

UltraAir Airborne-to-GEO Optical Communications Demonstrator: Fading Channel Characterization

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ABSTRACT

With the emergence of mega-constellations in recent years, space assets are becoming ubiquitous, enabling networked connectivity through optical inter-satellite links. Laser communication terminals (LCTs) deployed on these new generations of satellites offer the possibility of connecting user platforms via optical links. Recently, Airbus, Tesat, and TNO successfully demonstrated for the first time a Gbit/s laser link between an aircraft and a GEO satellite. Based on the data collected during this unique measurement campaign, we characterize the optical atmospheric channel from the perspective of fading statistics for the optical received power under different conditions, both in the downlink and uplink. This analysis offers valuable experimental data, particularly useful for sizing forward error correction (FEC) codes, long interleavers for a proper system sizing ensuring a link that can reliably support communications during severe atmospheric perturbations. Moreover, by analyzing the PSD of the optical receiver power in both downlink and uplink regimes, we identify the main contributing effects on the time-varying irradiance of the signal-carrying laser beam. In summary, this campaign provides an analysis of a rare, high-fidelity dataset that captures the full stochastic behavior of an airborne-space laser link under realistic atmospheric conditions. By extracting several metrics, for both uplink and downlink, we deliver a comprehensive channel model.

Keywords: airborne optical satellite communication, atmospheric turbulence, channel model.

1. INTRODUCTION

Recent years have seen a steady increase of space infrastructure equipped with optical communication capabilities, mostly driven by LEO constellation projects. Such space networks make use of laser communication terminals (LCT) to provide connectivity between their nodes. Although, optical communication solutions—also refer to as lasercom—for airborne platforms have been proposed for many years, it is only now with the advent of LCT enabled space infrastructure that the major barrier for its operational deployment is being significantly lowered. Constellations such as the US Proliferated Warfighter Space Architecture (PWSA) and European alternatives like IRIS² and Hydron-DS are including among their expected use cases connectivity from airborne platforms to their space infrastructure via laser. Nevertheless, airborne lasercom remains challenging due to the very nature of the implementation environment, where not only the atmospheric turbulence regime is different from the more common ground-space links, but the LCT host platform presents additional challenges. These stem mainly from the high vibration environment to be found in flying platforms, which requires a very performant pointing, acquisition and tracking (PAT) system, and has a direct impact on stability of the data carrying laser signal.

Recently in Q4 of 2025, Airbus, Tesat, and TNO successfully demonstrated for the first time a Gbit/s laser link between a Falcon-20 aircraft and Alphasat GEO satellite's Technology Demonstration Payload (TDP-1), in the framework of the UltraAir project [1]. The general experiment conditions are described in Section 2. Based on the data collected during this unique measurement campaign, Section 3 presents a fading channel characterization analysis, from the perspective of fading statistics under different conditions, including scintillation index, fade duration distribution of the optical received power; along with its power spectral density (PSD) and probability density function (PDF). Finally, Section 4 summarizes the main achievement and conclusions of the technical assessment performed in this work.

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2. EXPERIMENT SETUP

The UltraAir flight measurement campaign was conducted between 6 and 16 December 2025, demonstrating a bidirectional optical link between an airborne LCT (ALCT) and TDP1 onboard the geostationary satellite Alphasat. The campaign utilized a Dassault Falcon 20 aircraft, operated by AVdef, departing from Nîmes, France, with flight operations conducted over the Mediterranean Sea in Southern France. The aircraft was equipped with the Airborne Laser Communication Terminal (ALCT), installed within the cabin with the optical beam exiting through a custom fused silica window integrated into an emergency exit door.

The measurement campaign was composed of nine flights, with 33 optical link opportunities, successfully achieving acquisition and tracking in 31 of them—each between 6 to 14 minutes long. Prior to the flight campaign, a comprehensive ground-satellite campaign was conducted between September and December 2024 from the ESA Optical Ground Station (OGS) on Tenerife, Spain. This ground-based campaign served as a critical system validation and operational rehearsal, verifying terminal performance, link acquisition procedures, and operational workflows under realistic atmospheric conditions. The ground-satellite tests established baseline performance metrics and validated the PAT algorithms subsequently employed during the airborne campaign.

The demonstration employed two laser communication terminals operating at the CCSDS standard wavelength of 1064 nm. The ALCT embarked on the aircraft has an aperture diameter of 100 mm, designed with a maximum transmit power of 20 W. During flight operations, the transmit power was operated at an operational limit of 12 W average power due to laser eye-safety considerations. The TDP1 payload onboard Alphasat has a receiving aperture diameter of 135 mm, transmitting a 2.2 W nominal power.

Telemetry data was recorded at high sampling rates to capture the rapid fluctuations induced by atmospheric turbulence and aircraft vibrations. The ALCT fine detector recorded received optical power at a sampling rate of 20 kHz, providing detailed temporal resolution of the downlink signal dynamics. The TDP1 terminal provided telemetry at 25 kHz sampling rate for the uplink received power. The primary measurement parameter for analysis in this work is the optical received power referenced to the terminal's entrance pupil, measured independently at both the ALCT and TDP1 terminals. All telemetry data was time-synchronized using GPS timestamps to enable precise correlation between uplink and downlink measurements.

