Overview of the FASOLT Experiment and Final Results

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ABSTRACT

Within the frame of the FASOLT project the German Aerospace Center (DLR) performed channel measurements and optical data transmission tests on a 61 km near ground horizontal path. The transmitter was situated on a mountain top in the German Alps with the receiver placed on top of a building at the DLR site in Oberpfaffenhofen. Partners in the FASOLT project were Contraves Space, Switzerland and EADS Military Aircraft, Germany.

During a period of several months various data sets of scintillation data were recorded in one and two laterally separated transmitter configurations and under different environmental conditions. A significant decrease of number and depth of fades was observed for the two transmitter setup. This paper presents an overview on the scintillation statistics of this particular optical channel. Also beam offsets due to refraction have been measured and results are presented here.

As well as these measurements, data transmission tests at bit rates of 100 Mbps have been performed. A two transmitter configuration with a transmit power of 1 W per laser and a sensitive APD receiver front-end plugged in to a 75mm Rx telescope have been used. Despite severe scintillations, bit error rates (BER) below 1e-4 could be observed, though synchronization losses of the data and clock recovery affected the results. Tests at 155 Mbps (OC-3) and 270 Mbps (SMPTE 259M) were not successful due to high atmospheric attenuation. This paper gives an overview of the entire experimental setup, sums up the results of this long-haul data transmission experiment, and gives an outlook to further DLR activities in the field of free-space optics.

Keywords: Free-space laser communications, ground-to-ground link, atmospheric turbulence, scintillations, refraction

1 INTRODUCTION

Future global communications systems may involve networks of interconnected stratospheric platforms that are kept stationary over congested urban areas at an altitude of 15 to 30 km and serve as high bandwidth nodes for multimedia services. Optical cross-links offer the possibility to transport high data rates in such networks due to the small divergence angles and enormous bandwidths that are associated with the photonic technology. Free-space optics are one of the enabling technologies in this sector. However atmospheric disturbances diminish the advantages of optical links.

Working towards the goal of reliable optical high data rate links, the Wallberg experiment was performed to examine the properties of long-haul, highly turbulent transmission paths. Measurements of diurnal beam deviations, angle-of-arrival fluctuations and scintillations have been done [1]. Moreover a data communications experiment [2] was conducted to prove the feasibility of an optical link over more than 60 kilometers under the influence of strong optical turbulence. In the following we describe the scenario of the Wallberg experiment and the experimental setup with its boundary conditions as well as the results of the various measurements and the data communications experiment.

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2 CONSIDERATIONS IN ADVANCE

2.1 Boundary conditions

The FASOLT experiment was supposed to be a low-cost experiment, however capable of demonstrating high data rate communications over a rather long link path. Mainly off-the-shelf components had to be used. Especially no active pointing or tracking was foreseen. Wavelengths for beacon and Tx lasers were derived from the properties of a Contraves terminal, that should be used for demonstration purposes. Hence a beacon wavelength of 808nm and a communication wavelength of 975nm were fixed, even though not perfectly suited for an experiment like this. The desired data rate was 270 Mbps. Additional measurements of relevant parameters should be done as well.

2.2 Location

For this particular experiment the DLR site Oberpfaffenhofen was chosen as one location, due to its good infra-structure and accessibility. Oberpfaffenhofen is located in the south-west of Munich near the German Alps. As counter station a significantly higher location had to be chosen for an optical communications link over several kilometers. Finally the cable car station on Mount Wallberg was selected. It can be accessed using the cable car and has sufficient infrastructure in the station on its summit. Two rooms with one window each, physically separated by a distance of four meters, are at disposal there.

This choice results in a path length of 61 km (38 miles). Figure 1 renders a map of the southern Munich area showing Wallberg and Oberpfaffenhofen including an altitude profile for the optical link.

