

Impact of Beam Divergence and Transmitter Diversity on Off-Axis Scintillation Statistics in a 10.45 km Optical Uplink

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ABSTRACT

In free-space optical (FSO) satellite communications, collimated optical beams with wide divergence angles are typically used to mitigate the effect of beam wander and minimize the risk of losing link alignment due to pointing errors. However, reducing the beam divergence is essential to enhancing data transmission rates. Narrower divergence beams (beams with larger initial beam diameter) are more susceptible to atmospherically-induced scintillation, increasing with radial distance from the center of the beam. Although theoretical and simulation models on off-axis scintillation statistics have been documented in the literature, to the best of our knowledge, this work presents the first long-distance FSO experiment designed to empirically measure off-axis scintillation and fading statistics under real atmospheric conditions. This paper presents the design, implementation, and key findings. The experiment consisted of a terrestrial FSO link to a mountaintop, emulating a satellite uplink scenario. Two experimental configurations are implemented to evaluate the impact of different divergence angles and transmitter diversity under strong turbulence conditions. Results show that, for narrower beam divergence, angular misalignments result in stronger fluctuations and more frequent, rapid fading events at larger radial distances from the center of the beam. The scintillation index increases with radial distance within the region enclosed by the $1/e^2$ beam diameter of the received optical beam. Within this region, the measurement data shows a good fit to a Gaussian profile. When transmitter diversity is employed, the scintillation index decreases by approximately half and fading events are reduced. The primary objective of this experiment is to validate theoretical and simulation models of off-axis scintillation statistics by providing empirical data as reference for the design and optimization of future ground-to-satellite optical systems.

Keywords: free-space optical communications, collimated Gaussian beams, optical LEO uplink, beam wander, power fluctuations, fading, experimental validation.

1. INTRODUCTION

Free-space optical (FSO) communications offer higher data rates and more secure transmissions than radiofrequency communications. However, FSO links are susceptible to pointing errors and atmospheric effects, such as atmospheric attenuation, and atmospheric scintillation and beam wander caused by index-of-refraction turbulence (IRT). Pointing errors and atmospheric effects degrade link performance by inducing signal fading and irradiance fluctuations.

Atmospheric scintillation results from constructive and destructive interference of the propagating beam, leading to fluctuations in the received optical irradiance. Beam wander (random deviations of the transmitted optical beam due to atmospheric turbulence cells) can induce signal fading, additional beam spread, and scintillation beyond that caused by atmospheric scintillation alone.^{1,2} The conventional Rytov theory does not account for scintillation induced by beam wander of collimated optical Gaussian uplink beams and predicts a decrease in scintillation for beam diameters in the order of the turbulent cells.¹ However, wave optics simulation results have demonstrated an underestimation of the predicted on-axis scintillation.³⁻⁵ Furthermore, simulations show that scintillation increases with radial (off-axis) distance from the beam center, reaching a peak before

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saturating at larger off-axis positions.^{4,5} Theoretical models have considered these simulation results to model the beam-wander-induced scintillation for untracked uplink beams.^{2,5} It is then expected that beam wander will introduce additional optical fluctuations, in addition to those caused by atmospheric scintillation, when the turbulence cells are comparable to or larger than the initial beam diameter. Beam wander can dominate the scintillation index for satellite uplinks.⁴ Simulations also show that beam wander may also cause the received optical beam to have a distorted Gaussian profile.^{1,5}

Irradiance fluctuations are usually quantified by the scintillation index, which is defined as the normalized variance of the received irradiance. The beam divergence of a collimated, diffraction-limited Gaussian beam is inversely proportional to its initial diameter. It is then expected that collimated beams with wider beam diameters (i.e. narrower beam divergence) will cause a higher scintillation index, which increases with radial distance from the center of the beam. Transmitter diversity, which employs two or more uncorrelated transmitters, has been shown to be a technique that effectively mitigates irradiance fluctuations by reducing the scintillation index proportionally to the number of transmitters and by decreasing the probability of fading.⁶⁻⁸ This technique consists on placing transmitters at a separation greater than the atmospheric coherence width, ensuring that the received signals experience independent fading.

In FSO satellite uplinks (Figure 1), optical beams with wide divergence angles are typically used to mitigate the effects of beam wander and to minimize the risk of losing link alignment due to pointing errors. However, increasing the beam divergence reduces the received optical irradiance, thereby limiting data rates. Consequently, reducing beam divergence angles is essential to enhance data transmission rates. Pointing errors (such as an unaccounted point-ahead angle) cause angular deviations between the transmitted beam and the receiver, potentially resulting in significant off-axis signal fluctuations and power loss, especially when smaller divergence angles are used. For instance, in uplinks to low-Earth orbit (LEO) satellites, if the point-ahead angle is not corrected, it can cause an off-axis misalignment of up to about 48 μ rad between the optical beam and the satellite, leading to significant power losses that increase with narrower divergence angles.⁹

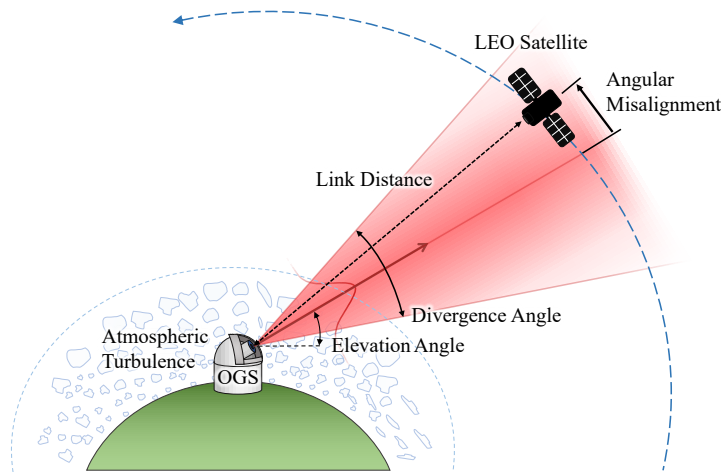


Figure 1. Uplink from an optical ground station (OGS) to a LEO satellite.

Optical links to and from LEO satellites differ as atmospheric optical IRT is present at the end of a downlink path, and at the beginning of an uplink path (Figure 1). This leads to beam deviations and large intensity scintillation structures at the satellite during an uplink.⁴ This link asymmetry can benefit from transmitter diversity at the uplink source to reduce scintillation through the superposition of independent intensity patterns. The transmitter beams must simultaneously have minimum divergence while minimizing losses due to point-ahead angle errors and beam wander due to atmospheric turbulence. An additional challenge is the increased scintillation of Gaussian beams at off-axis positions, which must be considered as well.

The uplink scenario has been investigated theoretically and experimentally, mostly for uplinks to geostationary (GEO) satellites. For instance, between the optical ground station (OGS) at Tenerife and the experimental GEO Artemis by the German Aerospace Center (DLR) and the European Space Agency (ESA)⁸ and also by the Japanese National Institute of Information and Communications Technology (NICT),¹⁰ and more recently with the HICALI mission.¹¹ For uplinks to LEO satellites, the NICT investigated the application of transmitter diversity with Gaussian beams with the OICETS satellite,¹² while DLR tested with the same satellite two uplink transmitters and flat-top beam profiles.^{13,14} Further experiments included bidirectional links to the ISS.¹⁵ Laboratory investigations of M-fold transmitter diversity were carried out¹⁶ and several terrestrial experiments, comparable in atmospheric impact to the satellite-link scenario, showed the feasibility of optical high-speed uplink communication.^{17,18}

The new advances of this study are the investigation of on- and off-axis scintillation of single and multiple transmitted Gaussian beams under strong-turbulence conditions, as it would be encountered at very low satellite link angles. Such low elevations are particularly interesting for links to LEO satellites, as these spend the majority of their pass at low elevation angles ($<20^\circ$), which leads to strong and even saturated atmospheric scintillation due to the vast turbulent volume.

