Measurements at a 61 km near-ground optical transmission channel

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ABSTRACT

An optical ground-to-ground direct-detection transmission experiment over 61km is being performed by the German Aerospace Center (DLR) in cooperation with the European Aeronautic Defence and Space Company (EADS) and Contraves Space AG, Switzerland. Transmission direction is from the mountain Wallberg in the German Alps down to Oberpfaffenhofen (west of Munich). This beam path suffers strongly from optical turbulence especially at the near-ground part along the last kilometers before the receiver. This causes a very demanding situation regarding received-power scintillations. Transmit power from one data source is 1W at 980nm. Of special interest is the effect of secondary transmitter apertures with 4m lateral offset to the first. Under strong turbulence conditions this provides statistically independent speckle patterns at the receiver thus improving system performance dramatically. This paper presents measurements at the transmission channel, with emphasise on statistical parameters of the scintillations and angle-of-arrival variations with one and two transmitter sources.

Keywords: atmospheric scintillations, optical direct detection, ground-to-ground link, multiple transmitter apertures

1. INTRODUCTION

The German Aerospace Center (DLR) together with EADS, Germany, and Contraves-Space, Switzerland, are cooperating in the project "FASOLT" to demonstrate the feasibility of aeronautical optical high data rate transmission with direct detection through the turbulent atmosphere. In Phase-1 of FASOLT, a 61km ground-to-ground transmission experiment has been set up to study the atmospheric effects in long transmission paths in the regime of strong refractive turbulence and thus high scintillation.

The primary goal of FASOLT is to test the suitability of optical transmission technology for the interconnection of aeronautical HAPs (High Altitude Platforms) or links between aircraft and satellites. This paper deals with the experiment setup and the received power statistics of FASOLT Phase-1, while a second publication [DAV2002] addresses the digital data transmission aspects.

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2. EXPERIMENTAL SETUP

2.1 Path Characteristics

The transmission path leads from the mountain station of the Wallberg (WB) cable-car (south of the Lake "Tegernsee") 61km north-west to a small room on top of the institute's building at Oberpfaffenhofen (OP) (see Figure 1):