3. DATA ANALYSIS

This section presents first a data analysis on the PSD and PDF of the optical received power, for which data sections of 30 s were extracted for the corresponding links being analyzed. After data inspection, this time window was deemed as large enough to capture the stochastic process of interest, while maintaining relative stable conditions in the channel behavior characteristics. For the fade event analysis, a time window of 160 s is a good compromise—in particular for the uplink channel—in order to capture enough deep fades events for a statistically relevant assessment.

3.1 Power Spectral Density

In this section, an analysis of the PSD behavior both in the downlink and uplink during the measurement campaigns is presented. Moreover, a comparison is presented between the channel characteristics observed when the ALCT was used for ground-space links, and with the ALCT embarked in the flight test aircraft. Figure 1 below presents the PSD for all scenarios analyzed.

3.1.1 Ground-Space links

Figure 1(a) and (b) show the experimental PSD during ground-space links for both the downlink and uplink, respectively. In the downlink direction, the expected PSD shape is observed with a flat f^0 behavior for the low frequency (LF) part of the spectrum up to about 20 Hz. The flat response in the Power Spectral Density (PSD) comes from blending different wind speeds and directions across multiple atmospheric layers. Next, a transition to the very well-known power law $f^{-17/3}$ for the inertial range of turbulence kicks in. In the mid-frequency (MF) range, from about 100-200 Hz onwards, a different slope is observed, which can be attributed to the PAT system plus detector noise performance.

In the low-frequency (LF) region, the uplink vector exhibits a typical slope of $f^{-2/3}$ due to tip-tilt, followed by an $f^{-11/3}$ power law. It is noteworthy that this transition in slope for tip-tilt has also been reported before by Conan *et al.* [2]. It is noteworthy that a $f^{-17/3}$ law is also observed in a rather narrow MF region around 100 Hz. This particular PSD shape clearly highlights that the uplink channel is dominated by atmospheric beam wander effects, as the vibration spectra of the

transmitter on ground is expected to be negligible. Finally, in the high frequency (HF) region from about 2 kHz the spectrum becomes practically flat potentially indicating the noise floor limit of the photodetection system on TDP1.

3.1.2 Aircraft-Space links

In the bottom row of Figure 1, both the downlink and uplink PSD are plotted for the aircraft-space links during the flight test campaign. Additionally, a critical frequency f_c marking the transition between the aperture averaged behavior and the inertial range of turbulence effects is shown with a vertical red dashed line. This frequency is directly calculated from the aircraft measured airspeed V and the ALCT aperture diameter D , using the expression given by Conan [2]

$$f_c = 0.3V/D. \quad (1)$$

In the downlink four regimes are clearly identified. Starting with the $f^{-2/3}$ slope due to tip-tilt observed in the LF up to about 10 Hz, which would be mostly attributed to platform micro-vibrations. In the MF region, the classical flat f^0 scintillation behavior in the downlink up to the critical frequency f_c , estimated at ca. 479 Hz, followed by the characteristic $f^{-17/3}$ coming from the atmospheric inertial range as expected from the Kolmogorov theory. A couple of spikes are found in this region indicating a resonant effect coming from the PAT system and its control loop, as these are found both in space-to-aircraft and space-to-ground links—see Figure 1(a) and (c). For HF above 2 kHz, a change in the PSD slope is observed, which follows the same empirically measured PSD behavior for the residual tracking error [3] (See Fig. 12 therein). Moreover, the fact that this behavior is very similar to that observed in the ground-space downlink channel, as depicted in Figure 1(a), reinforces the assessment made in Sec. 3.1.1 that the slope observed is related to the PAT system performance.