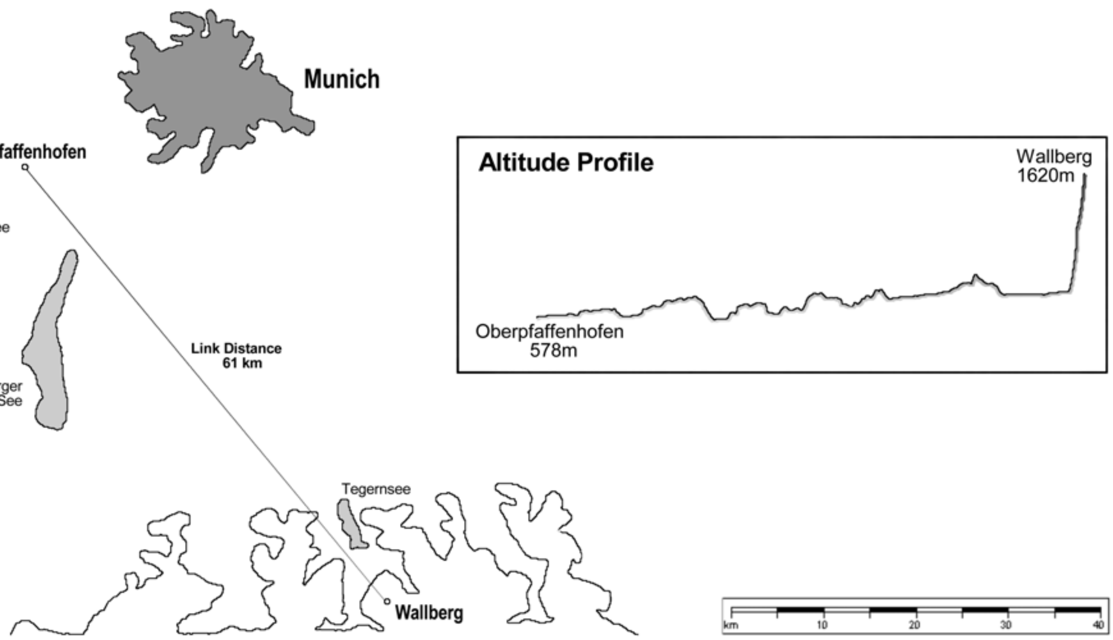

Figure 1: Location and altitude profile of the Wallberg-Oberpfaffenhofen link over 61 km

As can be seen in the altitude profile, there is a steep slope from the Wallberg mountain top to Lake Tegernsee on the plain. This gives reason to place the transmitter on top of the mountain, as little atmospheric disturbance can be expected there and hence strong beam wander can be avoided. However, the last few kilometers of the link are close to ground, therefore strong turbulences will be present there and strong scintillations and small speckle sizes can be expected.

2.3 Turbulence Profile

To estimate the influence of optical turbulence on the link from Wallberg to Oberpfaffenhofen, a turbulence profile has been derived from the path height over ground. It is based on the well-known Hufnagel-Valley model [3] for C_n^2:

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

where h is the height above ground in meters (dimensionless for this formula), v is the rms wind speed (typical 21m/s, not of interest for a near ground link) and A is the nominal value of C_n^2 at the ground. We used $A = 5 \cdot 10^{-14}\,m^{-2/3}$ for all further considerations.

For inner and outer scale (l_0 and L_0 respectively) a number of formulas can be found, that may hold for particular scenarios. As an average of those formulas, we used

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

and

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

However, a rather big uncertainty is inherent in all those expressions. The particular scenario of the Wallberg experiment, where an air-volume that was just close to the mountain top is driven to the plain at an altitude of several hundred meters above ground within a few seconds, seems unlikely to fit any height-profile model.

The models derived from the formulas given above are shown in figure 2.

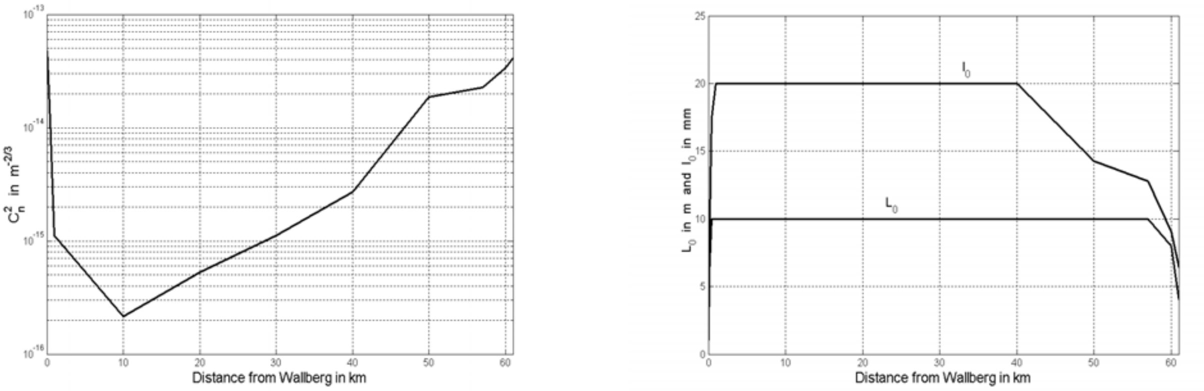

Figure 2: Profiles for C_n^2, L_0 and l_0

From the C_n^2-profile given, the Rytov variance can be calculated according to

$$\sigma_1^2 = 2.255 \cdot k^{7/6} \cdot \int_0^L C_n^2(z) \cdot (L - z)^{5/6}\, dz\,. \tag{4}$$

In this particular scenario the Rytov variance is much bigger than unity, hence the strong fluctuation regime applies. To get an estimate of the influence of those strong fluctuations, simulations have been done using PiLab, a proprietary simulation tool of DLR.

2.4 Scintillations, Aperture Averaging, and Spatial Diversity

For simulating the intensity distribution at the receiver as well as the Rx power distribution assuming a certain aperture size, the simulation tool PiLab has been used. PiLab was developed at DLR [4] and is based on the phase screen approach [5]. The C_n^2-profile and the assumptions on L_0 and l_0 given in the previous section have been used as baseline for the PiLab simulations. The intensity distribution at the receiver is thereby found to be approximately negative exponential. Using a second transmitter, that is laterally separated from the first one, is proved to reduce the probability of low intensity value significantly. Thereby the intensity distribution changes to something more lognormal-like. This method of suppressing fades is know as spatial diversity.