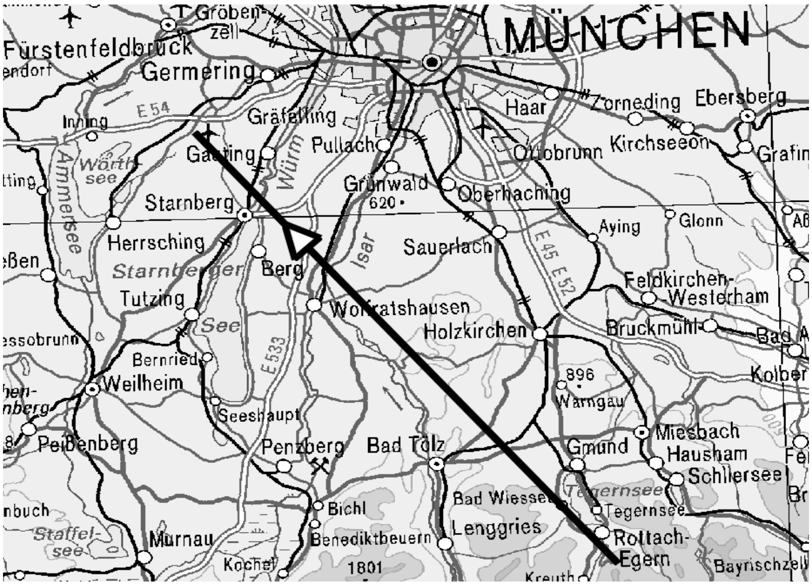

Figure 1: Map of the beam path

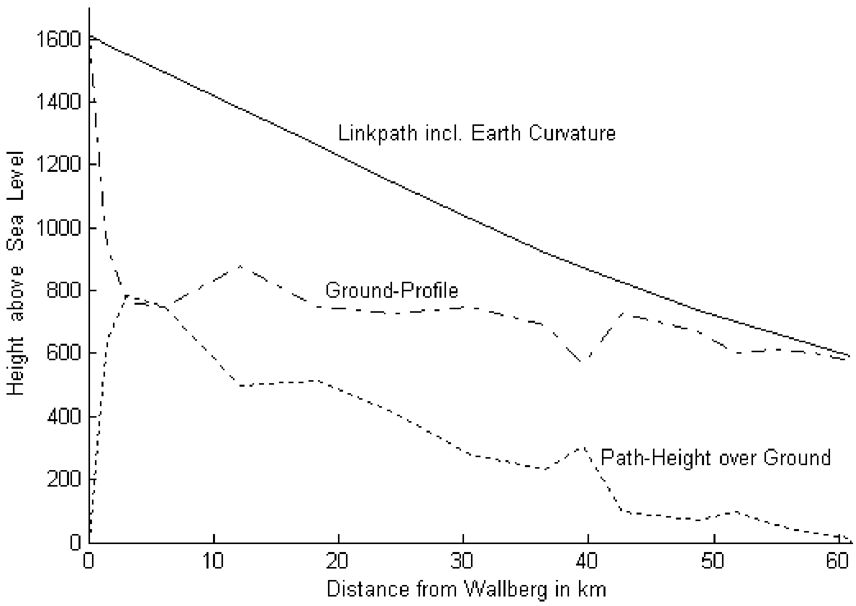

Figure 2: Height profile of the transmission path

With the steep beginning of the ground profile underneath the beam path (following the slope in front of the WB-Tx-housing) one can assume fairly weak turbulence for the first two thirds of the distance. The path then crosses the air above wetlands north of a lake (Starnberger See) which might account for most of the attenuation (through Mie-scattering). Finally, the near-ground propagation over forests along the last eighteen kilometers generates very strong turbulence conditions. The path height above ground is used to calculate C_n^2-profiles (refractive index structure parameter) according to the Hufnagel-Valley-model [AND2001]:

$$C_n^2(h) = 0.00594\cdot\left(\frac{v}{27}\right)^2\cdot\left(10^{-5}h\right)^{10}\cdot \mathrm{e}^{-h/1000} + 2.7\cdot 10^{-16}\,\mathrm{e}^{-h/1500} + A\cdot e^{-h/100} \qquad (1)$$

with h height above ground in meters (dimensionless for this formula)
v rms wind speed (typical 21m/s), defines high-altitude C_n^2 (not of interest here)
A nominal value of $C_n^2(0)$, defining low-altitude behaviour, here we use $A=5*10^{-14}$ [$m^{-2/3}$]

As it is difficult to find a consensus about the height dependence of the inner and outer scale of turbulence (l_0 and L_0, defining the bounds of the sizes of atmospheric turbulence cells), the following formulas represent a mean of different statements:

$$l_0 = \begin{cases} \sqrt{h}/700\mathrm{m}^{-1/2}; & h < 196\mathrm{m} \\ 0.02\mathrm{m}; & h > 196\mathrm{m} \end{cases} \qquad (2)$$

$$L_0 = \begin{cases} h/5; & h < 50m \\ 10m; & h > 50m \end{cases} \qquad (3)$$

For further information on C_n^2, l_0 and L_0 see [AND1998] and [STR1978]. The literature quotes different day- and night-time models for these profiles, but as stated later, in the experimental data no clear diurnal dependencies could be observed. Statements about those profiles are strongly dependent on local geographic circumstances (topology) anyway, thus the uncertainty about those profiles advices to stay with only one average model. This conflict becomes clear especially in mountainous areas, where the same air-volume that has just been flowing over an elevated area is taken by wind movements high above a valley only some seconds later. It seems quite unrealistic to expect that the turbulence structure inside this volume would then rearrange to match a certain height-profile formula. Therefore, these profiles feature a large amount of uncertainty.

