequently, accurate pointing, acquisition and tracking

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(PAT) systems are required to establish and maintain link alignment throughout the communication window. A common approach for achieving precise spacecraft pointing consists in using an optical beacon transmitted from the ground station and detected by the space terminal. Depending on the system architecture, this beacon may be implemented as a dedicated tracking signal or may be derived directly from the communication channel itself. In either case, the received beacon provides the information required by the spacecraft PAT system to estimate the line-of-sight direction and maintain accurate beam pointing.

For ground-to-space links, the atmospheric channel represents a major source of impairment, as turbulence-induced refractive index fluctuations distort the propagating optical beam and give rise to phenomena such as scintillation, beam wander, beam spreading, and angle-of-arrival fluctuations. These effects introduce temporal variations in the received optical power and apparent beam position, potentially degrading beacon detectability and tracking accuracy. Consequently, the impact of atmospheric turbulence must be carefully considered during the development and validation of optical and quantum communication terminals to ensure that the PAT system can maintain the required performance under representative operating conditions.

Different ways of modeling turbulence-induced irradiance fluctuations have been developed, both for space-to-ground^{1–4} and ground-to-space links,^{5–11} which can then be used to produce laboratory emulations for FSO hardware testing or to evaluate adaptive optics (AO) strategies. These range from high-fidelity wave-optics propagation methods, in which the atmosphere is represented by a sequence of random phase screens and the optical field propagation is evaluated numerically,^{4,7,10} to computationally efficient stochastic approaches that directly generate representative temporal and statistical channel characteristics.^{2,3,8,9} Such approaches include analytical spectral models, statistical fading synthesis methods, and reduced-order modal descriptions based on Zernike representations of turbulence-induced aberrations.

Correspondingly, various laboratory emulators have been developed to recreate these effects. These range from wavefront emulators, such as turbulent fluid chambers¹² and rotating transmissive phase screens,^{4,7,13} to intensity-only emulators which use programmable devices like variable optical attenuators (VOAs) based on micro-electro-mechanical systems (MEMS), silicon photonic, and electro-optic crystal technologies, as well as lithium-niobate intensity modulators.^{3,9,14,15}

This work presents an experimental framework for the laboratory emulation of turbulence-induced fading affecting optical uplink tracking beacons. Developed within the scope of the OPS-SAT VOLT optical and quantum communication terminal validation, the framework addresses the need for fast, representative, and consistent reproduction of turbulence-affected beacon signals during spacecraft PAT testing activities. The proposed methodology combines a physically motivated model of uplink irradiance fluctuations with a time-series synthesis technique capable of reproducing both the target irradiance statistics and temporal dynamics. The resulting fading sequences are implemented using a high-speed electrically variable optical attenuator, enabling controlled emulation of atmospheric turbulence effects relevant to optical beacon tracking.

The framework is further extended to investigate multiple-beacon configurations and the associated averaging of irradiance fluctuations. As such, it provides a practical tool for evaluating PAT system performance under realistic turbulence conditions and supports the development of future optical and quantum communication terminals for space applications.

2. METHODOLOGY

The methodology developed in this work is structured into two complementary parts. First, Sections 2.1 and 2.2 outline the numerical simulation chain and present the underlying theoretical models used to derive the fading statistics and its temporal characteristics. Second, Section 2.3 describes the experimental emulation concept, the laboratory setup, and the procedure used to reproduce the simulated irradiance fluctuations.

2.1 Simulation framework and theoretical background

The simulation framework is summarized in Figure 1. It maps a set of scenario-defining user inputs, including OGS location, orbit definition, elevation or satellite pass geometry, turbulence and wind models, beacon parameters, and time series settings, onto a synthetic irradiance sequence representative of uplink scintillation at the spacecraft.