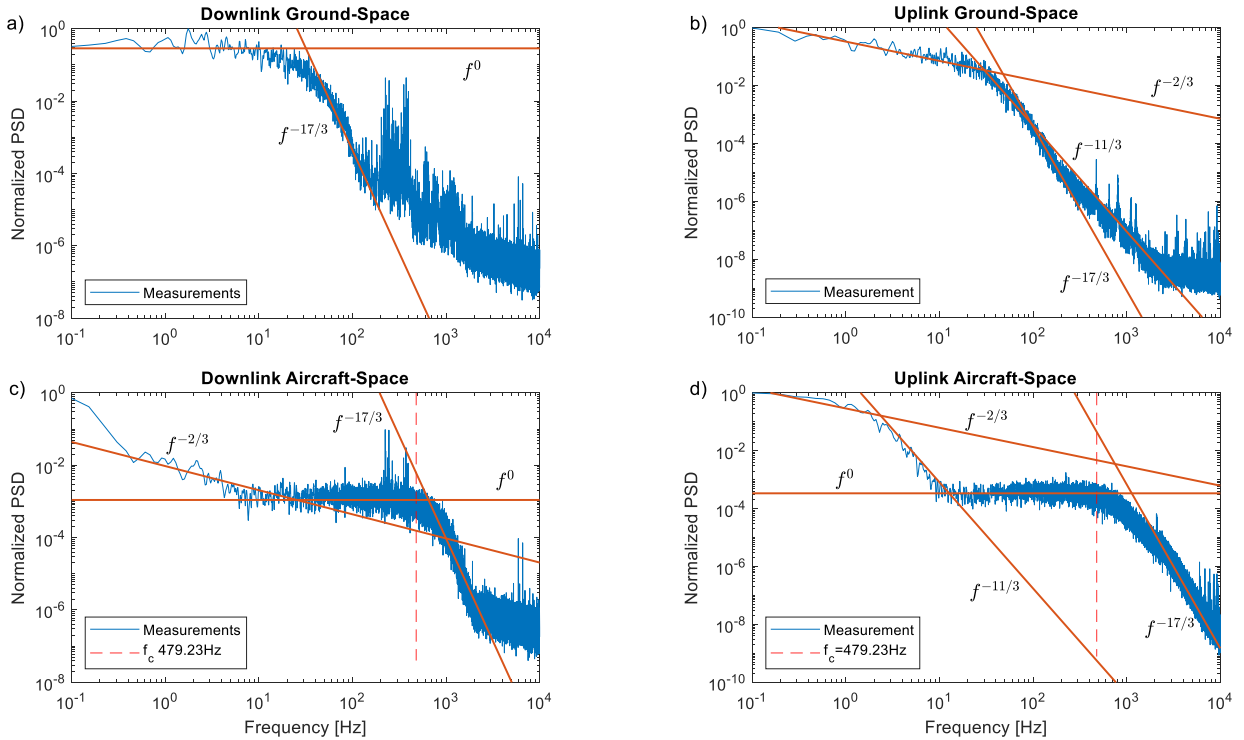


Figure 1. Typical PSD of the received optical power during the test campaign for both (top) ground-space and (bottom) aircraft-space links, and both (left) downlink and (right) uplink directions. For aircraft-space links, the vertical dashed line shows the critical frequency as given in (1), calculated from aircraft sensors data.

The PSD for the uplink direction is shown in Figure 1(d). Here, also four regimes are identified. The first two, up to ca. 20 Hz, present the expected $f^{-2/3}$ and $f^{-11/3}$ power laws characteristic of a random process dominated by tip-tilt. In this case, this corresponds to the combined effects of aircraft micro-vibrations and atmospheric beam wander. Next, the scintillation process exhibiting f^0 behavior is observed up to the same to critical frequency f_c shown in the downlink plot. Note how the high relative wind speed experienced by the ALCT governs the scintillation process cutoff frequency both

in the downlink and uplink vectors. Finally, after f_c , it is clear that the inertial range of turbulence with its $f^{-17/3}$ power law dominates in the HF region of the PSD spectrum.

3.2 Probability Density Function

Hereafter an analysis of the PDF of the optical receive power both in the uplink and uplink directions is presented. The data presented corresponds not only to the aircraft-space scenario, but also to the ground-space case. Results are presented in Figure 2. Furthermore, in each case analyzed the scintillation index (SI) is calculated. The SI σ_I^2 is directly estimated from the measurement data as

$$\sigma_I^2 = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1. \quad (2)$$

3.2.1 Lognormal distribution

The PDF of a random variable I described by the Lognormal (LN) distribution is given by

$$f_I(I; \sigma_{\ln I}^2) = \frac{1}{I \sqrt{2\pi\sigma_{\ln I}^2}} \exp \left[-\frac{[\ln(I) + 0.5\sigma_{\ln I}^2]^2}{2\sigma_{\ln I}^2} \right], \quad (3)$$

where $\sigma_{\ln I}^2$ is the variance of the log-irradiance, related to the scintillation index by $\sigma_{\ln I}^2 = \ln(\sigma_I^2 + 1)$.

3.2.2 Lognormal-Beta distribution

The PDF of a random variable I described by the Lognormal-Beta (LNB) distribution is given by [4]

$$f_I(I) = \beta \exp \left[\frac{\sigma_I^2}{2} \beta (1 + \beta) \right] I^{\beta-1} Q \left[\frac{\ln(I) + \sigma_{\ln I}^2 (\beta + \frac{1}{2})}{\sigma_{\ln I}} \right], \quad (4)$$

where the β parameter is related to the severity of fading events due to pointing errors, and $Q(x) = \text{erfc}(x/\sqrt{2})/2$ is the tail distribution function of the standard distribution. Note that the mean value is purely dominated by pointing errors, and is given by $\langle I \rangle = \beta/(\beta + 1)$.

3.2.3 Gamma-Gamma distribution

The PDF of a random variable I described by the Gamma-Gamma (GG) distribution is given by

$$f_I(I) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I}), \quad (5)$$

where α and β are shape parameters related to the scintillation index of small and large-scale fluctuation, according to the established theory on atmospheric turbulence [5].