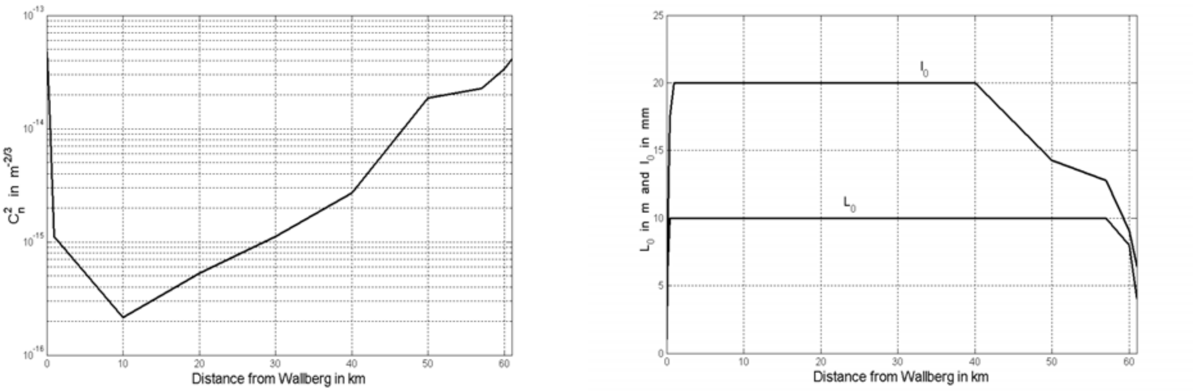

Figure 3: Profiles of C_n^2, L_0, and l_0 according to (1), (2), and (3)

2.2 Hardware Setup

Two equal transmitter telescopes with 4m lateral offset are being used as beam sources. This technique not only doubles transmission power, but also decreases received power variations dramatically, due to different air volumes passed which produces nearly independent intensity patterns at the receiver. Even if propagation takes place partly through the same volume, a tilt in the two wavefronts will produce some lateral offset of the two patterns which causes a similar effect. The minimum necessary lateral offset for an effective application of this technique can be calculated based on simple geometrical considerations according to:

$$d_{Tx} > L \cdot \sqrt{\frac{\lambda}{L_S}} \quad (4)$$

with λ denoting the wavelength and L_S the common pattern-forming turbulence path of both beams in front of the receiver (where the simple approximation $D_S = \sqrt{L_S \cdot \lambda}$ for the magnitude of the pattern sizes has been used). L_S is typically around five kilometers, as this distance is sufficient to produce extreme surges and fades in the intensity pattern. This formula cannot account for the large scale atmospheric effects such as beam-wander (caused by near-Tx turbulence), but is sufficient for the typical small-scale intensity modulating turbulence. In our case with L=61km and λ=0.98µm Eqn. (1) requires a minimum Tx-separation of less than 1m, which is fairly satisfied with the experimental setup.

Fiber-coupled laser diodes that can be intensity-modulated up to 270MBps with 1W cw-power (ex-fiber) are being used as data-beam sources. The beam out of the 100µm multimode fiber is collimated by a d=50mm/f=150mm achromatic lens which results in a minimum possible divergence angle of 0.67mrad (i.e. 41m spot diameter or 1300m^2 at the receiver position). This would produce a maximum mean intensity of 770µW/m^2 with one transmitter. Due to several reasons typical mean intensities of 20 to 200µW/m^2 are being measured at the receiver with one transmitter. These reasons include atmospheric attenuation of up to 13dB on moderately clear days, Tx-optical aberrations as well as Tx-telescope truncation, and beam spreading.

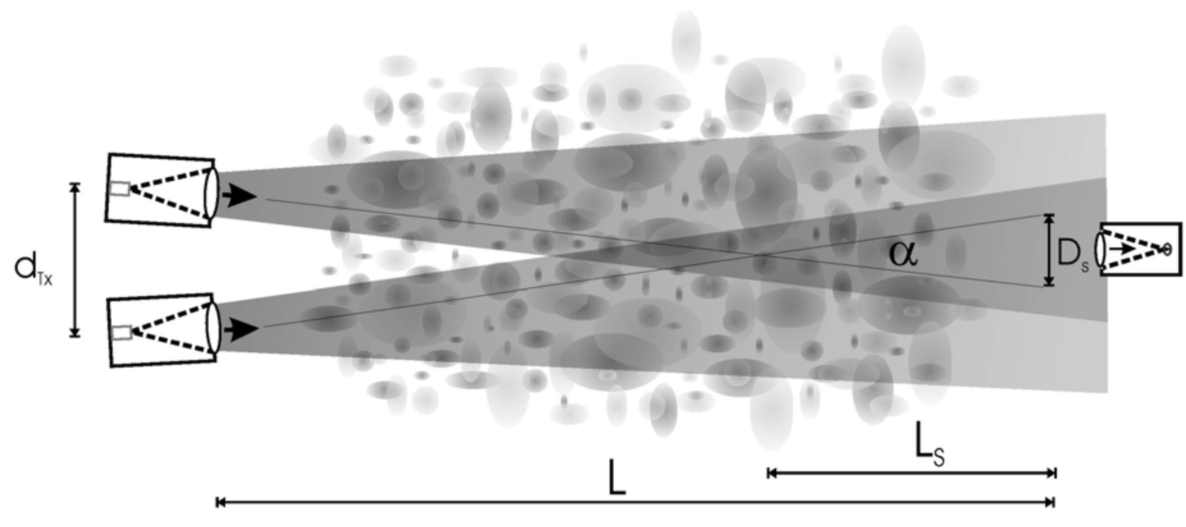

Figure 4: Double-transmitter setup for the reduction of air-turbulence effects; L=61000m, d_{Tx}=4m