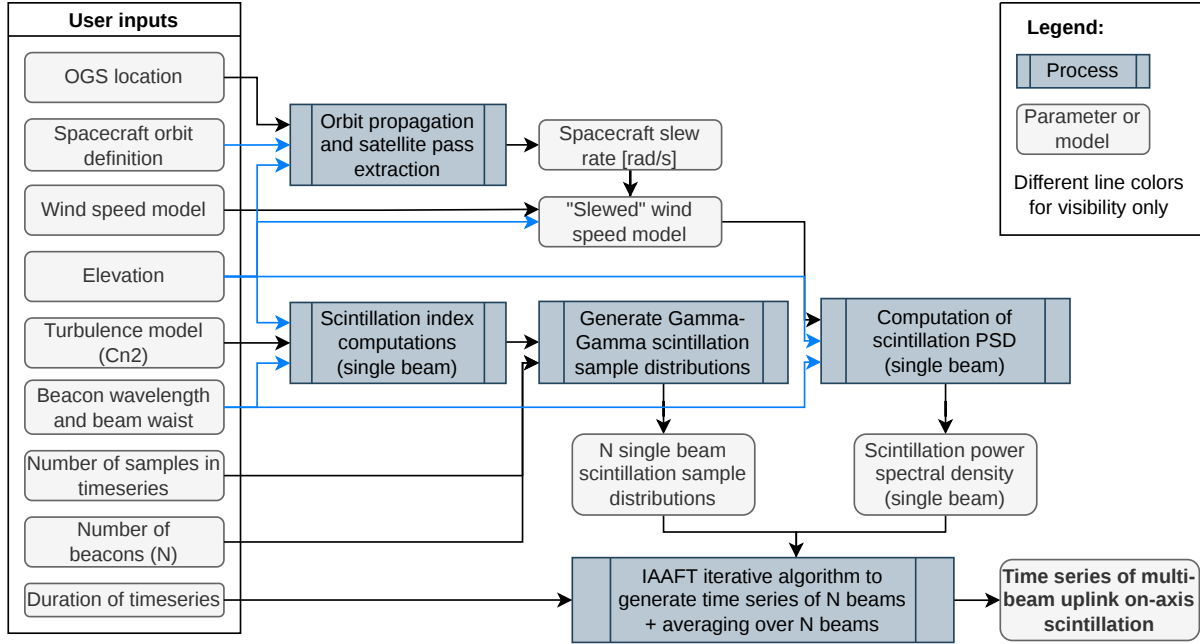


Figure 1: Uplink fading simulation flow diagram.

The simulation chain begins with the determination of the link geometry from orbit propagation and satellite pass calculation, from which the apparent spacecraft slew rate is obtained. Together with the wind model, this yields an effective transverse velocity, represented in the flow chart as a “slewed” wind-speed model. The irradiance fluctuations are then characterised through two complementary but distinct modelling branches. The first branch evaluates the single-beam scintillation index and uses it to parameterise a Gamma–Gamma irradiance distribution describing the expected fading amplitude statistics. The second branch determines the scintillation power spectral density (PSD), which describes the temporal structure of the fluctuations. Subsequently, these two outputs are combined within an iterative amplitude adjusted Fourier transform (IAAFT)-based synthesis procedure to generate irradiance time series consistent with both the target distribution and the temporal spectrum. In the multi-beacon case, several single-beam realisations are generated and averaged to obtain the composite on-axis uplink scintillation at the receiver.

The theoretical models forming the basis of the simulation chain are presented in the following subsections, together with the underlying assumptions and the principal limitations of the adopted methodology.

2.1.1 Link geometry and relative motion

Link geometry and relative motion are evaluated using the General Mission Analysis Tool (GMAT) v2025a through the ESA-developed Python free-space optical communications simulation framework `pyfsoc`, which interfaces with GMAT via its software development kit (SDK). Within `pyfsoc`, the user defines OGS locations and spacecraft orbit parameters, which in this work are selected to match the OPS-SAT VOLT mission. The user then specifies the satellite passes to be analysed, including a minimum elevation threshold used to identify suitable passes. For each selected pass, the apparent spacecraft slew rate as seen along the OGS line of sight is computed as a function of time. This quantity forms a key input to the scintillation PSD model, as it contributes to the effective transverse motion driving the temporal fluctuation behaviour.

2.1.2 Turbulence and wind models

The statistical properties of atmospheric turbulence are described through the refractive index structure parameter C_n^2 , which quantifies the strength of refractive index fluctuations induced by variations in temperature and

pressure. In this work, the vertical profile of C_n^2 is modelled using the Hufnagel–Valley formulation,¹⁶ given by

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

where h denotes the altitude above mean sea level and the parameters A and V_{rms} characterise the strength of near-ground turbulence and high-altitude wind speed, respectively. We assume the OGS is located at mean sea level altitude.

To capture the temporal dynamics of turbulence-induced irradiance fluctuations, a generalized altitude-dependent wind-speed profile is introduced,¹⁷

$$V(h) = V_g + V_{ht} \times e^{\left[-\left(\frac{h-H_t}{L_t}\right)^2\right]}, \quad (2)$$

where V_g represents the near-ground wind speed, while the second term models the high-altitude jet stream, with peak speed V_{ht} , centred at altitude H_t with characteristic width L_t . In the simulations, the parameter values corresponding to the Greenwood wind model are used,¹⁸ as listed in Table 2.

In addition to atmospheric wind, the apparent motion of the link induced by spacecraft dynamics contributes to the effective transverse wind velocity experienced by the propagating beam. This effect is included by combining the wind profile with the apparent spacecraft slew rate, resulting in an altitude-dependent effective transverse velocity v_n normal to the propagation direction,

$$v_n(h) = \left[\left(\omega \frac{h}{\sin \epsilon} \right)^2 + V(h)^2 \right]^{1/2}, \quad (3)$$

where ω and ϵ are the angular slew rate and elevation of the satellite with respect to the OGS respectively. The slew and wind directions are taken to be orthogonal, consistent with the prevailing west–east wind direction and typical north–south satellite passes of Sun-synchronous orbits. This effective velocity is used in the temporal modelling of scintillation through the frozen-flow hypothesis.