In this work, we present an FSO experiment conducted to observe the impact of different divergence angles and transmitter diversity on power statistics of the received optical signal. This ground-based FSO link emulates a satellite uplink scenario and enables the study of turbulence-induced effects, such as beam wander, scintillation, and signal fading under controlled yet realistic terrestrial conditions. Two experimental configurations are implemented, each designed to evaluate one of the two study cases. The structure of this paper is as follows. First, a description of the link geometry and experimental setup is presented in Sec. 2. Sec. 3 provides a description of the data-processing procedure and power-statistics calculation. The results of the on- and off-axis scintillation and fading statistics from both experimental configurations are presented in Sec. 4. Finally, the results are discussed in Sec. 5 and the conclusions are presented in Sec. 6.

2. EXPERIMENTAL SETUP

2.1 Link Configuration and General Setup

This ground-based experiment was conducted over a 10.45 km terrestrial FSO link between the DLR site in Weilheim and Hohenpeissenberg, which is located on a hill near the Bavarian Alps. The link was established at an elevation angle of approximately 2° relative to the horizontal. Due to the increase in altitude relative to the ground along the propagation path, the laser beams are expected to traverse stronger turbulence at the beginning of their propagation, as the stronger turbulence is located closer to the ground. This change in atmospheric conditions enables the emulation of a satellite uplink scenario, where the laser beams initially pass through stronger turbulence.

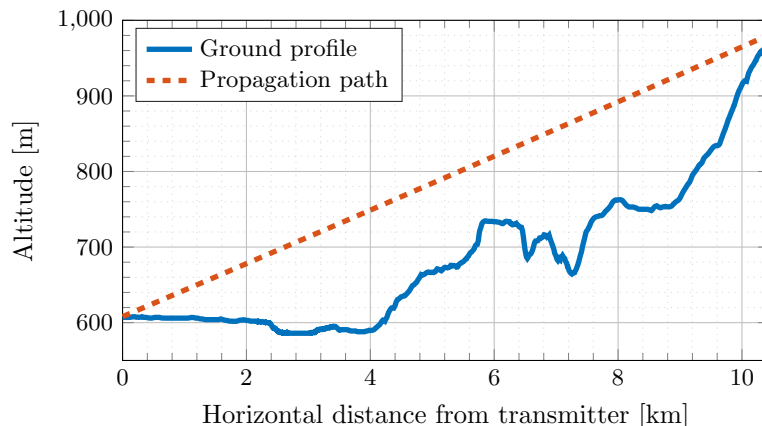


Figure 2. Ground profile and propagation path of the 10.45 km, 2° elevation FSO uplink.

The ground profile of the link, derived from Google Earth data referenced to the WGS84 ellipsoid,¹⁹ is illustrated in Figure 2. The red dashed line indicates the trajectory of the transmitted laser beams, showing the altitude change along the propagation path. The ground projection of the propagation path is predominantly located in rural terrain.

A schematic overview of the general experimental setup is illustrated in Figure 3. The transmitter system is shown on the left side, while the receiver and data acquisition system are at the right side. Further details regarding the transmitter and receiver setups are provided in Sec. 2.2 and 2.3, respectively.

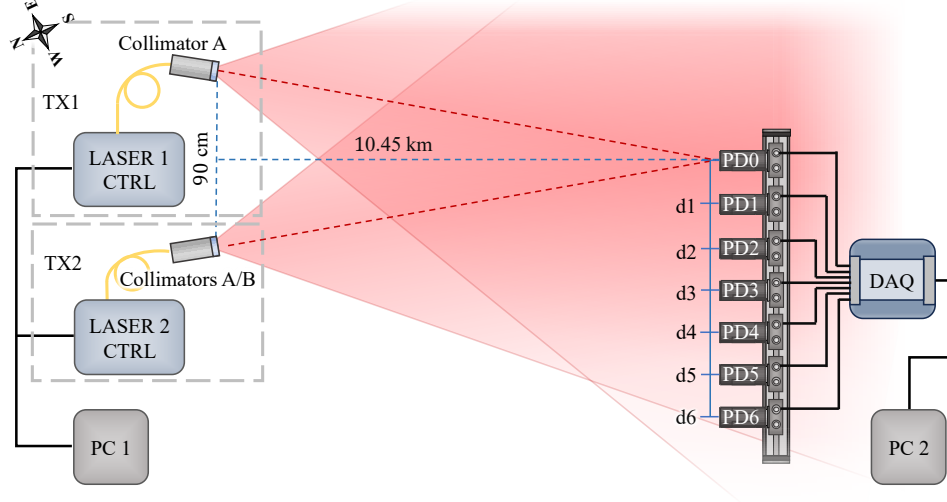


Figure 3. General experimental setup of the 10.45 km, 2° elevation FSO uplink.

2.2 Transmitter Setup

The transmitters are housed in a container. The transmitter setup (left side of Figure 3) consists of two independent continuous-wave (CW) laser sources (Laser 1 and 2), independently operated at the same nominal optical output power. Each laser module is mounted on a laser controller (“CTRL”) with temperature stabilization to minimize output power fluctuations caused by temperature changes in the lasers. These controllers are remotely controlled and monitored via a custom-developed LabVIEW software running on a dedicated computer (PC 1).

The single-mode optical fiber of each laser output is connected to a collimator. The combination of Laser 1 and Collimator 1 is labeled “Tx1”, and that of Laser 2 and Collimator 2 is labeled “Tx2”. The collimated output beams then propagate from Tx1 and Tx2 through free space along the slant path shown in Figure 2, where they are subject to distortion due to atmospheric turbulence. Two distinct collimators are used for this work (referred as “A” and “B” in Figure 4). The main characteristics of the laser transmitters and collimators are summarized in Table 1, where the divergence angle is given as the full width at half maximum (FWHM) value. The beam diameter is calculated based on the focal length of each collimator and a nominal mode field diameter of 10.4 μm for the optical fiber. The divergence angle is calculated by assuming a diffraction-limited collimated beam with ideal Gaussian beam quality. The collimator does not clip the output optical beam.

Both Tx1 and Tx2 are mounted on precision tip/tilt stages (see Figure 4) to enable fine pointing adjustments to align each transmitter to the same reference point at the receiver site. Each stage is mounted on a rigid aluminium support tube that is secured to a heavy tripod. To avoid mechanical vibrations that could affect pointing accuracy, the tripod is mounted directly on a solid surface, decoupling the transmitter setup from the container-induced vibrations.



Figure 4. Transmitter configuration.

Prior to each measurement, the two transmitters are aligned to the same reference photodetector at the receiver site. The laser alignment process is conducted in two stages, beginning with adjustments at the transmitter site and later refined with feedback from the receiver site. First, the alignment at the transmitter site is performed independently by roughly positioning the transmitters using a scope mounted parallel to the collimator (Figure 4). Fine alignment is achieved through a cross-scanning motion, adjusting horizontally and vertically until the reflection from a retroreflector foil positioned near the detectors is detected. This alignment is then optimized by observing the reflected beam’s intensity with the infrared camera at the transmitter site. Once the initial alignment is complete, the second stage begins by maximizing the received power by an infrared camera and the photodetectors at the receiver site. The collimators are fine-tuned based on real-time feedback from the measured power.