The receiver at OP consists of one d=75mm/f=300mm achromatic lens focussing the received light into a 100µm multimode fibre. This provides a field of view for the receiver of 333µrad. A beam-splitter plate in front of the focus reflects 14% of the received light onto a CCD for acquisition and observation purposes.

3. ANGLE-OF-ARRIVAL JITTER AND DIURNAL BEAM OFFSET VARIATIONS

Fast variations in the Angle-of-Arrival (AOA) which are caused by refractive wavefront distortion are measured using a CCD positioned in the focus of a long focal length telescope and a software monitoring the movements of the center-of-gravity of the focal spot. As expected, the AOA jitter shows a normal distribution in the horizontal and vertical directions with a typical standard deviation of 40µrad and maximum tilt-spans of 230µrad for both horizontal and vertical directions. No difference in these angles is evident using both or only one Tx-source. The field-of-view of the receiver telescope matches these angles, thus no fast tracking of the received focal spot is necessary.

Similar measurement hardware is used to determine the beam-offset variations caused by diurnal variations of the atmospheric temperature layers. As per theory this effect should be especially severe in our case, as the beam is going from 1600m, through different atmospheric layers, down to 600m and might require an active transmitter beam steering. However, the measurements showed only smaller variations in the range of some meters (Figure 5) which stay within the Rx-spot diameter of 40m.

One problem with measuring the direction of the incoming beam at OP-site was the tilting of the measurement devices (e.g. optical tables, telescope-bases) caused by thermal expansion due to heating by the sun. This was avoided by taking the measurements at the WB-site which is facing towards the mostly shaded north-west direction.

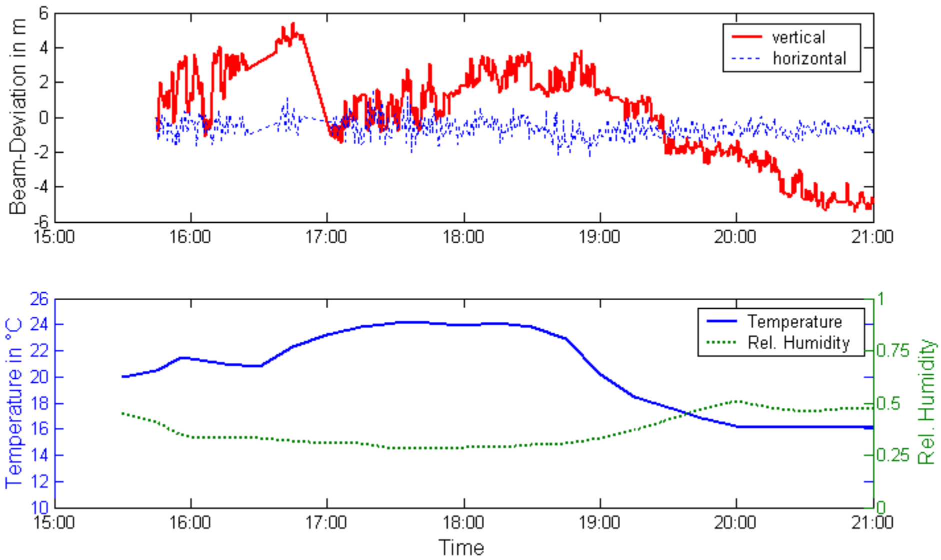

Figure 5: Beam-deviations due to diurnal variations of atmospheric layers and meteorological data (measured 02.10.2001)