3.2.4 Exponentiated Weibull distribution

The PDF of a random variable I described by the Exponentiated Weibull (EW) distribution is given by [6]

$$f_I(I) = \frac{\alpha\beta}{\eta} \left(\frac{I}{\eta} \right)^{\beta-1} \exp \left[-\left(\frac{I}{\eta} \right)^\beta \right] \left\{ 1 - \exp \left[-\left(\frac{I}{\eta} \right)^\beta \right] \right\}^{\alpha-1}, \quad (6)$$

where α and β are shape parameters related to the scintillation index (2), and η is a scale parameter related to mean received value of the irradiance. Hereafter the EW parameters are calculated using exclusively the scintillation index σ_I^2 from the optical received power data as given by the following expressions

$$\alpha \cong \frac{7.220\sigma_I^{2/3}}{\Gamma(2.487\sigma_I^{2/6}-0.104)}; \quad \beta \cong 1.012(\alpha\sigma_I^2)^{-\frac{13}{25}} + 0.142; \quad \eta = \frac{1}{\alpha\Gamma(1+\frac{1}{\beta})g_1(\alpha,\beta)}, \quad (7)$$

where the definition of $g_1(\alpha, \beta)$ can be found in [6].

3.2.5 PDF results

Hereafter, the GG and EW distributions are evaluated for all presented cases. Additionally, a LN PDF is presented for the downlink, while a LNB is used for the uplink.

In the plots shown in Figure 2, the PDF parameters for the LN and EW are calculated directly from the experimental data through the estimated empirical SI value, using equation (2). Meanwhile, as the GG and LNB distributions do not have known expressions to calculate their governing parameters directly from the optical received power time series data, these are estimated via standard curve fitting algorithms directly from the empirical PDF plots shown as circles in Figure 2.

From inspecting the PDF plots in Figure 2, for the different scenarios, it is noticeable that the fitted GG distribution provides a very good estimation in every case except for Figure 2(d), i.e., airborne-space uplink, where it fails to follow the steeper slope present on the left tail of the empirical PDF. Furthermore, the EW PDF—with all its parameters directly estimated from the empirical SI data—also provides an excellent fit, except for the airborne-space downlink as shown in Figure 2(c). In this case, the downlink received signal is very stable as indicated by the rather low SI value of about 0.012. This seems to indicate that the expressions to estimate the EW model parameters given in (7) do not cope well in regimes of very low SI and require further revision.

On the other hand, for the downlink data the LN distribution offers a good fit of the empirical PDF, although it tends to underestimate the left tail of the curve, in particular for the airborne-space downlink case shown in Figure 2(c). For the uplink direction, a standard least-square curve fitting approach was tried to estimate the LNB model parameters. Although the results show that both PDF slopes can be fairly well reproduced, the PDF peak of the fitted LNB distribution is shifted to the left. This mismatch appears due to the fact that the empirical PDF is normalized with respect to its received power mean value, while the LNB model in (4) is defined through a non-unity mean value.