Finally, also aperture averaging has been simulated by converting the intensity patterns at the receiver to Rx power values by integrating over a certain finite aperture size. The results for one and two transmitters are shown in figure 3. Clearly, the second transmitter shifts the Rx power distribution towards higher values of receive power and reduces the probability of low values, as expected from theory and previously reported results [6]. Note that both plots are normalized to the respective mean value.

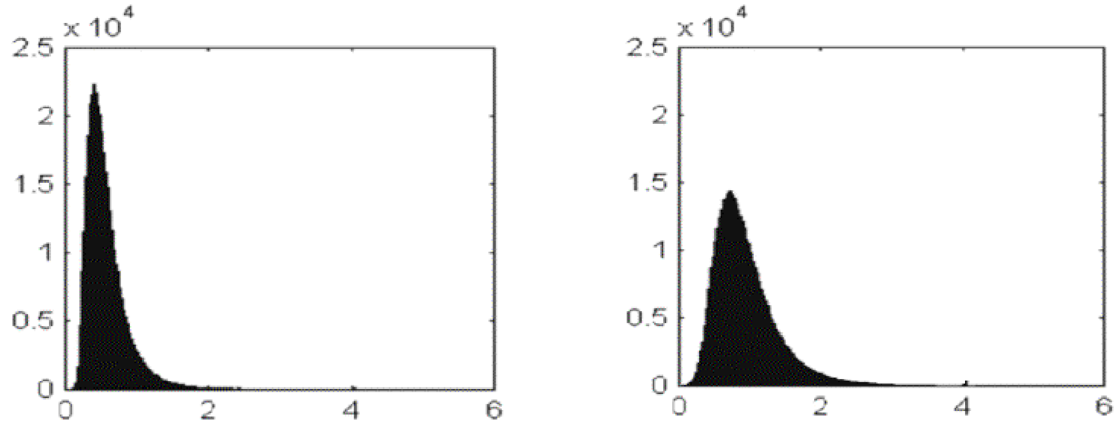

Figure 3: Typical histograms of simulated Rx power with single- (left) and double-transmitters (right).
Rx power has been normalized to mean value in both cases.

2.5 Refraction

The refractive index n of air is not constant but a function of pressure and temperature [3]:

$$n(P,T) = 1 + 77.6\times10^{-6}\left(1 + 7.52\times10^{-3}\cdot\lambda^{-2}\right)\cdot\frac{P}{T} \tag{5}$$

where λ is the wavelength in μm, P the air pressure in mbar and T the temperature in K. Both air pressure and temperature depend on the height above ground *h*. Whereas the air pressure P can be estimated from the well-known barometric height formula:

$$P = P_0 \cdot \exp\left(-h/8\text{km}\right) \tag{6}$$

with P_0 = 1013 mbar, the temperature shows a gradient δT/δh ranging from 0.5 K/100m in higher altitudes to values of 3.42 K/100m close to ground.

Due to these dependencies the refractive index usually varies on a transmission path like the one considered here. The optical beam from Tx to Rx passes different height levels with different indices of refraction and hence will be bended by refraction. This effect shows diurnal variations depending on the refraction coefficient k, which describes the bending of the beam with respect to the surface of the Earth and itself is greatly influenced by the temperature gradient.

Common values for k are 0.13 around noon, 0.20 in a cloudy night, and up to 0.30 in nights with clear skies. From the actual value of k and the geometry of the optical link the beam offset Δh can be calculated from [7]:

$$\Delta h = s \cdot \sin z_1 + (1-k) \cdot \frac{s^2 \cdot \sin^2 z_1}{2R_E} \tag{7}$$

where z_1 is the zenith angle at the transmitter, s is the slant range and R_E is the Earth´s radius. Based on this expression and assuming the range of values of k given above, the diurnal variation of beam offsets can be estimated to be

$$|\delta h| = \frac{(60.9\text{km})^2}{2 \cdot 6378\text{km}} \cdot \delta k = 290.75\text{m} \cdot (0.30 - 0.13) \approx 50\text{m} \tag{8}$$

which corresponds to an angular deviation of roughly 820µrad. This value was used for specifying the communications system.

2.6 Attenuation

Atmospheric attenuation arises from absorption of radiation by atmospheric constituents and scattering by particles in the atmosphere. The transmissivity τ can be described by an exponential law [8]:

$$\tau = \exp\left[-\alpha(\lambda) \cdot L\right], \tag{9}$$

where L is the pathlength and $\alpha(\lambda)$ is the extinction coefficient given in km^{-1}. Attenuation due to absorption is shown in figure 4 for the wavelength region around 975nm.