2.1.3 Uplink scintillation index and statistics

The irradiance statistics are derived from the uplink scintillation model of Andrews and Phillips.¹⁶ For a ground-to-space link, the propagation coordinate is expressed using the normalized path variable

$$\xi(h) = 1 - \frac{h}{H}, \quad (4)$$

where H is the satellite altitude. The Gaussian beam parameters at the transmitter and receiver are defined as

$$\Theta_0 = 1, \quad \Lambda_0 = \frac{2L}{kw_0^2}, \quad (5)$$

and

$$\Theta = \frac{\Theta_0}{\Theta_0^2 + \Lambda_0^2}, \quad \Lambda = \frac{\Lambda_0}{\Theta_0^2 + \Lambda_0^2}, \quad (6)$$

where L is the slant range, w_0 is the transmitter beam waist, and $k = 2\pi/\lambda$ is the optical wavenumber. The choice $\Theta_0 = 1$ corresponds to a collimated Gaussian beam. The on-axis, weak-fluctuation uplink scintillation strength excluding beam wander is then written as

$$\sigma_{B,u}^2 = 8.70k^{7/6}H^{5/6}\sin^{-11/6}(\epsilon) \int_0^H C_n^2(h) \operatorname{Re} \left\{ \xi^{5/6} [\Lambda\xi + i(1 - (1 - \Theta)\xi)]^{5/6} - \Lambda^{5/6}\xi^{5/3} \right\} dh. \quad (7)$$

This quantity represents the longitudinal component of the uplink scintillation predicted by extended Rytov theory for a finite Gaussian beam under weak-fluctuation conditions. To extend the applicability beyond the

weak-fluctuation regime, $\sigma_{B,u}^2$ is employed to parameterise a Gamma–Gamma fading model through the large-scale and small-scale shape parameters α and β ,

$$\alpha = \left[\exp \left(\frac{0.49 \sigma_{B,u}^2}{\left[1 + 0.56(1 + \Theta) \left(\sigma_{B,u}^2 \right)^{6/5} \right]^{7/6}} \right) - 1 \right]^{-1}, \quad (8)$$

and

$$\beta = \left[\exp \left(\frac{0.51 \sigma_{B,u}^2}{\left[1 + 0.69 \left(\sigma_{B,u}^2 \right)^{6/5} \right]^{5/6}} \right) - 1 \right]^{-1}. \quad (9)$$

A unit-mean irradiance sample I is generated as the product of two statistically independent Gamma-distributed random variables,

$$I = XY, \quad X \sim \Gamma \left(\alpha, \frac{1}{\alpha} \right), \quad Y \sim \Gamma \left(\beta, \frac{1}{\beta} \right), \quad (10)$$

where the first and second arguments denote the shape and scale parameters, respectively. The scintillation index of the resulting irradiance process is

$$\sigma_I^2 = \frac{1}{\alpha} + \frac{1}{\beta} + \frac{1}{\alpha\beta}. \quad (11)$$

2.1.4 Uplink scintillation power spectral density

The temporal behaviour of turbulence-induced irradiance fluctuations is modelled using the uplink scintillation formulation developed by Yura and McKinley.¹⁹ This model provides an analytical expression for the PSD of log-irradiance fluctuations for a spherical wave propagating from ground to space through a turbulent atmosphere. The PSD is expressed as a path integral over the turbulence strength, weighted by an altitude-dependent spectral kernel, i.e.

$$P(f) \propto \int_0^H \frac{C_n^2(h) h^{\frac{4}{3}}}{v_n(h)} \int_0^\infty \left[x^2 + \frac{f^2}{f_0^2(h)} \right]^{-11/6} \sin^2 \left[x^2 + \frac{f^2}{f_0^2(h)} \right] dx dh, \quad (12)$$

where f denotes temporal frequency in units of Hz. The characteristic frequency $f_0(h)$ is defined as

$$f_0(h) = v_n(h) \sqrt{\frac{2k \sin \epsilon}{h}}, \quad k = \frac{2\pi}{\lambda}, \quad (13)$$

where λ is the optical wavelength and $v_n(h)$ is the effective wind transverse velocity, as seen in Equation 3.

The spectral model relies on assumptions that partly overlap with those of the scintillation-strength model introduced above. In particular, both the scintillation-index and temporal-PSD formulations assume Kolmogorov refractive-index fluctuations, leading to the characteristic $-11/3$ spatial spectral slope. The Yura–McKinley PSD is based on a Rytov treatment of log-irradiance fluctuations and is therefore most rigorously applicable in weak-to-moderate fluctuation regimes. For cases with high scintillation index, the PSD should be interpreted as an approximate temporal-shape model, since the breakdown of first-order log-irradiance theory and the onset of scintillation saturation can alter the irradiance covariance and redistribute fluctuation power over temporal frequency. In the present framework, the PSD is therefore used as a representative normalized temporal-shape model, while the fluctuation strength and irradiance statistics are imposed separately through the scintillation-index and Gamma-Gamma model. The spherical-wave approximation is considered appropriate for the wide-divergence uplink beacons modelled in this work.

Another effect of turbulence is beam wander. Beam wandering describes angular deviations of the beam from the boresight and can cause fading of the beacon that varies over time. For the wide-divergence uplink beacons considered in this work, the expected RMS beam wander angle remains small compared to the beacon divergence (smaller than 10% of beam divergence in the strongest turbulence scenario considered). Consequently, the resulting centroid displacement is expected to introduce only a minor contribution to the received irradiance fluctuations relative to scintillation effects and is therefore not addressed in this work.

2.2 Numerical simulation

This section describes the required steps to calculate the time series of irradiance fluctuations, starting with the numerical solution of Equation 12.

2.2.1 PSD calculation and validation

The numerical simulation begins with the solution of the PSD equation (12). A careful discretization is necessary due to the rapidly varying behaviour of the integrand across the integration domain. For the same reason, Simpson's method has been chosen as the integration method. Additionally, integration limits can be truncated without loss of accuracy, as the contributions to the total integral value at the extremes of the domain are negligible. The PSD is then evaluated for a range of temporal frequencies f , to build the log-irradiance fluctuations across the full spectrum.