4. SCINTILLATIONS OF RECEIVED POWER

4.1 Numerical Simulation of Intensity Distributions

The analytical theory for calculation of statistical parameters of atmospheric optical propagation is treated in detail in [AND1998] and [AND2001]. Here we present the results of a numerical beam propagation simulation based on the phase-screen method as described in [FLE1976], where turbulent path volumes are regarded step-wise as phase distorting planes with free-space diffractive propagation between them. Simulations are performed using the MatLab-Toolbox "PILab" which was developed at DLR [JUN2001]. The wave from each transmitter is propagated separately (but through the same turbulence volume) and the resulting intensity matrices are added at the observation position. This is feasible as the two sources are independent laser diodes and thus incoherent with each other. The turbulence parameter profiles [$C_n^2(z)$, $l_0(z)$, $L_0(z)$] used for the simulations are according to Figure 3. In Figure 6 the probability density functions (PDF) of the resulting intensity distributions at the receiver site are shown.

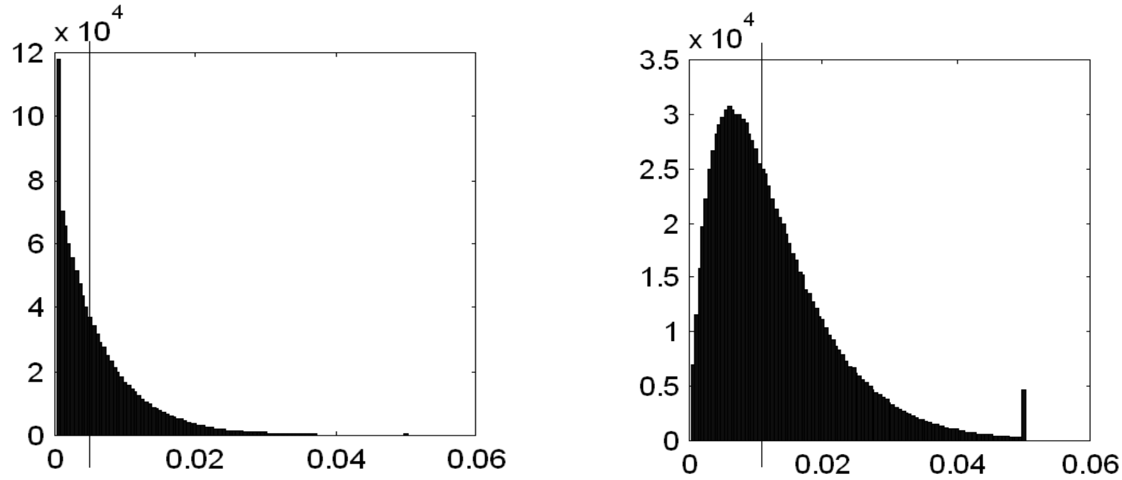

Figure 6: Typical PDFs of simulated intensity distribution at OP with single- (left) and double-transmitters (right) (arbitrary units of intensity)

As the stochastic processes of the two-dimensional intensity matrix and the received power-over-time are ergodic with each other, instead of calculating numerous matrix samples to produce time-series it is much faster to move the integrating receiver aperture with a typical lateral wind speed (here 5m/s) over the intensity matrix to produce time-vectors of received power as they are measured with a real telescope. The resulting PDFs of this processing are shown in Figure 7.