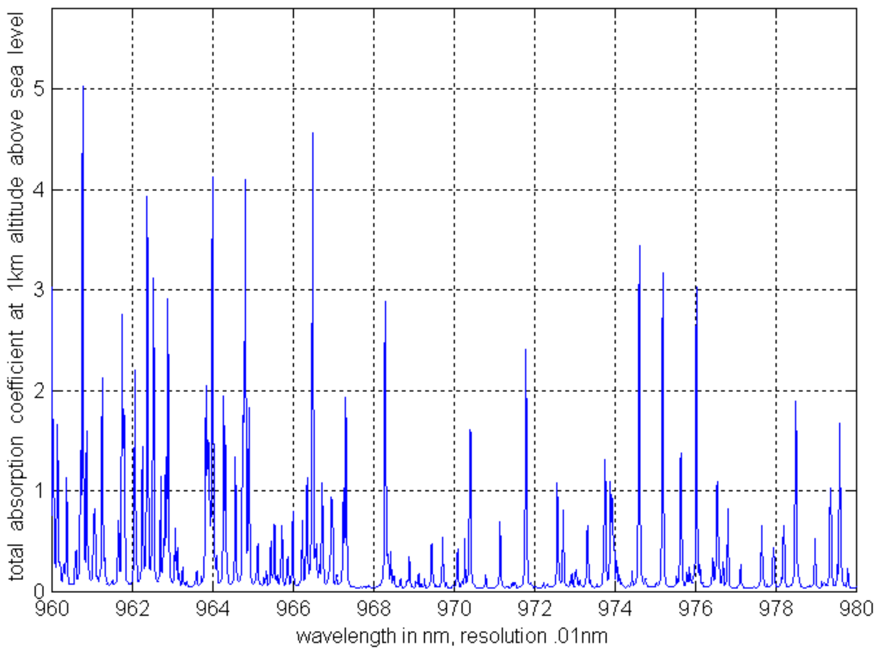

Figure 4: Absorption coefficient at 1km altitude above sea level in km^{-1}

Atmospheric scattering is either Rayleigh or Mie scattering, depending on the particle size. Usually Mie scattering is predominant. It can be described by the following empirical relation:

$$\alpha_{Mie} = \frac{17}{V/km} \cdot \left(\frac{0.55}{\lambda / \mu m} \right)^{0.195 \cdot V/km} \qquad (10)$$

where V is the visibility range.

Under certain weather conditions the visibility between Wallberg and Oberpfaffenhofen is extremely good, though these days are very rare. Using a theodolite, single buildings of the DLR site can easily be seen from Wallberg, which is at a distance of 61 km. Therefore very low values of Mie scattering can be expected.

However the range of possible attenuation values is extremely large. A reliable fore-cast derived from environmental conditions like temperature, air pressure, and relative humidity can not be given.

3 MEASUREMENTS

To verify the assumptions made in the pre-considerations reported in the paragraph above, various measurements have been carried out during a period of several months. Thereby the weather conditions had an impact on the practicability of these measurements and long idle times had to be accepted.

3.1 Scintillations

Scintillation measurements have been done on various days using 808 nm and 975 nm sources. Figure 5 shows typical results for one and two transmitters. The cut-off frequency of scintillation spectra is on the order of 1 to 10 Hz. In accordance to the theoretical and simulation results, the histogram of receive power shifts towards higher powers for two transmitters. Some characteristic values for probability of fade and duration of fade as well as the power scintillation index given by

$$\sigma_P^2 = \left\langle P(t)^2 \right\rangle \Big/ \left\langle P(t) \right\rangle^2 - 1, \qquad (11)$$

can be found in table 1.

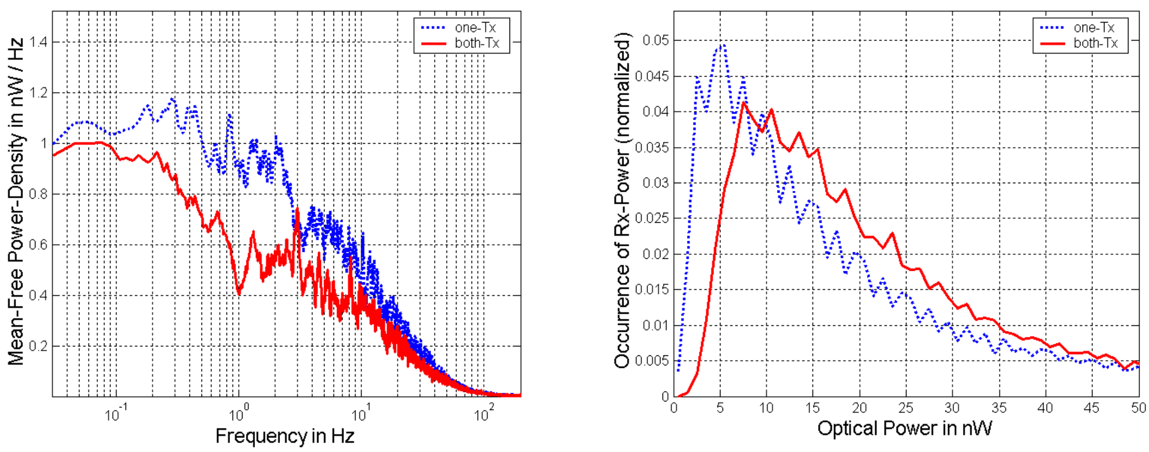

Figure 5: Typical frequency spectra (left) and normalized histograms (right) of received power with single- (dotted line) and double-transmitters (solid line).