2.2.2 IAAFT process and time series generation

The IAAFT process, originally proposed by Schreiber and Schmitz,^{20,21} is an iterative optimization algorithm used to create surrogate time series that simultaneously reproduce a target PSD and a target amplitude distribution. A high-level overview of the algorithm is shown in Figure 2 (adapted to this work from the general Schreiber and Schmitz definition). The inputs to the algorithm are a target PSD and a log-irradiance distribution that needs to be preserved. It is important to note that the Gamma-Gamma distribution of irradiance fluctuations previously described needs to be transformed into a distribution of log-irradiance fluctuations (this step is not shown in the diagram).

Each iteration consists of two consecutive operations: PSD matching and amplitude matching. During the PSD matching step, the Fourier transform of the current time series is computed and the magnitudes of the Fourier coefficients are replaced with those corresponding to the target PSD, while the associated phases are left unchanged. An inverse Fourier transform is then performed to obtain a new time series whose PSD matches the target spectrum. However, this operation generally alters the amplitude distribution of the signal. An amplitude matching step is subsequently performed through rank-order remapping. Specifically, the samples of the original time series are reassigned according to the rank ordering of the signal obtained from the PSD matching step. As a result, the output time series has exactly the same amplitude distribution as the target one. This remapping, however, slightly perturbs the PSD that was enforced during the previous step. The two operations are then repeated iteratively and the process is terminated once the convergence criterion is met. The convergence criterion is defined through two thresholds. The first is an absolute PSD error threshold, computed as the discrepancy between the PSD of the current surrogate realization and the target PSD. The second is a surrogate variation threshold, defined as the difference between two consecutive surrogate realizations. The iterative process is terminated when either the PSD error falls below its prescribed threshold or the change between successive surrogate realizations becomes smaller than the corresponding threshold, indicating that further iterations produce negligible improvements. The last remaining step, once a surrogate time series has been obtained, is to transform it back from a time series of log-irradiance fluctuations, to one of irradiance fluctuations (this step is also not included in the diagram).

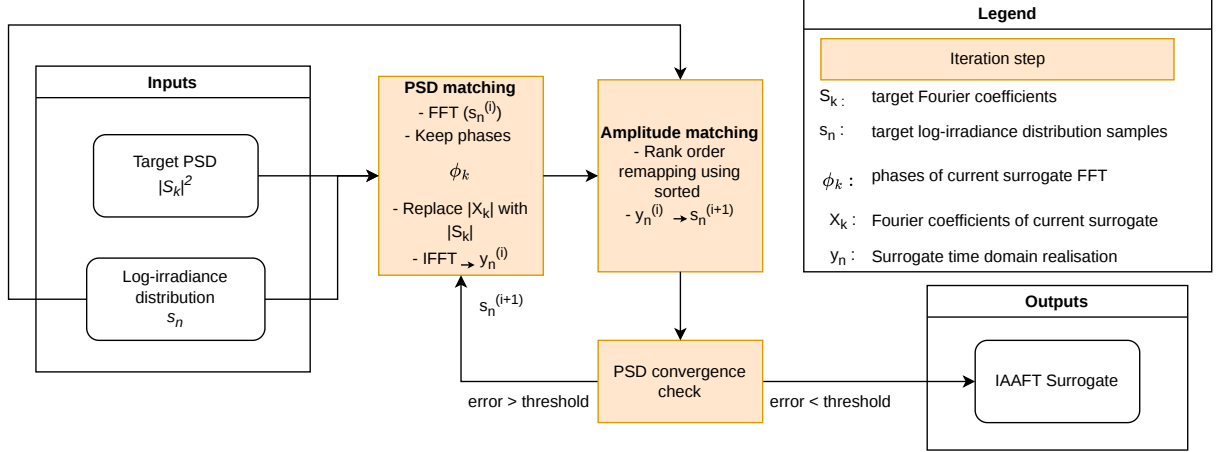


Figure 2: High-level schematic of the IAAFT optimization algorithm.

In this work, the process is applied to the Gamma-Gamma sample distributions, to obtain a surrogate time series that consists of the input irradiance samples, but incorporates the temporal behaviour described by the target PSD of Equation 12.

For multi-beam uplink configurations, N statistically independent single-beam irradiance realisations are generated, corresponding to spatially sufficiently separated beacons, as defined in the diagram of Figure 1. The composite received irradiance is then obtained by averaging the individual realisations,

$$I_N(t) = \frac{1}{N} \sum_{n=1}^N I_n(t). \quad (14)$$

2.2.3 Simulation scenarios

In this work, four low Earth orbit (LEO) scenarios are selected for simulation (representative of the conditions in which the OPS-SAT VOLT satellite will fly), and two geostationary (GEO) orbit scenarios. The LEO scenarios are the result of the combination of two variables: elevation and turbulence strength. Two elevations have been considered, a “high” and a “low” elevation case, and two turbulence strength cases, a “high” and a “low” turbulence case. In the GEO scenarios, the only variable to be changed is the turbulence strength, as the elevation is fixed. As with the LEO cases, the two scenarios present a “high” and “low” turbulence as differentiation. The parameters characterizing each scenario are presented in Table 1.