Table 1. Characteristics of the transmitter setup in Figure 4.

Parameter	Value
Distance between TX1 and TX2	90 cm
Lasers	
Wavelength	Laser 1: 1562.4 nm Laser 2: 1561.2 nm
Mean output power	50 mW
Modulation	Continuous Wave (CW)
Collimators	
Focal length	Collimator A: 150 mm Collimator B: 11.3 mm
Beam diameter ($1/e^2$)	Collimator A: 28.6 mm Collimator B: 2.2 mm
Full-beam divergence	Collimator A: 40.8 μ rad (FWHM) Collimator B: 542 μ rad (FWHM)
Clear aperture	Collimator A: 49 mm Collimator B: 7.2 mm

2.3 Receiver Setup and Data Acquisition

Upon reaching the receiver site, the atmospherically distorted optical beams are captured by seven identical photodetectors (“PD” on the right side of Figure 3) arranged horizontally along a rigid aluminium support (Figure 5). The horizontal position of the photodetectors can be adjusted, with PD0 serving as the reference point at 0 cm (all other photodetector positions are measured relative to this point). This spatial configuration enables the simultaneous measurement of off-axis mean power and optical fluctuations under the same atmospheric conditions. The key receiver characteristics are listed in Table 2.



Figure 5. Receiver configuration. Seven identical photodetectors are arranged horizontally to enable the measurement of off-axis power statistics. PD0 (Figure 3) is the photodetector located furthest to the right and is used as the reference point at 0 cm (all other photodetector positions are measured relative to this point). The cables connected to the photodetectors were secured after this photo was taken to prevent misalignment due to their movement.

Each photodetector is equipped with a lens tube housing a band-pass filter to block most of the background light and an achromatic lens, which focuses the incoming optical power onto the active area of the photodetector. The photodetectors feature switchable gain settings, allowing adjustment of the signal amplification to prevent saturation, especially under strong turbulence conditions where strong signal fluctuations occur. Adjusting the gain affects the bandwidth and power resolution of the system. The photodetectors convert the received optical signal into an electrical signal, which is then sampled by a data acquisition (DAQ) device. Signal acquisition is performed at 10 kS/s to fully capture fast signal fluctuations and fading events associated with atmospheric turbulence. The DAQ device is connected to a second computer (PC 2 in Figure 3), which timestamps and stores each measurement from each photodetector.

Table 2. Optical and data acquisition parameters of the receiver configuration in Figure 5.

Parameter	Value
Number of photodetectors	7
Optics	
Aperture size	20.7 mm
Band-pass filter	1550 nm $\pm$ 40 nm (99% transmission at 1560 nm)
Focal length of lens	31 mm
Field of view	65 mrad
Photodetectors and DAQ	
Active detector size	2 mm (diameter)
Bandwidth	260 kHz
Sampling frequency	10 kS/s
Power resolution	6.2 nW

Prior to the measurement campaign, the distance between photodetectors is fixed and each photodetector is carefully aligned to maximize the optical power incident on its active area. The elevation angle of all photodetectors is adjusted simultaneously via the aluminium profile mounted on a tripod. The azimuth angle of each photodetector is adjusted individually using its mount. These steps ensured consistent coupling conditions and reproducible power measurements throughout the experiments. To minimize the effects of direct solar irradiation, the receiver setup is placed under a movable tent. Throughout the campaign, the tent is repositioned as needed to shade all photodetectors, preventing temperature- and stray-light induced variations in their response.

2.4 Experimental Cases

Two different experimental configurations are presented. In the first configuration (Figure 6), Tx1 and Tx2 use different collimators (A and B in Table 1). In this case, the lasers operate in an alternating sequence to enable on- and off-axis power measurements caused by different divergence angles under the same turbulence conditions. The second configuration (Figure 7) uses identical collimators (A) for Tx1 and Tx2 to measure the impact of transmitter diversity. In this configuration, the lasers are operated similarly to the first configuration, with the addition that both lasers are switched on simultaneously before the next cycle begins. The lasers are controlled using the LabVIEW software. The main characteristics of these experimental configurations are summarized in Table 3.

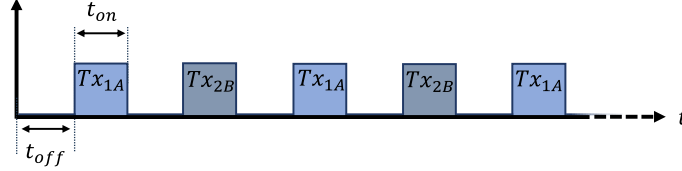


Figure 6. Experimental configuration 1: different divergence angles. Two different collimators are used: collimator A (40.8 μ rad FWHM) for Tx1 and collimator B (542 μ rad FWHM) for Tx2. The transmitters operate in alternating sequence with the same optical output power.

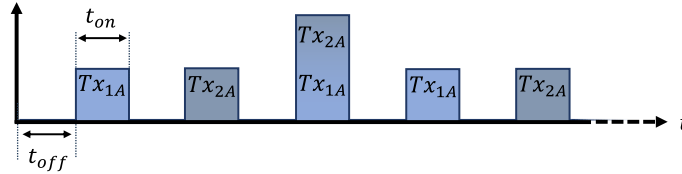


Figure 7. Experimental configuration 2: transmitter diversity. Identical collimators (40.8 μ rad FWHM) are used for both transmitters (Tx1 and Tx2). The transmitters operate in the following sequence: Tx1, Tx2, and Tx1 and Tx2 together. Both transmitters operate with the same optical output power.

Table 3. Summary of the two experimental configurations (EC) presented in this work.

Parameter	EC 1: different divergence angles	EC 2: transmitter diversity
Collimators used	Tx1: 40.8 μ rad (FWHM) Tx2: 542 μ rad (FWHM)	Tx1: 40.8 μ rad (FWHM) Tx2: 40.8 μ rad (FWHM)
t_{on}	11.5 s	11.5 s
t_{off}	2.5 s	2.5 s
PDs position (PD0 to PD6)	0, 20, 50, 80, 110, 150, 190 cm	0, 10, 20, 35, 50, 150, 190 cm

The results presented in this work are obtained from data collected during two experiments conducted under daylight conditions, during which background illumination contributes to the received signal. To measure the effects of background light and photodetector electronic noise and offset, the laser transmitters are switched off during measurement intervals. The measured offset, captured during the “off” cycles, is then subtracted from the corresponding “on” cycle signal, as described in Sec. 3.1. The on-cycle durations are extended beyond the desired 10 seconds to accommodate for possible response delays in the laser control software and laser controllers (t_{on} in Table 3).

3. DATA ANALYSIS

3.1 Power Vectors Preprocessing

For each measurement, the signal offset, due to background light and photodetector electronic offset and noise, is measured during the off-cycles (t_{off} in Figures 6 and 7). The offset is determined from the mean of the 100 ms acquired immediately before and after the signal measurement. The change on the mean offset is modeled with a linear approximation and is subtracted from the measured signal. This procedure is applied independently to each on-cycle of every photodetector measurement. This correction minimizes the influences of environmental and hardware noise, resulting in a power signal that reflects only the received optical signal from the laser sources.

After offset subtraction, the voltage signal is converted to optical power considering the photodetector's responsivity and amplifier gain. Individual 10-second-long on-cycle power vectors are then concatenated to form a continuous power vector of certain temporal duration. From this power vector, long-term power and fading statistics are calculated.