For better comparison, the received power values of the double-Tx measurements have been devided by two, resulting in the same mean power for both measurements.

	Single Tx		Double Tx	
	max	**Min**	**max**	**Min**
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 %	5 %	8 %	1 %
mean duration of 6dB-fades	21 ms	8.5 ms	14 ms	4.4 ms
std-deviation of duration of 6dB-fades	25 ms	12 ms	14 ms	6.2 ms

Table 1: Typical statistics of optical Rx-power

3.2 Refraction

Refraction measurements have been carried out in cooperation with consulting engineers for surveying and mapping. Two parallel measurements, using hand-operated theodolites and an automated device respectively (using a CCD camera and performing center-of-gravity calculations, developed at DLR), have been done and showed consistent results. Temperature as well as air pressure have been recorded in Oberpfaffenhofen and on Wallberg. The data taken is shown is figures 6, 7, and 8. The maximum beam deviation in a period from 8:45am to 4:20pm was only 4.5 m or 73.9 µrad.

From the temperature values recorded, an average temperature gradient can be calculated, which is close to the adiabatic value of 1K/100m. A refraction coefficient can be calculated from the measured zenith angle z on Wallberg using (12):

$$k = \frac{2R_E}{s} \cdot \left(\cot z - \frac{\Delta h}{s} \right) + 1 \qquad (12)$$

Local refraction coefficients k_1 and k_2 at the transmitter and receiver respectively can be calculated from the meteorological data:

$$k_{1,2} = c_2 \frac{P_{1,2}}{T_{1,2}^2} \left(1 - c_3 \frac{\delta T_{1,2}}{\delta h} \right) \qquad (13)$$

where c2 = 17.189 and c3 = 0.2925. All values of k range between 0.125 and 0.155. This explains the small beam offset measured, but does not match the expectations at all (compare section 2.5).

4 DATA COMMUNICATIONS EXPERIMENT

4.1 Setup

Based on the assumptions reported in chapter 2, a communications system has been developed that was supposed to work up to 270 Mbps. Since no active pointing system was foreseen, the full divergence angle of the Tx telescope was chosen to be 660 µrad, which covers the most probable beam offsets due to refraction effects. This could be achieved by collimating the beam exhibited from a 100µm multimode fiber by a d=50mm/f=150mm achromatic lens. A multi-mode approach had to be pursued, since single-mode transmitters do not supply sufficient output power, when using that large divergence angles.

Since the scintillation effects can significantly be reduced by spatial diversity, two transmitters were set up and placed in either window of the Wallberg facilities at a distance of 4m. The minimum distance d_{Tx} between the two transmitters can be estimated from the relation

$$d_{Tx} > L \cdot \sqrt{\frac{\lambda}{L_S}}, \qquad (14)$$

where L_S is the common path of the two beams as shown in figure 9. In this particular scenario, d_{Tx} is less than 1m.

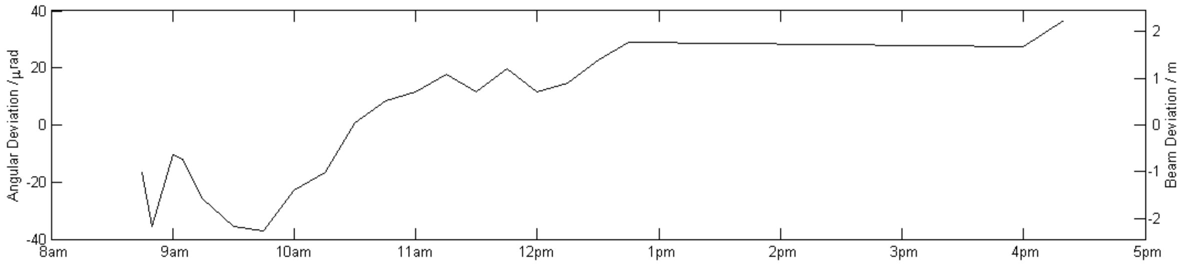

Fig. 6: Beam deviation from mean due to diurnal variations of refractive indices. Source of data: [9]

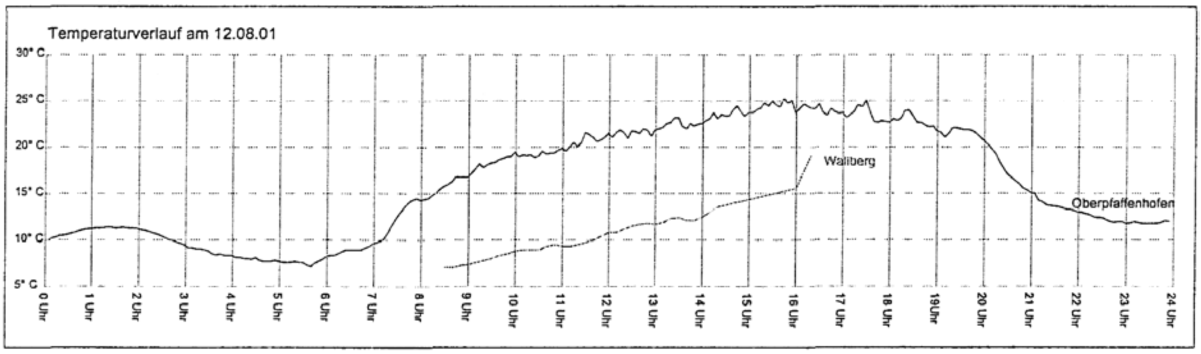

Fig. 7: Local temperatures in Oberpfaffenhofen and at Wallberg cable car station on August 12, 2001. Source: [9]