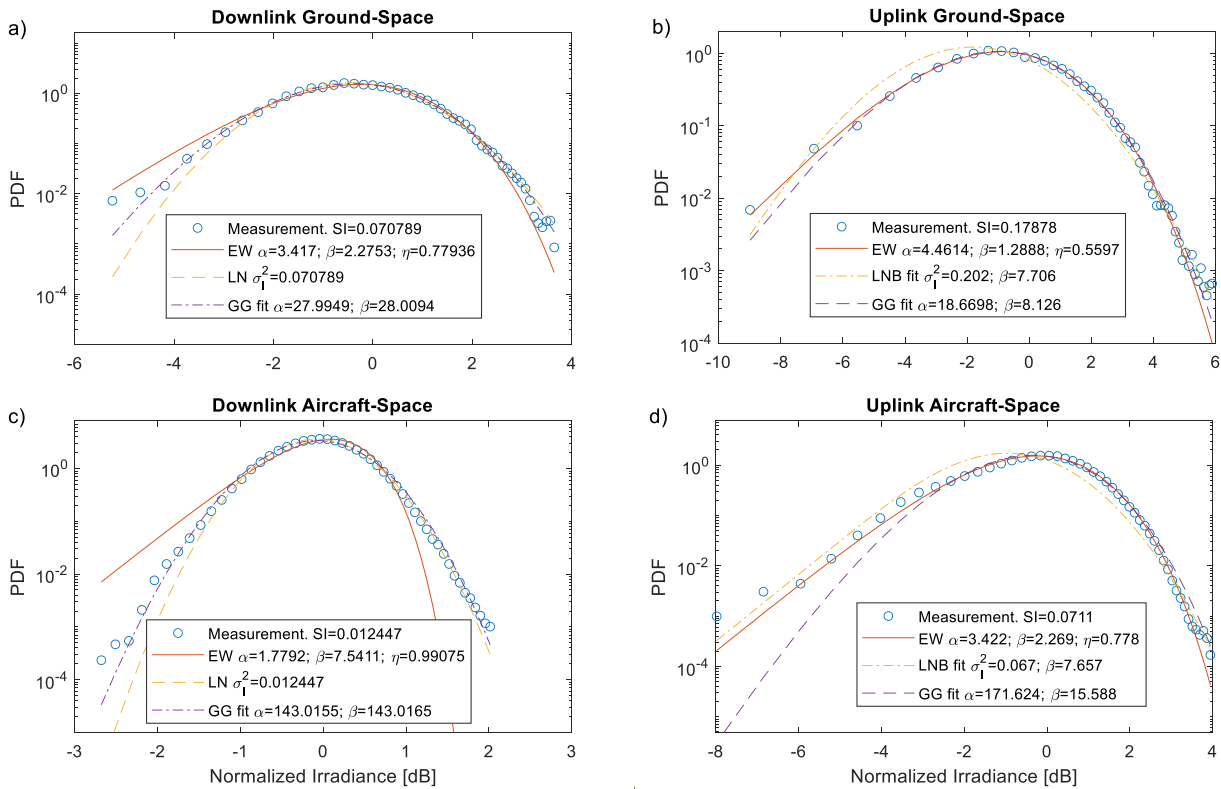


Figure 2. PDF of the received optical power during the test campaign for both (top) ground-space and (bottom) aircraft-space links, and both (left) downlink and (right) uplink directions.

From the analysis performed, for the different use cases both in the downlink and uplink, the GG and EW models present the better fit and wider range of applicability. Note that a similar conclusion has also been drawn by Kolev and Toyoshima [7], when analyzing the received-power fluctuations for ground-LEO experimental data. Finally, it is noteworthy that the LNB model is also applicable for both downlink and uplink, as for high β values (4) tends towards a simple LN distribution.

3.3 Fade Distribution

A fade event is defined as an interval where signal attenuation causes the received power to drop below the threshold, P_{thr} here defined in dBm, needed for reliable decoding. On top of this, once the signal optical power rises above the same threshold, the receiver must reacquire bit and frame synchronization. This “hysteresis-like” behavior induces an additional loss of communication, which can severely degrade the link performance if the intervals between the drops of signal power below P_{thr} are shorter than the synchronization time. By defining the time interval T' during which the optical power is below P_{thr} , and T'' as the synchronization time, one can define the duration of a single fade event as $T = T' + T''$.

A fade analysis was carried out for Aircraft-Space links, on both downlink and uplink measurements. The threshold values of interest were different for each channel, due to the distinct receiver sensitivities of the airborne and GEO satellite nodes. To account for synchronization losses, this work leveraged on the framing and synchronization specifications included in SDA OCT [8], a *de facto* standard widely adopted by the industry and largely interoperable with other space-agency-driven standards, such as CCSDS or ESTOL [9][10].

Communication can only be resumed after the receiver correctly decodes a specific number of data frames, which requires frame synchronization achieved via detection of a fixed preamble. While an ideal receiver requires only one frame for synchronization, realistic implementations may require more. This analysis considers synchronization requirements of 1, 3 and 5 frames—representing ideal, average and poor synchronization performance, respectively. Frame durations T_f were selected based on Table 3-20 in [8]. The analysis focuses on $T_f = 14.34 \mu s$ (Manchester encoding, LDPC rate 1/2) and $T_f = 229.38 \mu s$ (Manchester-BM16 encoding, LDPC rate 1/2). These values represent a standard 2.5 GHz OOK signaling configuration and a long-range optimized configuration, respectively.