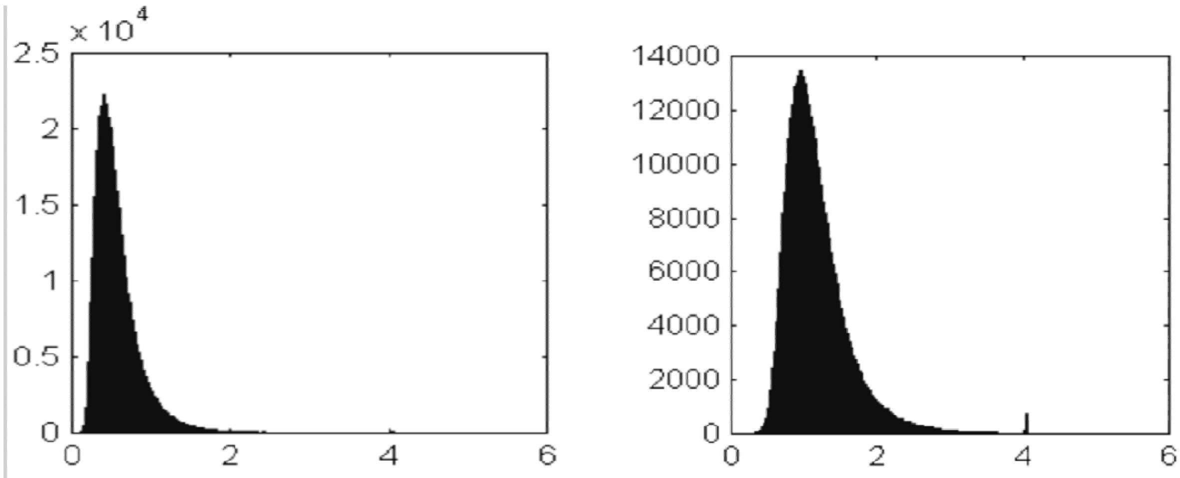

Figure 7: Typical PDFs of simulated reception power with single- (left) and double-transmitters (right) (arbitrary units of received power)

Contrary to weak-turbulence situations where normal or lognormal intensity-distributions are predominant, FASOLT experiences very strong turbulence (both due to the long path as well as the near-ground propagation which features a high degree of turbulence). The PDF of Rx-intensity approaches inverse-exponential behaviour (Figure 6). The aperture-averaging effect of the Rx-lens then reduces this extreme distribution back to a more lognormal-like as shown in Figure 7.
Obviously the double-transmitter setup provides an increase in the minimum received power. This is crucial for reduction of the bit error rate with optical data transmission as treated in [DAV2002]. Next we will compare these simulation results with measurements.

4.2 Measurements of Rx-Power Scintillations

Scintillation-monitoring has been performed at OP using the 75mm-Rx-telescope together with the 100µm multimode fibre as receiver area in the focal plane (which captures all incoming power even with high AOA jitter) and an optical power meter connected to an ADC which samples the data using data acquisition software at 1000 samples/s. Each record has a length of 64*1.024 seconds resulting in 65536 sample values. For further evaluation, the background light power has been subtracted from the optical Rx-power. The background light power is typically 2nW in daylight when measured behind a 40nm interference filter in the receiver telescope path.

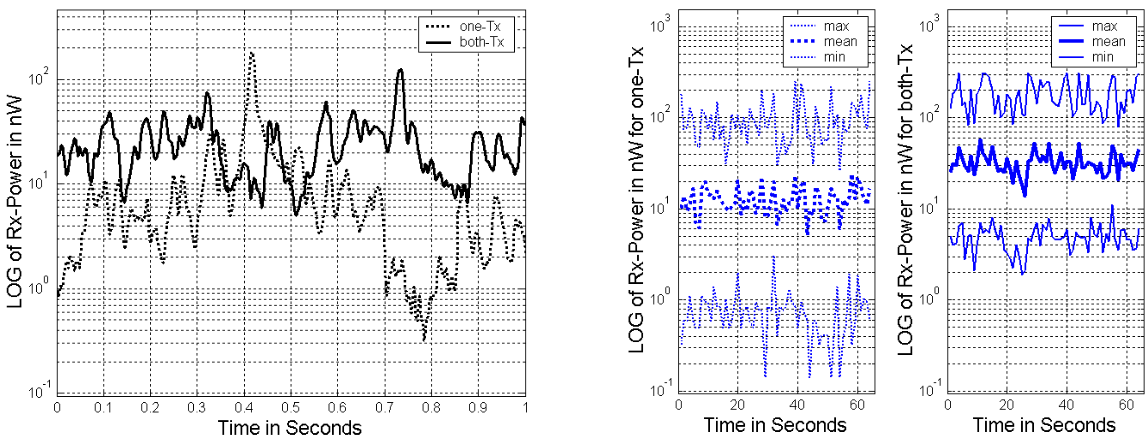

Figure 8: Typical measured absolute received power with single- (dotted line) and double-transmitters (solid line) during one second (left plot) and during 65 seconds with one second time-window (right plot) showing the minimum (-> fades), mean, and maximum (->surges) values during each second

Besides the doubling of the mean received power with "both-Tx", the minimum power values (=fades) in the right plot of Figure 8 become much less significant which explicitly improves quality of data transmission.