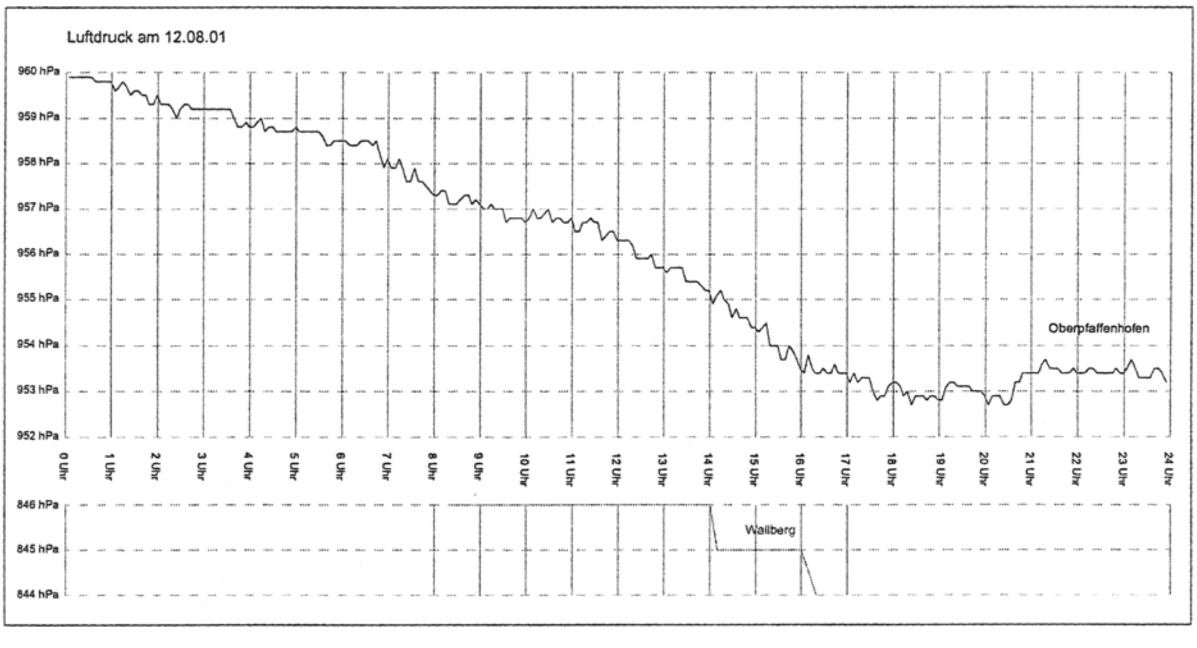

Fig. 8: Local air pressure in Oberpfaffenhofen and at Wallberg cable car station on August 12, 2001. Source: [9]

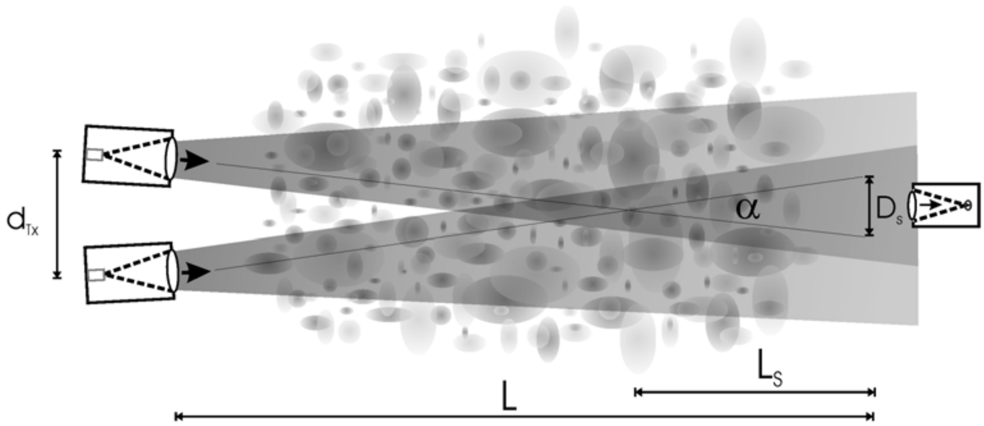

Figure 9: Double transmitter setup

As transmitters, 1 Watt laser diodes at a nominal wavelength of 975nm are used. The maximum diode current is approx. 2 Amps. Since no driver available on the market is capable of driving such currents at data rates up to 270 Mbps, a special design was commissioned. In a first stage, drivers for data rates up to 100 Mbps were delivered. Later they were improved for use up to 270 Mbps.