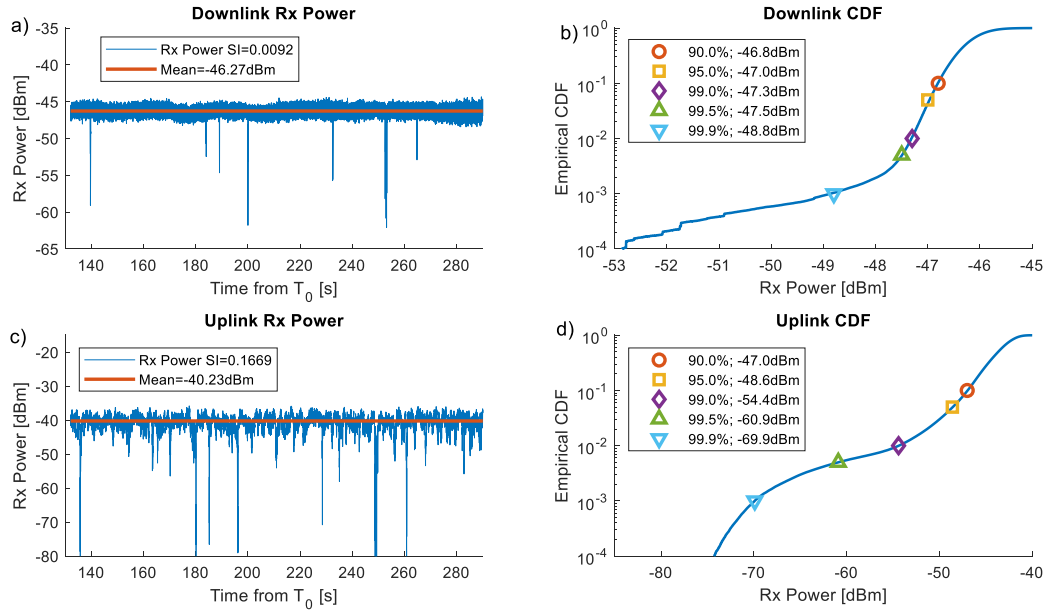


Figure 3. Link ID 143 received optical power (left) time series and (right) CDF, for both (top) downlink and (bottom) uplink directions. The CDF curve is displayed along with points for specific outage probabilities.

The first time series analyzed—for a link session starting at 15h01UTC, 13 Dec 2025 (Link ID 143)—corresponds to a portion of 160 seconds during which the communications link was stable and the uplink was performed with constant beam parameters. Time series of the downlink and uplink measurements are presented in Figure 3 left column, along with the cumulative distribution function (CDF) of the received optical power on the right column. The received power values for specific outage probabilities help link budget designers determine the necessary fade margin for a target availability under specific atmospheric turbulence conditions. A comparison between Figure 3(a) and (c) highlights the increased severity of uplink dynamic losses with respect to the downlink channel. In the uplink, deep fades reaching losses in excess of 30 dB below the mean received power are due to the large pointing errors, caused by atmospheric beam wander and system

pointing jitter. The latter is expected to be a dominant contributor in airborne links. The downlink, on the other hand, displays fades mostly limited to 2.5dB below the mean received power.

Results from the fades analysis are shown in Figure 4. For each threshold of interest, the curves are plotted for different receiver performances. The baseline is given by the black curves, which are obtained for a null synchronization period ($T'' = 0$). This represents the minimum possible fade time given only by the channel ($T = T'$). The other curves are representative of the two sets of cases described above, where a different number of correctly received frames are required to resume communications. Given the measurements' sampling rate linear interpolation of the received time series was performed in this analysis to achieve a temporal resolution of $1 \mu\text{s}$. As a result, $T_f = 15 \mu\text{s}$ is representative of the Manchester encoding, LDPC rate 1/2, and $T_f = 230 \mu\text{s}$ of the Manchester-BM16 encoding, LDPC rate 1/2.

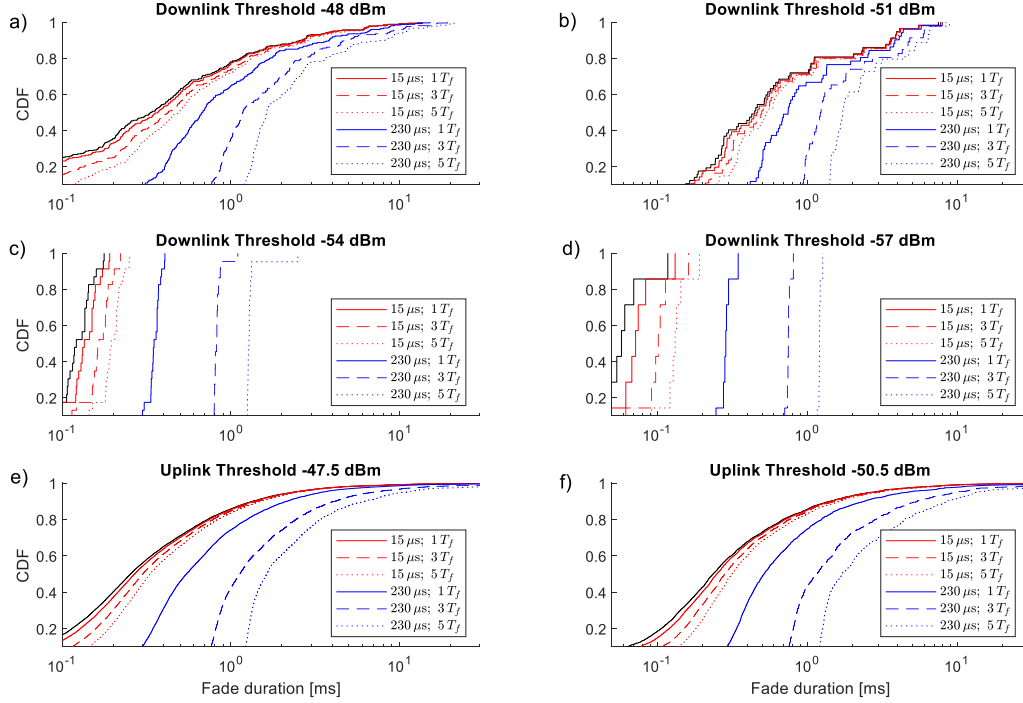


Figure 4. Link ID 143 CDF of the (a)-(d) downlink and (e)-(f) uplink fade events' duration. Black curves are representative of fades excluding the receiver synchronization time. For a 2.5 GHz signaling rate, frame sizes considered are for (red lines) Manchester coding $T_f = 15 \mu\text{s}$ and (blue lines) Manchester-BM16 $T_f = 230 \mu\text{s}$, both at LDPC code rate 0.5. Different receiver frame sync conditions are shown for (solid lines) $T'' = 1T_f$, (dashed lines) $T'' = 3T_f$ and (dotted lines) $T'' = 5T_f$.