3.2 Power Statistics Metrics

The power fluctuations are quantified by the power scintillation index (PSI), which is the normalized power variance. The PSI is defined as

$$\sigma_P^2(t) = \frac{\langle P^2(t) \rangle - \langle P(t) \rangle^2}{\langle P(t) \rangle^2} = \frac{\langle P^2(t) \rangle}{\langle P(t) \rangle^2} - 1 \quad (1)$$

where $P(t)$ is the power at time t , and $\langle \rangle$ denotes average. The PSI is calculated for the received signal at each photodetector, considering that photodetector's mean power ($\langle P(t) \rangle$). Due to the rapid temporal fluctuations of the received optical signal, the PSI calculation is sensitive to the length of the analyzed power vector. To ensure consistent long-term power statistics comparisons across detectors and transmitter configurations, the results are derived from 100-second-long power vectors.

Power fluctuations due to atmospheric turbulence can drive the received signal below a predefined power threshold (P_T), leading to signal fades that cause signal loss. The probability of such fades occurring can be calculated from the cumulative distribution function of the received power with Equation (2), where $p(P)$ is the probability distribution function (PDF) of the received power.

$$P_F(P \leq P_T) = \int_0^{P_T} p(P) dP \quad (2)$$

When low power levels are received, the offset becomes comparable to the received power signal, making the power statistics calculation more sensitive to offset estimation errors. In this case, quantization errors from the analog-to-digital converter (ADC) in the DAQ, electronic noise in the photodetectors, and changes in background light can impact the received power statistics. In this work, the uncertainty of the mean power and power scintillation index are estimated by propagating the uncertainty associated with the offset estimation. The difference between the nominal (unperturbed) and the perturbed values is used to estimate the standard (1σ) uncertainty. This procedure assumes a linear variation of the background light during the on-cycle. Consequently, different offset subtraction methods can influence the resulting uncertainty estimate. The standard offset uncertainty is estimated by combining the standard error of the mean offset and the ADC quantization uncertainty and it is calculated as

$$\epsilon_{1\sigma} = \sqrt{SEM_{before}^2 + SEM_{after}^2 + 2u_q^2} \quad (3)$$

where SEM is the standard error of the mean of the analyzed 100-ms-long off-cycle vector immediately before or after the on-cycle of interest and u_q is the standard quantization uncertainty of the ADC considering a uniform distribution ($LSB/\sqrt{12}$), with LSB being the least significant bit value in Volts).²⁰

4. RESULTS

The results for the first and second experimental configuration are presented in Sec. 4.1 and 4.2, respectively. Table 4 shows the temperature, pressure and humidity values recorded at the transmitter and receiver sites during each measurement.

Table 4. Environmental measurements (temperature, pressure, and humidity) recorded at the transmitter and receiver sites under constant solar irradiation with no cloud cover. The reported values are the average over the measurement period, with the superscript and subscript indicating the maximum and minimum deviations from the mean, reflecting the short-term environmental changes. Data collected for the experimental configuration 1 (19.08.2025 13:08–13:14 local time) and 2 (18.08.2025 13:53–14:01 local time).

Parameter	EC 1: different divergence angles	EC 2: transmitter diversity
Temperature [°C]	TX: $28.3^{+0.2}_{-0.5}$	TX: $27.2^{+0.2}_{-0.1}$
	RX: $26.6^{+0.1}_{-0.1}$	RX: $25.9^{+0.1}_{-0.1}$
Pressure [mbar]	TX: $944.3^{+0.1}_{-0.2}$	TX: $947.3^{+0.1}_{-0.1}$
	RX: $904.3^{+1.1}_{-1.1}$	RX: $907.1^{+0.0}_{-0.1}$
Humidity [%]	TX: $45.8^{+0.9}_{-1.6}$	TX: $43.5^{+0.6}_{-0.3}$
	RX: $61.5^{+2.2}_{-1.6}$	RX: $60.1^{+1.7}_{-1.8}$

4.1 Experimental Configuration 1: Different Divergence Angles

The received power time series for the first experimental configuration (Table 3) is shown in Figure 8. The signal offset was already removed as described in Sec. 3.1. Although both transmitters have the same output power at the source (Figure 6), differences in received power are observed at the receiver primarily due to free-space loss, resulting from beam spreading at different divergence angles.

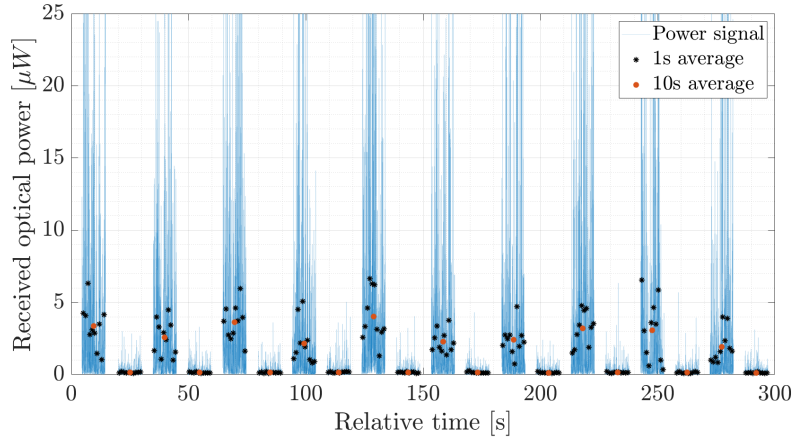


Figure 8. Mean received optical power detected at PD0 (at position 0 cm) for the experimental configuration 1, which uses different divergence angles at the transmitter site (Figure 6). The mean power calculated for 1-second and 10-seconds-long vectors is shown as black and red dots, respectively, plotted at the midpoint of each vector. The figure has been zoomed in. Due to power fluctuations, the peak received power reaches $120.1 \mu W$.

For long-term statistics, 100-second-long vectors are concatenated. Figure 9 presents the mean received optical power at each photodetector distance. The drop in power with radial distance is more noticeable for Tx1

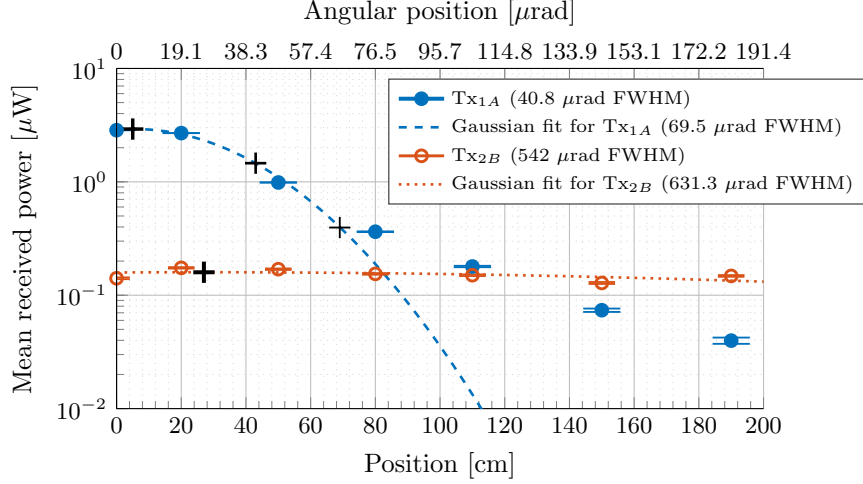


Figure 9. Mean received optical power of 100-second-long power vector. Horizontal error bars represent the 1σ uncertainty due to background offset estimation. The maximum mean power detected is $2.85 \mu\text{W}$ for Tx1 (at PD0 at position 0 cm) and $0.17 \mu\text{W}$ for Tx2 (at PD1 at position 20 cm). Dashed lines indicate the best Gaussian fit for the measurement data. The black crosses indicate (from left to right) the maximum, half and $1/e^2$ of the peak beam value, as estimated from the Gaussian fit. In the case of Tx2, only the center of the beam is indicated because of the wide beam spot caused by the large divergence angle.

because of its smaller divergence angle. The error bars indicate the 1σ uncertainty due to the standard offset uncertainty (Equation 3).