The receiver telescope consists of a d=75mm/f=300mm achromatic lens focussing the received light into a 200µm multimode fibre. This results in a field of view of 660 µrad. As receivers two APD-modules were at disposal. One having a bandwidth of 140 MHz suitable for 270 Mbps, but having a rather low sensitivity. The other, a special design of DLR, having a bandwidth of 50 MHz only, but showing a superior sensitivity. All additional electronics such as post amplifiers, decision circuitry and clock recovery were also developed by DLR.

Figure 10 gives an overview of the entire experimental setup for the atmospheric measurement and the data communications experiment.

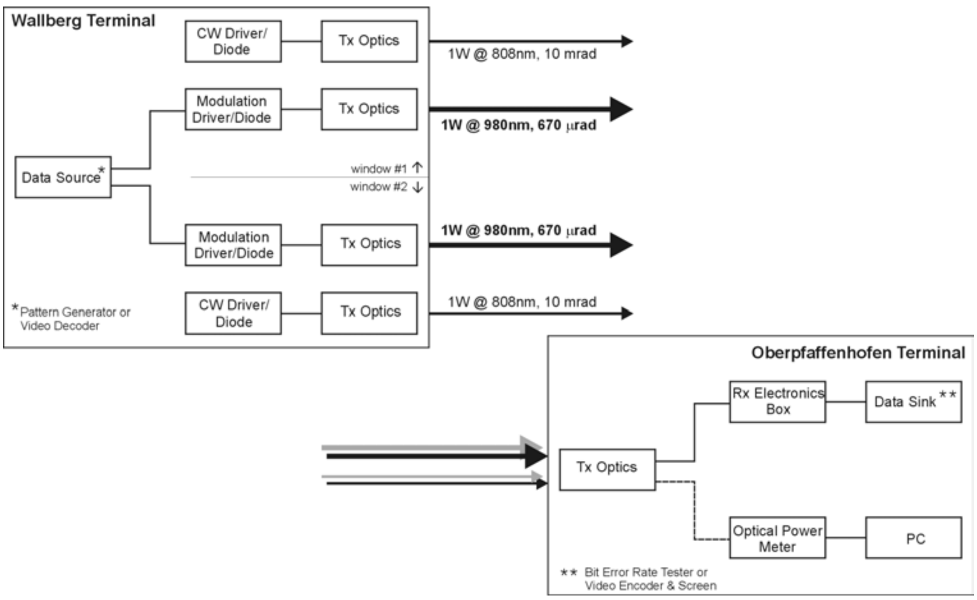

Figure 10: Schematic of the complete experimental setup

4.2 Component Test Results

To refine initial link budget calculations, laboratory tests were done to characterize Tx and Rx components. The transmitter modules in their final version show rise and fall times of 0.8 ns and 1.4 ns respectively. The extinction ratio achieved is 10dB. Figure 11 shows an eye-pattern, that was recorded using a wide-band receiver.

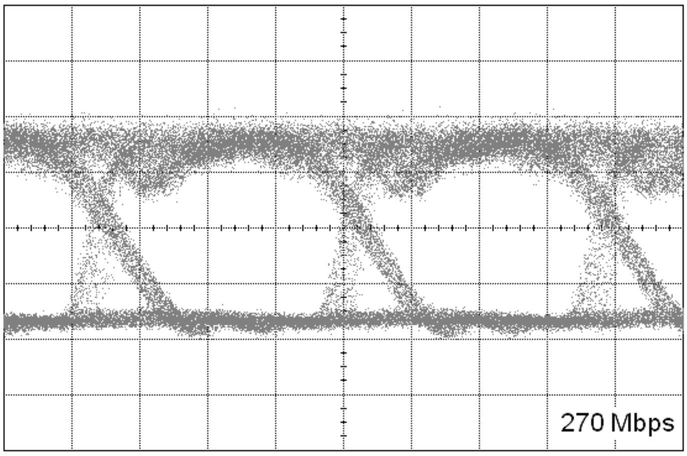

Figure 11: Eye Pattern of Tx module, recorded with wideband receiver

Both available receivers where tested for their optimum performance at arbitrary optical input levels. The results for the DLR front-end at a data rate of 100 Mbps are shown in figure 12. The proprietary development of DLR shows a significantly higher sensitivity and was therefore preferred for communication tests at 100 Mbps. For a bit error rate of 1e-6 an optical input power of 2.56 nW or –55.9 dBm is required.

A simple Rx model was fitted to the measured values, to allow for an exact investigation of the impact of scintillations on the bit error rate. E.g. assuming the Rx power distribution given in figure 5, a mean received optical power of 12.3 nW or -49.1 dBm is required for BER = 1e-6, when using the DLR front-end. Hence, atmospheric turbulence results in a loss of 6.8dB for two transmitters, which can also be seen in figure 12.