Parameter [unit]	LEO				GEO	
	LE - LT	LE - HT	HE - LT	HE - HT	LT	HT
RMS wind speed - V_{rms} [m/s]	21	30	21	30	21	30
Ground turbulence - A [-]	1.7×10^{-14}	10^{-13}	1.7×10^{-14}	10^{-13}	1.7×10^{-14}	10^{-13}
Slew rate - ω [rad/s]	0.01536	0.01536	0.00349	0.00349	0.0	0.0
Elevation - ϵ [deg]	20	20	90	90	20	20
Fried parameter - r_0 [cm]	5.82	2.28	11.07	4.33	5.82	2.28

Table 1: Parameter definition for the simulated LEO and GEO cases. LE = Low Elevation, HE = High Elevation, LT = Low Turbulence, HT = High Turbulence.

Static parameters common to all scenarios are listed in Table 2.

Parameter [unit]	Value	Description
λ [nm]	976	Beacon wavelength.
V_g [m/s]	8	Near-ground wind speed parameter.
V_{ht} [m/s]	30	Peak high-altitude wind speed contribution associated with the jet stream.
H_t [m]	12448	Altitude of the jet-stream centre.
L_t [m]	4800	Characteristic width of the jet-stream layer.
N [-]	2	Number of uplink beacons considered in the multi-beam configuration.
Θ [mrad]	1.5	Uplink beacon divergence (half angle).

Table 2: Simulation parameters common to all scenarios.

2.3 Fading emulation in the lab

The high-level schematic of the lab setup is shown in Figure 3. It illustrates the emulator concept rather than a specific test configuration. A fiber splitter after the EVOA allows the signal to be emitted towards a device under test (DUT), whether in fiber or in free space. This DUT can be a modem, PAT (sub)system, laser communications terminal, or other.

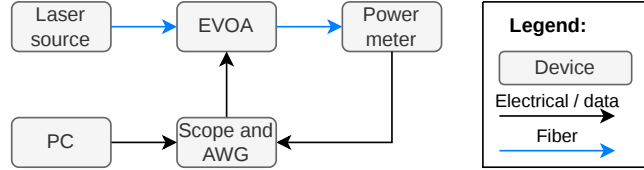


Figure 3: Fading emulation lab setup schematic.

The selection of the key components shown in Table ?? allows for a cost-effective setup capable of reproducing effectively any turbulence attenuation time series, with a dynamic range up to 40 dB (limited by the ADP3450 resolution) and a bandwidth reaching 50 kHz. Although the simulated beacon wavelength is 976 nm, the laboratory emulation was performed at 1550 nm using available C-band fibre-optic components. An equivalent EVOA, power meter and laser source can be sourced at various wavelengths. Lessons learned to achieve high-fidelity emulation have been to:

- employ an electro-optic attenuator, avoiding a MEMS-based attenuator which has much more limited bandwidth;
- operate the ADP3450 in its high accuracy mode with limited 2 V measurement range;
- perform electrical bias calibration (and subtraction of this bias) of the ADP3450 input before every test run;
- establish a unique AWG voltage-to-attenuation calibration table before each run to minimize any impact of changing environmental and thermal effects.

The system is operated through the ADP3450 Python Waveforms SDK, which allows for flexible test scripting and integration in larger test setups.

The behaviour shown by the spectra is matching expectations. For the same elevation, a higher turbulence scenario leads to larger fluctuations in irradiance. At the same time, a lower elevation presents stronger perturbations compared to a higher elevation case, due to the beam having to travel through a larger portion of the atmosphere. The cases showing the strongest effects are the low elevation and high turbulence cases, as expected. Another element that can be seen from the comparison is how the scenarios with 90° elevation present a spectrum shifted towards higher frequencies, with a higher cut-off frequency, due to the increased slew rate compared to the scenarios at 20° elevation. On the other hand, the cut-off frequency for the GEO cases is shifted to lower frequencies, as the slew rate for these scenarios is zero. It is worth noting that the power contained in the signal is the same between the GEO and LEO cases at low elevation angles, it is simply distributed at different frequency ranges due to the slewing in the LEO scenarios. Finally, when comparing the dual-beam cases with their respective single-beam plots, an observation about the power in the signal can be made. The power contained in the dual-beam case is roughly half of the one of the single-beam case (with the dual-beam case being the average of two uncorrelated beacons), which matches the expected behaviour.

Additionally, we can use the frequency-weighted PSD to gain more insight into the temporal behaviour of the signals as shown in Figure 5.