The power fluctuations for each photodetector measurement is quantified with the PSI -Equation (1)- and shown in Figure 10. Higher on- and off-axis PSI values are observed for the transmitter with the narrower divergence angle, as well as an increase in PSI with radial distance. For this measurement, a drop in PSI values is observed when the received power is less than 6.3% of the maximum detected power (at PD4 at position 110 cm).

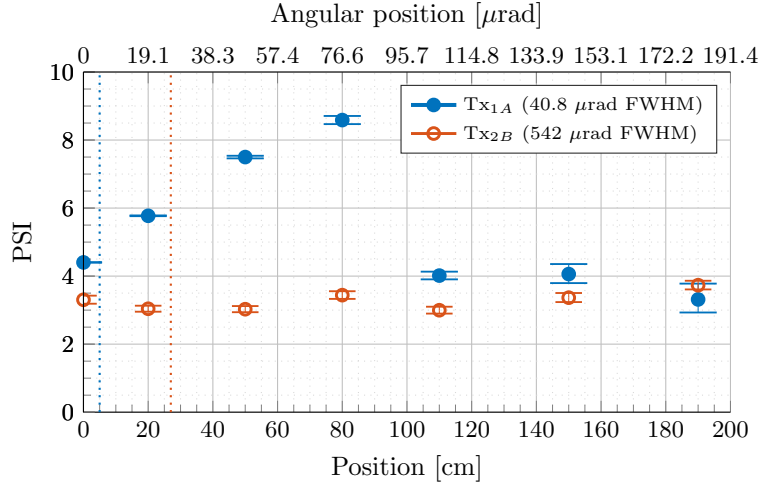


Figure 10. Power scintillation index calculated from 100-second-long power vector. Horizontal error bars represent the standard uncertainty due to background offset estimation. Vertical lines indicate where the theoretical beam center for each transmitter is located (Figure 9).

The mean number of fades that occur per second and their mean duration are shown in Figures 11 and 12, respectively. Two power thresholds (-3 dB and -6 dB) relative to the mean received power at each photodetector

(Figure 9) are considered. It is evident that, for Tx1 (narrower divergence angle), the frequency of fades increases with the distance from the center of the beam, while their duration decreases (Figure 12).

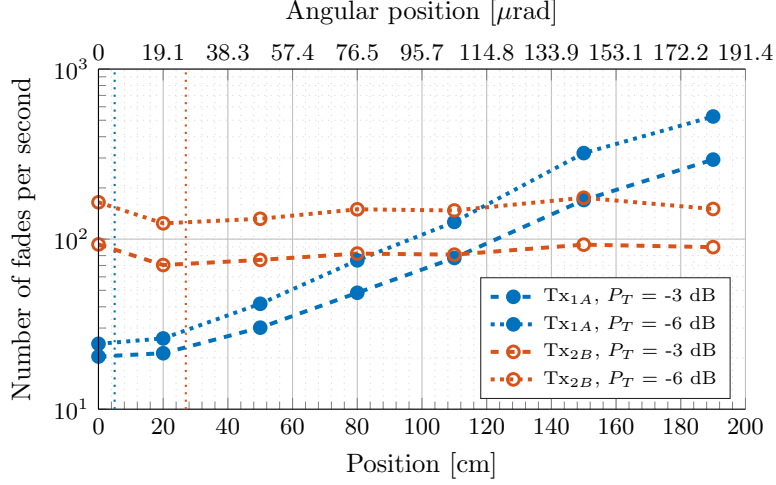


Figure 11. Mean number of fades per second for Tx1 ($40.8 \mu\text{rad}$ FWHM) and Tx2 ($542 \mu\text{rad}$ FWHM) for two different power thresholds relative to the mean received power at each photodetector. Vertical lines indicate where the theoretical beam center for each transmitter is located (Figure 9).

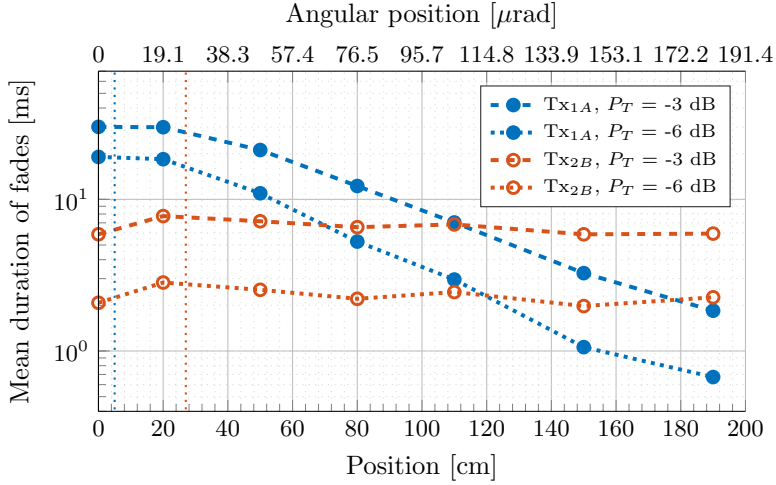


Figure 12. Mean duration of fades for Tx1 ($40.8 \mu\text{rad}$ FWHM) and Tx2 ($542 \mu\text{rad}$ FWHM) for two different power thresholds relative to the mean received power at each photodetector. Vertical lines indicate where the theoretical beam center for each transmitter is located (Figure 9).

The power distribution of the received optical power for each transmitter is obtained using a kernel density estimation and is shown in Figure 13. Although both PDF curves are normalized to a mean of one, differences are visible. For Tx2 (wider divergence angle), the mean received power and the PSI remain relatively constant across off-axis positions (see Figures 9 and 10). Therefore, the PDF of the received power is nearly invariant with radial distance. On the contrary, for Tx1 (narrower divergence angle), the PDF of the absolute power values shifts towards lower values at greater radial distances. This leads to an increased probability of fading at off-axis locations. Figure 14 shows the probability of signal fading for two power thresholds: -3 dB and -6 dB relative to the maximum mean power detected for each transmitter. Both divergence angles have a similar probability of

fading at the on-axis location. However, the probability rapidly increases at off-axis positions for the narrowest divergence angle.

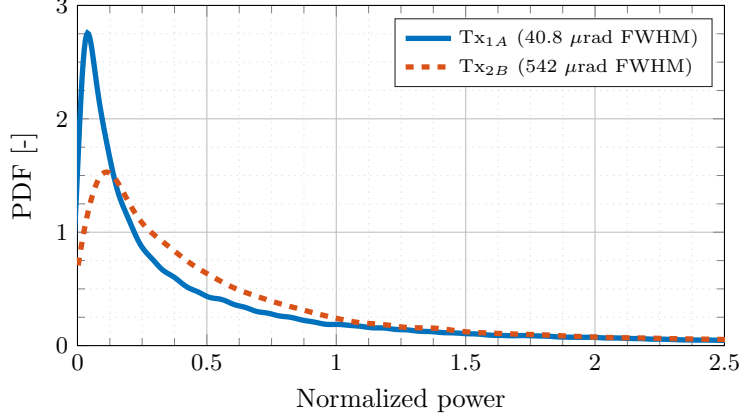


Figure 13. Probability density function of the optical power received at the first photodetector (PD0 at position 0 cm) for Tx1 and Tx2. Both PDF curves are normalized to a mean of one to highlight the differences of power distribution for two different beam divergence angles under the same atmospheric conditions.