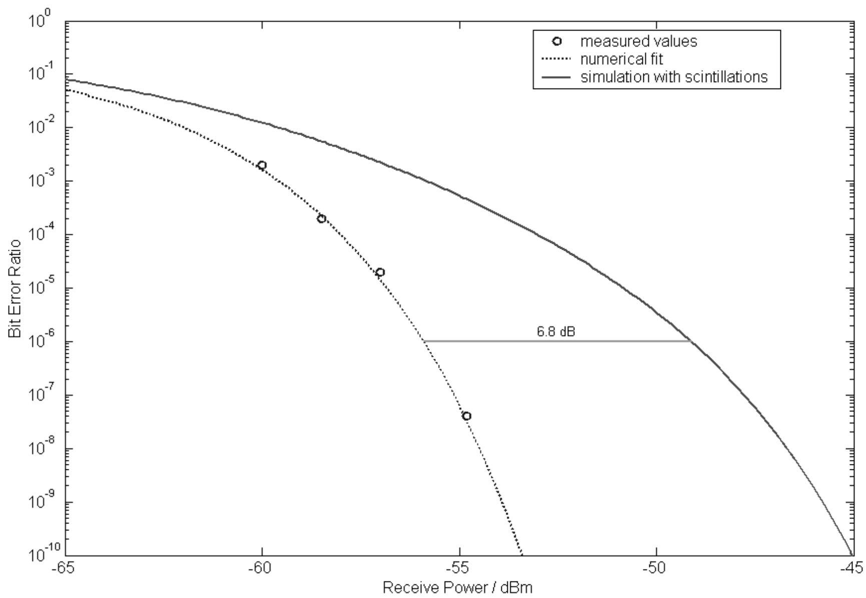

Figure 12: Bit error probability of DLR Rx module at 100 Mbps depending on optical input power (measured values, numerical fit, and simulated deterioration due to scintillations

4.3 Link Budget

Prior to the data communication experiments, link budget calculations regarding the optical and electrical properties of the experimental setup have been done to prove the feasibility of a communication link from Wallberg to Oberpfaffenhofen. Later, based on the component test results and based on scintillation measurements, link budgets were revised. Table 2 shows the adapted link budget for one particular day, when communications test were done successfully at a data rate of 100 Mbps. The visibility was good, but not excellent and atmospheric absorption turned out to be about 15 dB. Much higher values of received optical power have been observed during the measurement campaign. However, this fairly high attenuation leaves a margin of 5.2 dB in the link budget, which can easily be used up, when facing higher attenuation or stronger scintillations.

Tx Mean Power	1W	30 dBm
Tx Losses		-2.5 dB
Tx Antenna Gain	670 µrad	+75.5 dB
Range Loss	61 km	-237.9 dB
Rx Antenna Gain	75 mm	+107.6 dB
Rx Losses		-1.5 dB
Atmospheric Attenuation		-15.1 dB
Received Mean Power		-43.9 dBm
Margin		5.2 dB
Required Mean Power	BER=1e-6	-49.1 dBm
Scintillation Losses		-6.8 dB
Receiver Sensitivity	BER=1e-6	-55.9 dBm

Table 2: Exemplary link budget for day with good, but not excellent visibility. Data rate: 100 Mbps

4.4 Transmission Test Results

Transmission tests at a data rate of 100 Mbps were performed successfully on several days, when the visibility was good. The bit error rates achieved were very good (<<1e-6) in short term measurement. Long term measurements resulted in bit error rates on the order of 1e-4, which is worse than predicted by the revised link budget. The reason for this discrepancy are losses of clock synchronization during long and deep fades, that produced even more bit errors than really received.

Transmission tests at 155 Mbps and 270 Mbps could not be performed during the FASOLT experiment, since the delivery of the final version of the laser diode drivers was delayed and after that, the observed values of attenuation were too high for proper operation of the comms system. However, the feasibility of long-haul links could be shown. The possibility of stable transmission was limited to days with very good visibility.

5 RESULTS AND OUTLOOK

The goal of the FASOLT experiment was to do measurements of the properties of an atmospherical transmission path with strong turbulence and to demonstrate long-haul optical transmission at high data rates. As locations the DLR site in Oberpfaffenhofen and the station of the Wallberg cable car at an altitude of 1622m have been chosen. Hence the path length was 60.9 km. Measurements have been done that focused on beam offsets due to refraction and laser beam scintillations. A low cost communications system has been designed for transmission of 270 Mbps. However, data communications test could only be done at a data rate of 100 Mbps, since the delivery of an improved version of the special designed laser diode drivers was delayed. Very good short term bit error rates could be observed, though the mean bit error rate was limited to 1e-4. This is due to deep and long fades and the occurrence of clock synchronization losses.

These results clearly show a demand for improvement of the link performance by the application of diversity techniques and coding. For coding, the main problem will be the very long duration of fades (with respect to the bit duration) observed on this channel, which requires interleavers with deep memory and long delay respectively. First results of the investigation of the performance of block codes and interleaving are presented in this issue [10].

To reduce the disturbances due to scintillation, spatial diversity was applied in the FASOLT experiment and was proven to work quite well. However, other diversity concepts such as array detectors are under investigation at DLR as well. Result of the investigation of wavelength diversity are also presented in this issue [11].

Future projects and experimental work at DLR will focus on the application of optical cross-links to networks of stratospheric platforms.

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