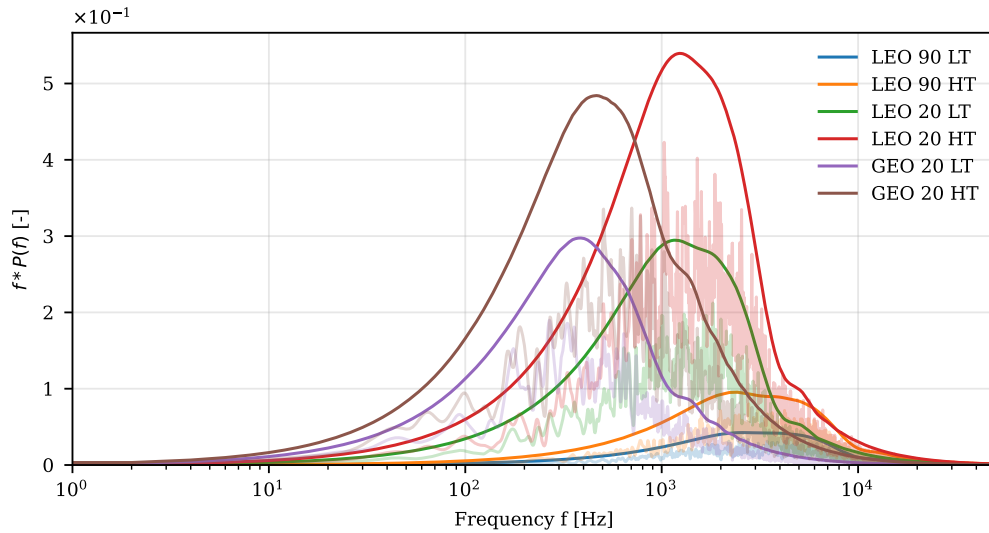


Figure 5: Comparison of different irradiance temporal frequency spectra multiplied by frequency for the cases presented in Table 1. Dual-beam scenarios are shown with a fainter line.

In Figure 5, the variability in cut-off frequencies between the scenarios can more easily be observed. It also visualizes the critical frequency ranges responsible for the largest contribution to total scintillation strength. For all scenarios, frequencies above several hundred Hz dominate the signal power and are even in the kHz regime for uplink to LEO scenarios, significantly higher as compared to typical downlink scenarios. It is critical to take this into consideration when designing closed-loop tracking systems relying on ground-based beacons. The cases for a LEO orbit with 90° elevation are difficult to visualize in the congregate plots and are therefore repeated in Figure 6.

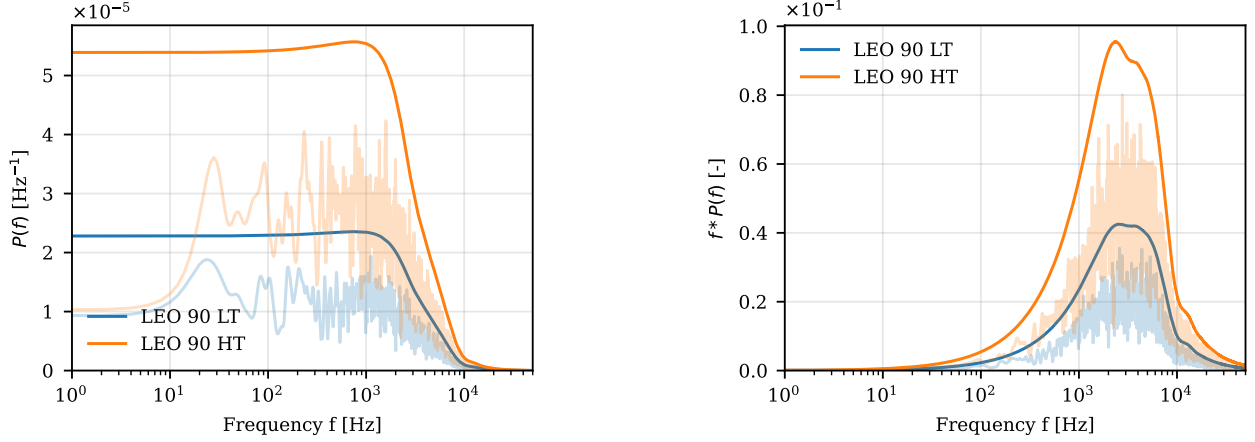


Figure 6: Temporal frequency spectra of irradiance fluctuations for LEO cases at high elevation. Dual-beam scenarios are shown with a fainter line.

3.2 Time series

The IAAFT process has been validated by comparing the PSD obtained from Equation 12 with the PSD of the resulting time series, and by comparing the original Gamma-Gamma distribution with the final time series distribution of samples. The before and after PSDs match in terms of slope and cut-off frequency, demonstrating an agreement in spectral properties, and the sample distributions remain the same after the IAAFT process.

To compare the scintillation strength and distribution, Figure 7 presents the cumulative distribution function (CDF) of three scenarios. The first observation that can be made from the plots is how the perturbations are significantly stronger for the low elevation - high turbulence case, compared to the high elevation - low turbulence one. This is expected, and matches with the considerations already made when examining the spectral results. A similar result can be seen when comparing the single beacon with the respective dual-beam scenario. The averaging between two uncorrelated beams flattens the amplitude of the perturbations.