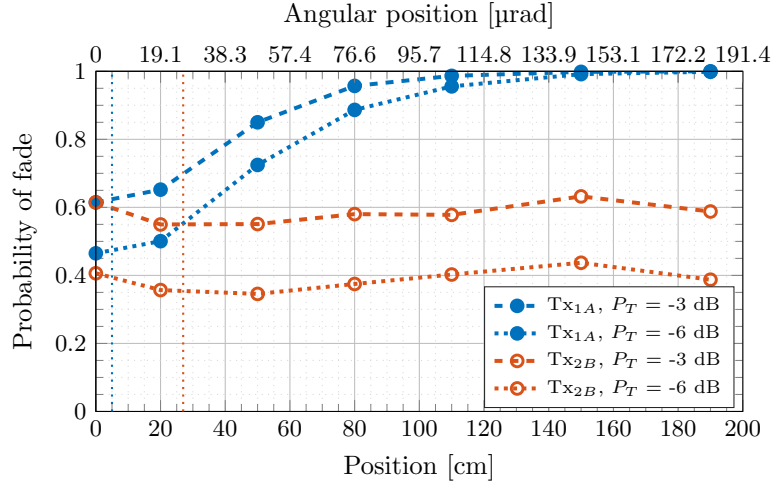


Figure 14. Probability of fade for power thresholds of -3 dB and -6 dB relative to the maximum mean received power detected for each transmitter (2.85 μ W for Tx1 and 0.17 μ W for Tx2) for Tx1 (40.8 μ rad FWHM) and Tx2 (542 μ rad FWHM). Vertical lines indicate where the theoretical beam center for each transmitter is located (Figure 9).

The correlation time is calculated from the autocovariance function as the lag at which the autocovariance value drops to half of its maximum. For Tx1 (narrowest divergence angle), a decrease in correlation time with increasing radial distance from the center of the beam is evident, with values of 10.5 ms at position 0 cm, 10.7 ms at 20 cm, 8.4 ms at 50 cm, 6.3 ms at 80 cm, and 6.2 ms at 110 cm. For Tx2 (larger divergence angle), the correlation time varies from 7.8 ms to 9.2 ms without a clear trend, with a mean of 8.6 ms across all positions.

4.2 Experimental Configuration 2: Transmitter Diversity

The received power time series for the second experimental configuration (Table 3) are shown in Figure 15. The signal offset was removed as described in Sec. 3.1. Both transmitters have the same output power (Figure 7). Therefore, when both transmitters are switched on at the same time, the power is double.

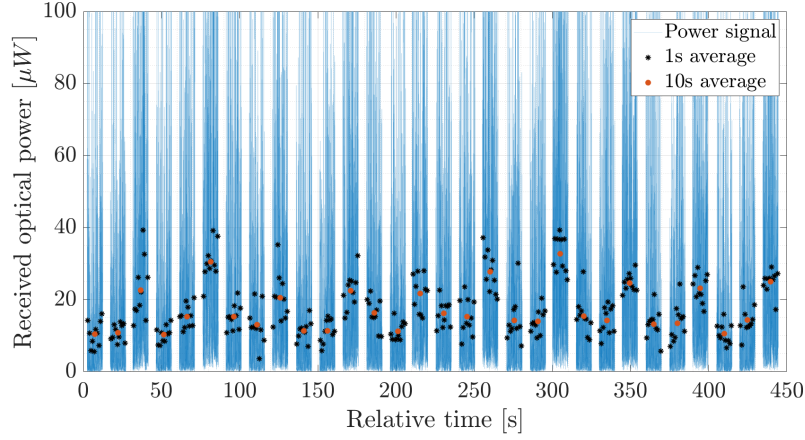


Figure 15. Received optical power for experimental configuration 2: transmitter diversity (Figure 7). Power received at the position where the maximum mean power was detected (by PD3 at position 35 cm). The figure has been zoomed in to show the mean power of 1- and 10-second-long power vectors (black dots and red circles, respectively, plotted at the midpoint of each vector). Due to power fluctuations, the peak received power reaches $207.2 \mu W$.

The mean power for the 100-second-long power vector is shown in Figure 16. The mean received power roughly doubles when both transmitters are switched on. The best Gaussian fit for the measurement data is shown in dashed lines. As expected, the beam profile of the received beam is similar for both transmitters.

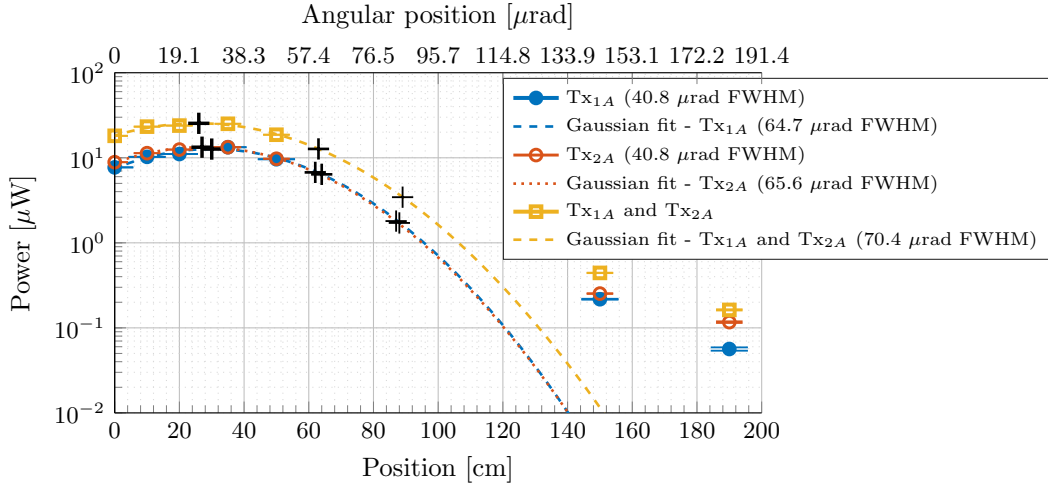


Figure 16. Mean received optical power of 100-second-long power vector. Horizontal error bars represent the 1σ uncertainty due to background offset estimation. The maximum mean power is detected by the photodetector at position 35 cm, with values of $13.32 \mu W$ for Tx1, $13.33 \mu W$ for Tx2, and $25.11 \mu W$ when Tx1 and Tx2 operate simultaneously. Dashed lines indicate the best Gaussian fit to the measurement data. The black crosses indicate (from left to right) the maximum, half and $1/e^2$ of the peak beam value, as estimated from the Gaussian fit of the received optical beam.

The power fluctuations at each off-axis position (Figure 17) are quantified with the PSI, calculated with Equation (1). An increase in off-axis PSI is observed for both transmitters, as well as when both transmitters operate simultaneously. It is evident that the PSI is reduced across all positions when transmitter diversity is used. In the region near the center of the beam, the PSI decreases to approximately half the value of that observed for a single transmitter. A decrease in PSI is observed for off-axis positions farther away from the beam center, particularly in the tail region, similar to the PSI observed in the first experimental configuration (Figure 10).