A similar analysis was conducted on a link starting at 15h38UTC, 13 Dec 2025 (Link ID 144). In this case the aircraft turbine was set to idle to reduce the pointing errors experienced in the uplink due to the system vibrations. An interval of 160 seconds was selected, corresponding to the time during where the aircraft altitude was between 5800 and 3800 m above mean sea level. Despite not being the most stable segment of the link, this set of measurements was of more interest for the fade analysis as a moderate number of outages with respect to the same P_{thr} values considered in Figure 4 was recorded.

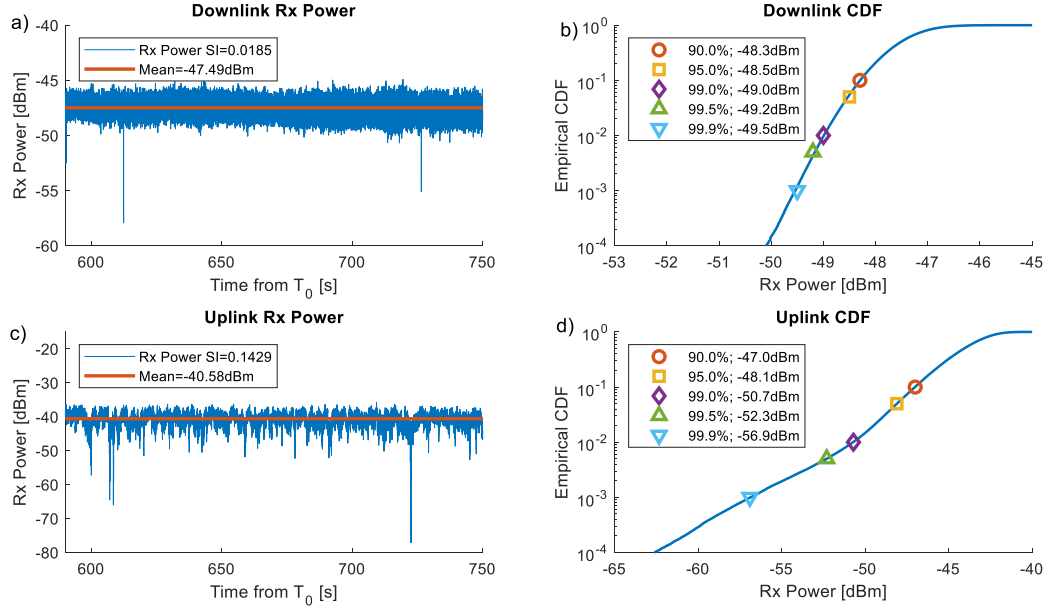


Figure 5. Link ID 144 received optical power (left) time series and (right) CDF, for both (top) downlink and (bottom) uplink directions. The CDF curve is displayed along with points for specific outage probabilities.