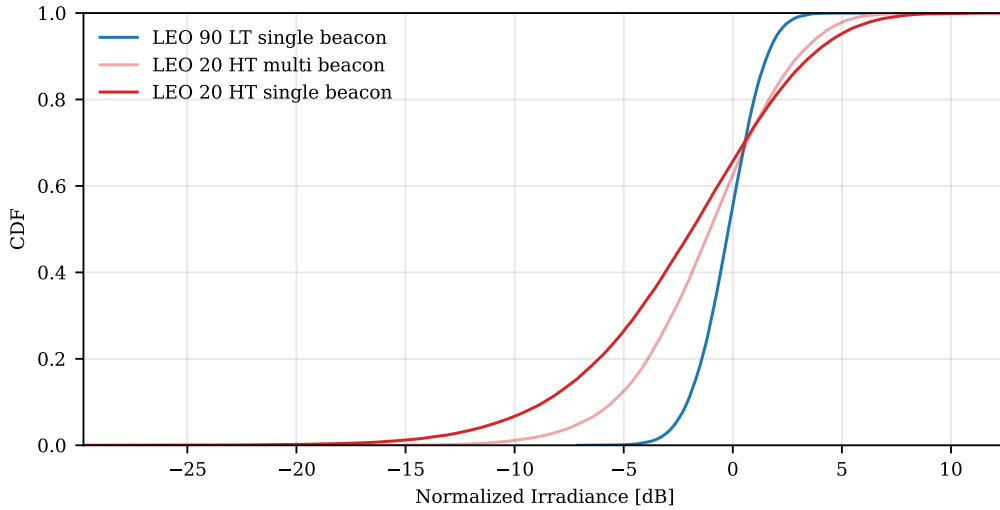


Figure 7: Comparison of cumulative distribution functions of irradiance fluctuation samples between the LEO high elevation and low turbulence case and the LEO low elevation and high turbulence case. The multi-beacon scenario for the LEO high elevation low turbulence case is shown with a fainter line.

Small portions of the time series of the same scenarios as presented in Figure 7 are shown in Figure 8. We can observe slower but larger variations of atmospheric scintillation for the low elevation scenarios as compared to the high elevation scenario, which is in line with the previously shown PSDs.

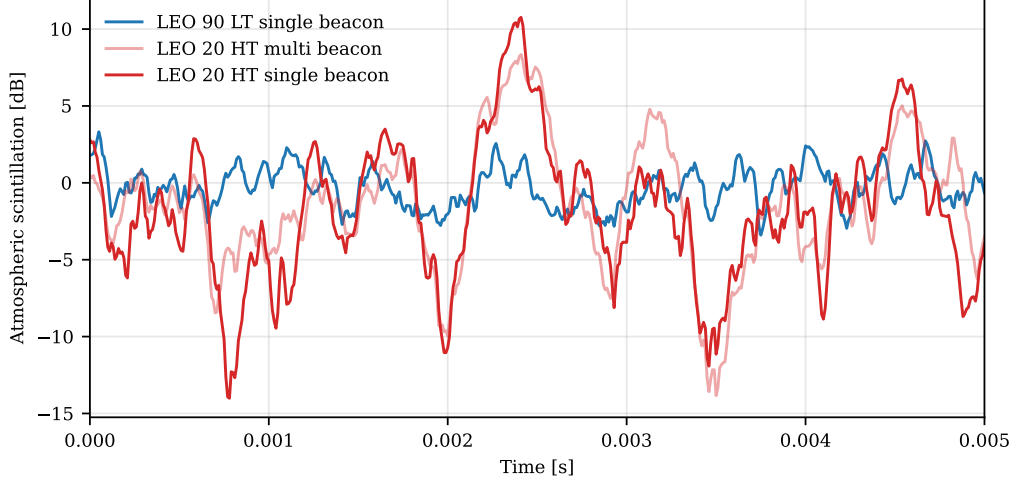


Figure 8: Time series of irradiance fluctuations for the LEO high elevation - low turbulence case and the LEO low elevation - high turbulence case. The multi-beacon scenario for the LEO high elevation low turbulence case is shown with a faint line.

Finally, the scintillation indices and mean frequencies for all simulation cases are summarized in Table 4. Those two parameters are representations of the scintillation strength and speed, respectively. The scintillation index results from Equation 11 and the mean frequency is computed as the PSD-weighted spectral centroid of the normalized irradiance fluctuations.

Parameter [unit]	LEO				GEO	
	LE - LT	LE - HT	HE - LT	HE - HT	LT	HT
Scint. index (single beam) - σ_I^2 [-]	0.6793	1.1975	0.1081	0.2397	0.6793	1.1975
Scint. index (dual beam) - σ_I^2 [-]	0.3384	0.6119	0.0536	0.1166	0.3537	0.6197
Mean freq. (single beam) - f_{mean} [Hz]	1601	1634	3690	3568	570	776
Mean freq. (dual beam) - f_{mean} [Hz]	1654	1695	3686	3630	568	828

Table 4: Simulated scintillation indices and mean frequencies for all simulation cases of Table 1.

3.3 Fading emulation in the lab

Following the methodology outlined in Section 2.3, we first present an example of a VOA calibration table, which is generated before each test run and used for interpolating the intended attenuation time series onto an AWG voltage time series. We found the range between 0.7 and 5.0 V ideal as the attenuator operating range. The resulting calibration is shown in Figure 9.