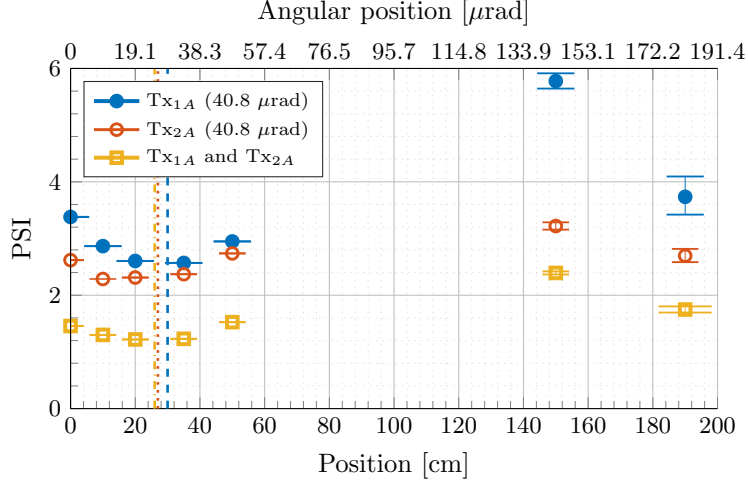


Figure 17. Power scintillation index calculated from 100-second-long power vector. Horizontal error bars represent the standard uncertainty due to background offset estimation. Vertical lines indicate where the theoretical beam center for each transmitter is located (Figure 16).

The mean number of fades per second and their duration are shown in Figures 18 and 19. The -3 dB and -6 dB values below the mean received power at each photodetector (Figure 16) are considered as power thresholds. Due to the proximity of the photodetectors, the change in fading statistics is less evident near the center of the beam compared to the first experimental configuration (Figures 11 and 12). However, at positions farther from the on-axis, an increase in the number of fade events and a decrease in their mean duration are observed.

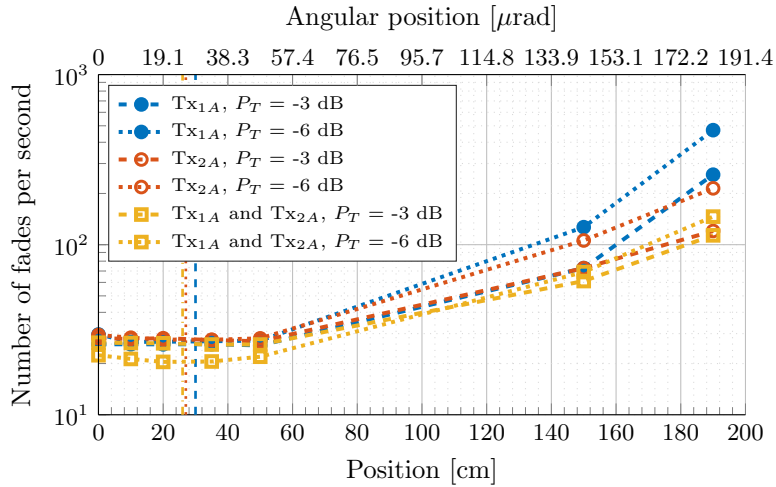


Figure 18. Mean number of fades per second for two different power thresholds relative to the mean received power at each photodetector. Tx1 and Tx2 have identical collimators ($40.8 \mu\text{rad}$ FWHM). Vertical lines indicate where the theoretical beam center for each transmitter is located (Figure 16).

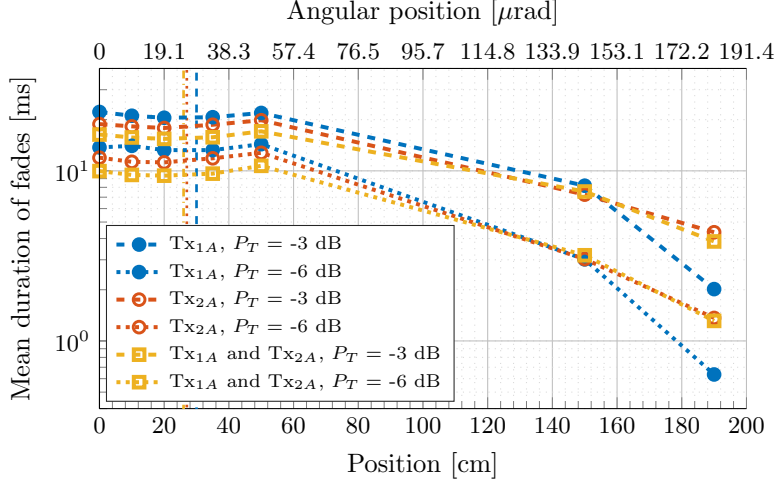


Figure 19. Mean duration of fades for two different power thresholds relative to the mean received power at each photodetector. Tx1 and Tx2 have identical collimators ($40.8 \mu\text{rad}$ FWHM). Vertical lines indicate where the theoretical beam center for each transmitter is located (Figure 16).

The probability density function of the received optical power, obtained using a kernel density estimation, is shown in Figure 20. All PDF curves are normalized to a mean of one. The power distributions for Tx1 and Tx2 are similar. It is evident that, under transmitter diversity, the probability of observing very low or high power values decreases, consistent with a reduction in power fluctuations (Figure 17).

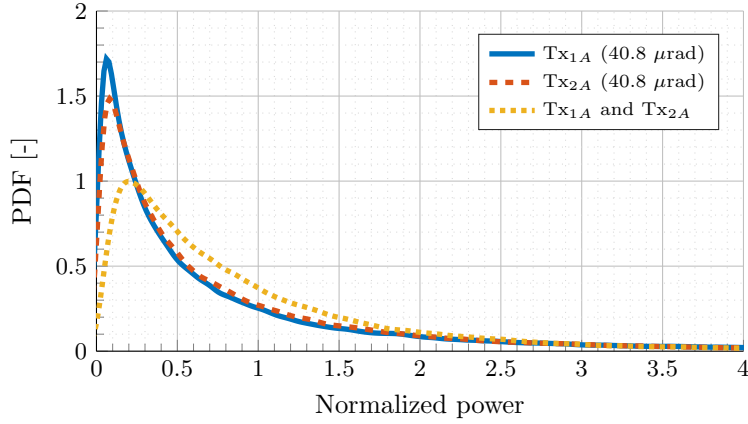


Figure 20. Probability density function of the optical power received at the position where the maximum mean power was detected (PD3 at position 35 cm). All curves are normalized to a mean of one to emphasize the differences in power distribution under transmitter diversity.

The probability of the signal falling below a fixed power threshold increases with off-axis positions from the center of the beam (Figure 21). Power thresholds of -3 dB and -6 dB relative to the maximum mean power detected for each transmitter are used to quantify the fading events. The correlation time, calculated as the lag at which the autocovariance function decays to half of its peak value, is found to be approximately 8.2 ms for Tx1, 8 ms for Tx2, and 8.4 ms for transmitter diversity across positions from 0 to 55 cm.