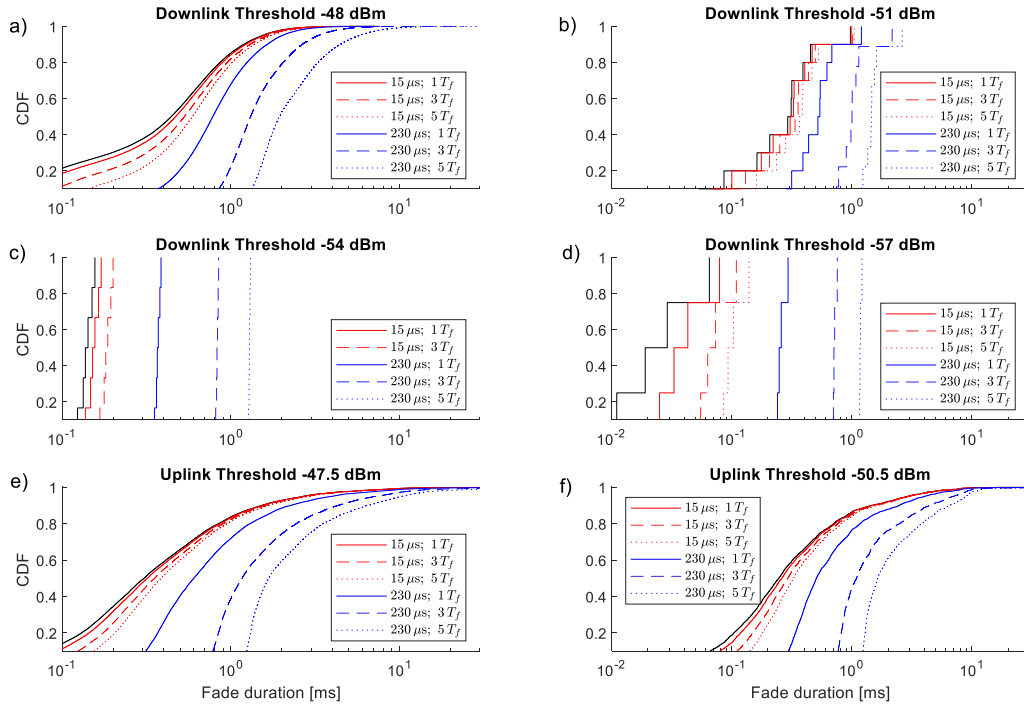


Figure 6. Link ID 144 CDF of the (a)-(d) downlink and (e)-(f) uplink fade events' duration. Black curves are representative of fades excluding the receiver synchronization time. For a 2.5 GHz signaling rate, frame sizes considered are for (red lines) Manchester coding $T_f = 15 \mu$ s and (blue lines) Manchester-BM16 $T_f = 230 \mu$ s, both at LDPC code rate 0.5. Different receiver frame sync conditions are shown for (solid lines) $T'' = T_f$, (dashed lines) $T'' = 3T_f$ and (dotted lines) $T'' = 5T_f$.

Time series of the downlink and uplink measurements, with the CDF curves, are presented in Figure 5. A narrower envelope in received optical power for Link ID:143 indicates greater signal stability and reduced power fluctuation over the observed timeframe. Losses with respect to the mean received power are within 2.4 dB and 12.9 dB in 99.9 % of the time, for the downlink and uplink channels, respectively.

The fades' duration cumulative distributions are presented in Figure 6. With respect to Link ID:143, the uplink channel presents very similar characteristics. In fact, despite the strong reduction of deep fades, outages with respect to the thresholds investigated remain similar. Regarding downlink measurements, fade events are typically shorter (0.1 to 1 ms), but high CDF values occur more frequently for outages below -48 dBm. This happens because the threshold is very close to the mean received power of -47.5 dBm, which increases both the frequency and proximity of these fade events. This increases also the detrimental effect of the receiver synchronization on the overall link performance.

4. CONCLUSIONS

This work summarizes the channel model analysis for the UltraAir flight test campaign, which took place in Nîmes, France, during December of 2025. With a total of nine flights performed—comprising the execution of 31 optical links between the ALCT and Alphasat GEO satellite hosted payload TDP1—the two main objectives of the UltraAir flight test campaign could be successfully met. These were, demonstrate air-to-space tracking during links between the ALCT flying in an aircraft and a counter terminal at a GEO satellite in a reproducible way, and gather experimental data which allows the characterization of the channel for air-space communications, serving as input for the atmospheric model characterization.

The PSD analysis of the optical received power confirms the uplink channel to be completely dominated by the dynamics of the pointing errors, arising from both the atmospheric induced beam wander and aircraft microvibrations regime. Moreover, it is evident that the relative airspeed across the aircraft has a significant impact on the dynamics of the received power, increasing the spectral content in frequency by up to one order of magnitude compared to a ground-space scenario. By examining the PDF (Probability Density Function) of the optical received power in both the downlink and uplink, it appears that the models best suited for various link conditions are the LNB and GG models (via a best-fit approach), whereas the EW model reproduces all presented cases fairly well using just a single parameter, namely the empirically calculated scintillation index. It is noteworthy that although the scintillation index values recorded during the flight campaign are lower, with respect to the ground-space links, there is still a noticeable influence from the deep fade events, in particular for the uplink channel.

The discussion presented on the duration of a fade event is a key metric that depends on the atmospheric channel, the receiver synchronization performance and the target link availability. This set of conditions should always be stated in the system design processes. The analysis performed on sections of interest of links ID 143 and 144 show that for higher target availabilities the uplink channel poses more stringent constraints. This is because of the higher occurrence of deeper fades which cause longer link outages with respect to those experienced in the downlink channel. By modelling variable receiver synchronization performances, it was observed that longer synchronization times do indeed affect the overall fade durations. However, this seems to pose strong constraints only for outages with respect to higher thresholds (see -48 dBm cases). For lower thresholds, synchronization does increase the fade event duration – as obviously expected – though the resultant values of T are generally dominated by T' . This is explained by the fact that the interval between deeper fades is generally longer than the synchronization times investigated.

Through the analysis conducted in this work—for the several metrics presented in Section 3—for both uplink and downlink, we deliver a comprehensive channel model. This model directly supports system-level trade-offs, offering valuable insights to link designers on the airborne-space channel expected behavior under realistic conditions. These insights will accelerate the integration of robust optical links into upcoming mega-constellation architectures and airborne platform concepts.

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