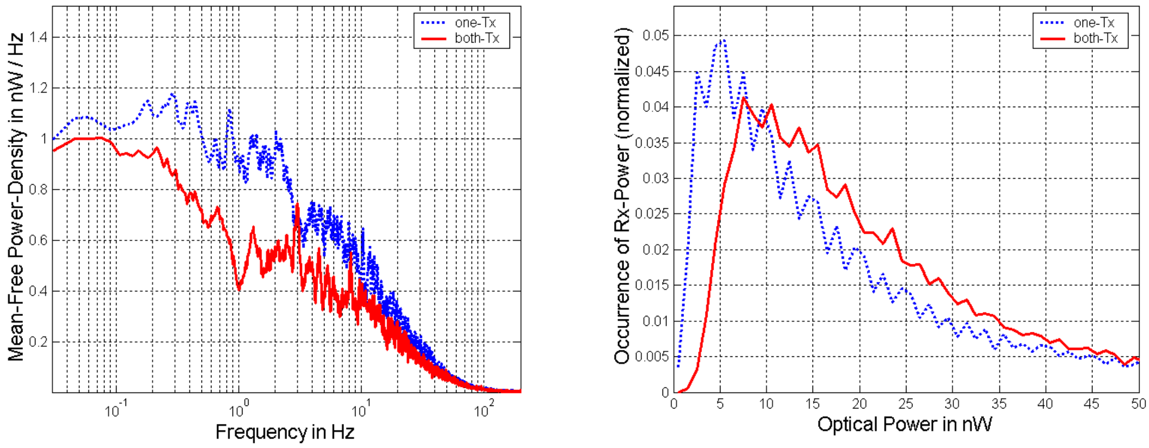

Figure 9: Typical spectrums (left) and normalized PDFs (right) of measured received power with single- (dotted line) and double-transmitters (solid line). *For better comparison, in these plots the received power values of both measurements (one-Tx and both-Tx) have been normalized so they have the same mean power!*

The double-transmitter spectrum shows a quicker drop-off than the single-transmitter spectrum. Both drop to 1% at around 100Hz, this can of course vary with mean wind speed. The PDF shows very explicitly the advantage of two transmitters. The occurrence of small power values diminishes substantially. The gradient of the PDF-curve near zero changes from a very steep behaviour with one-Tx towards an initially flat characteristic with both-Tx. This behaviour resembles results presented in [BIS2000].
Table 1 summarizes the statistics of the received power with the 75mm-diameter Rx-lens during different meteorological situations (but all during winter) with "best"-case denoting turbulence situations with smallest scintillations.

	one Tx (worst - best)	**both Tx (worst - best)**
power scintillation index	2.0 - 0.7	0.9 - 0.4
probability of 3dB-fade from mean	46 - 25 %	33 - 15 %
probability of 6dB-fade from mean	21 - 4.9 %	8 - 1 %
mean duration of 6dB-fades	21 - 8.5 ms	14 - 4.4 ms
std-deviation of duration of 6dB-fades	25 - 12 ms	14 - 6.2 ms

Table 1: Typical statistics of optical Rx-power

The power scintillation index here is calculated from received power as ($\langle P(t)^2\rangle / \langle P(t)\rangle^2 - 1$) in contrast to the usual definition of the scintillation index as normalized irradiance variance. The power scintillation index yields values much smaller than the irradiance's scintillation-index due to aperture averaging. Surprisingly, with our tests we observed that strong scintillation was correlated with high optical attenuation by near-ground fog and mist in front of the receiver. No distinct diurnal dependences could be observed, time of day seems to have lesser influence on this near-ground propagation scenario than other meteorological parameters. However, only few different measurement sessions were performed and thus no reliable diurnal statistics can be stated here. It has to be regarded that values in Table 1 are for received optical power, a direct-detection receiver suffers even stronger from power fades as its electrical SNR has twice the values of the optical SNR in dB. This is because the detector's electrical signal power is proportional to the square of the optical Rx-power.

5. CONCLUSIONS AND OUTLOOK

The double-transmitter concept proved extremely valuable for the reduction of signal fading. Further on, the application of channel coding techniques for this fading channel promises substantial improvements of transmission quality, this will be investigated in theory and experiment. The numerical simulation showed good agreement with experimental results. More measurement sessions will be performed together with data transmission experiments which have been impaired by frequent bad weather conditions during winter. Future project phases shall include ground-air and air-air transmission experiments. For reasons of space-restrictions on small aeronautical carriers we will also evaluate wavelength-diversity transmission additionally to space-diversity by simulation and experiment.

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