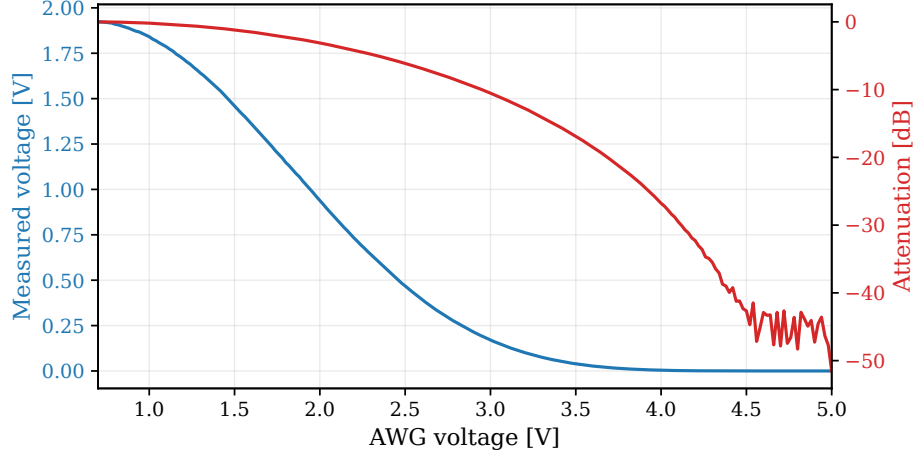


Figure 9: VOA calibration.

Two y-axes are shown with the measured voltage on PDA20CS2 shown on the left axis and the computed attenuation on the right axis. With this setup, a dynamic range up to 40 dB can reliably be achieved, limited by the ADP3450 resolution.

The two most stringent turbulence scenarios are emulated and their comparison to the intended (simulated) time series is shown in Figure 10.

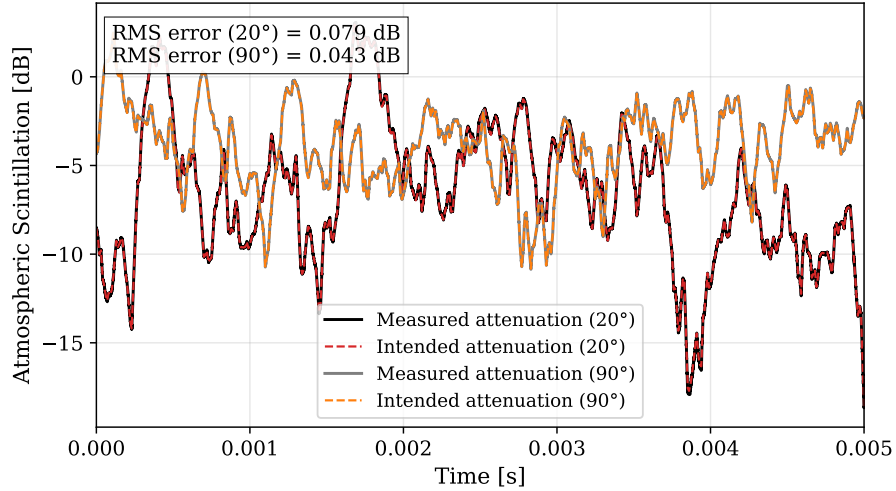


Figure 10: Comparison of intended (simulated) and measured (emulated) attenuation for uplink to LEO, single beacon and strong turbulence scenario.

In addition to the scenarios presented in Figure 10, all other scenarios defined in Table 1 have been emulated successfully. For all cases, an RMS error between intended and measured attenuation of less than 0.1 dB has been achieved.

4. CONCLUSION AND RECOMMENDATIONS

This work presents a framework for the simulation and laboratory emulation of turbulence-induced irradiance scintillation affecting wide-divergence uplink beacons in ground-to-space optical communication links. Developed in support of the OPS-SAT VOLT optical and quantum communication terminal programme, the framework

provides a representative and repeatable method for evaluating atmospheric scintillation effects on optical communication (sub)systems under controlled laboratory conditions. The method combines an uplink scintillation model, a temporal scintillation PSD model, and an IAAFT-based synthesis procedure to generate irradiance time series, reproducing both the target scintillation statistics and temporal spectral behaviour. The approach was demonstrated for representative LEO and GEO cases, covering different elevation angles, turbulence strengths, slew rates, and single- and multi-beam configurations. Its applicability is limited to intensity-only emulation of turbulence-induced scintillation. It is applicable when scintillation is the dominant received-power impairment and when beam wander is small compared to the beacon divergence.

The results confirm that low elevation and stronger turbulence increase fading severity, while LEO slew motion shifts scintillation power towards higher temporal frequencies. In the analysed cases, significant scintillation content extends beyond several hundred Hz and, for high-elevation LEO cases, into the kHz range. This highlights that representative PAT testing should account for both fading depth and temporal bandwidth. The multi-beacon simulations demonstrate the expected averaging of independent fading channels, reducing fluctuation severity and producing a more stable received irradiance signal.

Experimentally, the simulated attenuation profiles were reproduced using an electro-optic VOA driven by an AWG. The setup demonstrates a usable dynamic range of approximately 40 dB, bandwidth up to 50 kHz, and high reproduction accuracy, with RMS error between intended and measured attenuation below 0.1 dB across all scenarios. These results demonstrate the suitability of the emulator for repeatable hardware-in-the-loop testing.

Future work should focus on extending the applicability of the simulation framework to narrow-beacon scenarios that include the effect of beam wander and pointing errors. Furthermore, the combination of intensity fading with wavefront or pointing-error emulation can be considered where required.

Overall, the work establishes a practical and verified method for translating atmospheric turbulence models and mission geometries into reproducible laboratory fading tests. The demonstrated combination of time-series generation, calibrated high-bandwidth attenuation, and sub-0.1 dB RMS reproduction accuracy provides a strong basis for PAT subsystem verification and future optical and quantum communication terminal testing.

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