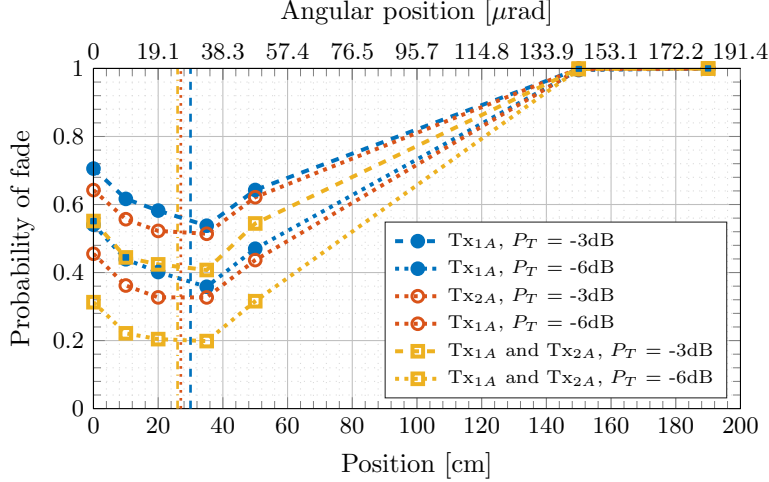


Figure 21. Probability of fade for power thresholds of -3 dB and -6 dB relative to the maximum mean received power detected for each transmitter (13.32 μW for Tx1, 13.33 μW for Tx2, and 25.11 μW when Tx1 and Tx2 operate simultaneously). Tx1 and Tx2 have identical collimators (40.8 μrad FWHM). Vertical lines indicate where the theoretical beam center for each transmitter is located (Figure 16).

5. DISCUSSION

Two experimental configurations are presented. The first allows for a comparison of the power statistics resulting from the use of collimated beams with different divergence angles (40.8 and 542 μrad FWHM) under same atmospheric conditions. The second configuration enables the evaluation of the impact on power statistics when using one or two transmitters. To account for signal offsets due to background light and receiver noise and offset, the offset signal is measured before and after each on-cycle (Figures 6 and 7) and later subtracted from the received signal. The resulting signal is used to calculate the on- and off-axis scintillation and fading statistics of 100-second-long power vectors.

If there were no atmospheric turbulence, the beam spot at the receiver site would be expected to be around 43 cm and 5.7 m (FWHM), respectively. However, for the narrowest beam divergence, the beam spot measured at the receiver appears to have a larger divergence angle when fitting the mean power measurements with a Gaussian profile (Figures 9 and 16). This suggests additional beam spread beyond diffraction only, caused by beam wander. Despite transmitting the same power in both experiments, the mean received power is lower in the first configuration (Figures 9 compared to 16). This is attributed to greater power loss caused by greater beam wander, as evidenced by higher scintillation (Figures 10 compared to 17) and larger beam divergence of the received optical beam.

It is evident that, under the same atmospheric conditions, a narrower beam divergence leads to higher scintillation, even at on-axis positions (Figure 10), which is attributed to beam-wander-induced scintillation. This is consistent with theoretical and simulation models, which predict increased scintillation for larger beam diameters (narrower beam divergence angles), contrary to the predictions of conventional Rytov theory.^{1,2,4} An increase in the scintillation index is observed until the off-axis power drops to 12.7% of the maximum peak value (Figures 10 and 17). Beyond this point, a saturation in scintillation is observed in the tail regions of the received beam when the mean received power is at least 6.3% of the peak value. This indicates that, for these experimental results, scintillation increases within the region enclosed by the $1/e^2$ beam diameter of the received optical beam, when approximated to a Gaussian profile. Within this region, the measurement data shows a good fit to a Gaussian profile (Figures 9 and 16).

For the first experimental configuration (different divergence angles), reducing beam divergences increases the mean received power at the center of the beam. It is observed that both divergence angles exhibit similar probability of fade at on-axis position (Figure 14). However, for a narrower beam divergence, fades are less frequent and longer within the region enclosed by the $1/e^2$ beam diameter of the received optical beam (Figures

11 and 12). Additionally, smaller angular misalignments result in stronger fluctuations, a higher probability and number of fades, and a decrease in the mean duration of fades with increasing off-axis distance. This indicates more probable, frequent and rapid fading events at larger radial distances from the center of the beam.

For the second experimental configuration (transmitter diversity), despite the collimators being identical, the PSI of Tx1 is higher than that of Tx2 (see Figure 17). This may be due to temperature variation caused by Tx1 being closer to the heated southeast wall (see Figure 3), or to possible slight differences in beam divergence or quality. In the case of transmitter diversity, a small decrease in the mean duration of fades is observed compared to a single transmitter (Figure 19). A reduction in the number of fades is evident only when the power threshold is -6 dB relative to the mean received power (Figure 18). A decrease in probability of fade is clear for both power thresholds (-3 dB and -6 dB relative to the mean power), with a constant reduction of at least 0.11 in regions close to the beam center when transmitter diversity is used (Figure 21).

The purpose of this campaign was to evaluate the impact of different divergence angles and transmitter diversity on optical uplinks to LEO satellites. The inclined 10.45 km FSO link presented in this work emulates a satellite uplink. However, the temporal behaviour during real LEO uplinks is expected to be more severe due to the slow rate of the satellite. Using smaller divergence angles increases the mean received power at the receiver. However, these results show that, under strong turbulence conditions, misalignments in the uplink beam caused by pointing errors⁹ can lead to stronger power fluctuations induced by beam wander and more frequent, rapid fades that cause signal loss. To further reduce data loss, other techniques such as forward-error correction and interleaving could be implemented. It has been demonstrated that transmitter diversity can effectively reduce the magnitude of power fluctuations and the probability of fading, and slightly reduce the mean duration of fades, making it a suitable technique for optical uplinks.

6. CONCLUSION

The experimental results confirm that narrower beam divergence angles lead to higher scintillation indices, increasing at off-axis positions, due to increased susceptibility to atmospheric turbulence and beam wander. This trend aligns with theoretical predictions and simulations, but this study provides (to the best of our knowledge) the first empirical validation of off-axis power statistics over a long-distance (10.45 km) terrestrial link emulating a satellite uplink. Additionally, we show that transmitter diversity using two uncorrelated transmitters reduces the scintillation index by approximately 50%, mitigating fading events. This finding is consistent with prior theoretical work on diversity techniques but extends it to real-world conditions with strong turbulence, as encountered in uplinks to satellites at low elevations. Compared to earlier uplink experiments, such as the DLR-Artemis GEO link or NICT's OICETS LEO demonstrations, this study uniquely focuses on off-axis scintillation and fading statistics, which are critical for misaligned or dynamically-tracked satellite links.

For satellite uplinks, particularly for LEO constellations, these results highlight the importance of optimizing beam divergence and employing transmitter diversity to counteract the severe scintillation and beam wander encountered at low elevation angles. The results presented in this work suggest that transmitter diversity could be a practical solution to improve link reliability without sacrificing data rates, as narrower beams (which enable higher rates) can be mitigated against turbulence-induced fluctuations through diversity. This is especially relevant for future high-throughput optical feeder links, where atmospheric-induced fading remains a major bottleneck. Prior experiments, such as NICT's HICALI or DLR's KIODO missions, have tested diversity with flat-top beams, whereas our use of Gaussian beams provides complementary insights for systems where collimated Gaussian profiles are preferred.

Future work should explore the scalability of transmitter diversity beyond two sources, as well as the integration of adaptive optics or hybrid beam profiles (e.g. combining Gaussian and flat-top beams) to further suppress scintillation. Additionally, complementing these experiments under varying atmospheric conditions, such as different turbulence strengths (C_n^2 profiles) or elevation angles, would help generalize the findings for diverse satellite link scenarios. Future work could investigate how the spatial distribution of turbulence along the path affects off-axis scintillation, particularly in comparison between GEO and LEO uplink scenarios. Finally, incorporating real-time tracking and point-ahead angle correction into the experimental setup would bridge the gap between terrestrial emulation and operational satellite links, providing actionable data for next-generation FSO system design.

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