Modeling of 830 nm FSO Link Attenuation in Fog or Wind Turbulence

Jiri PESEK [1], *Ondrej FISER* [2], *Jaroslav SVOBODA* [2], *Vladimir SCHEJBAL* [1]

[1] University of Pardubice, Pardubice, Czech Republic
[2] Institute of Atmospheric Physics. Bocni II/1401, 141 31 Prague 4, Czech Republic

pesek@free-soft.cz, ondrej@ufa.cas.cz

Abstract. *This study is focused on the experimental research of the atmosphere impact on FSO link attenuation. Experiment is performed on a mountain observatory Milesovka of severe weather conditions. The empirical relationships on 830 nm only between FSO attenuation A on one hand and atmospheric visibility V or wind turbulent energy E_T on the other hand are presented and discussed. In the fog case it was found* $A = 401.4V^{-0.5738} - 1.462$ *dB/60m (V in meters) while for the attenuation due to the wind turbulence E_T it holds* $A = 2.112 - 2.213\exp(-0.2867E_T)$ *dB/60m (E_T in m^2s^{-2}, it was derived for 830 nm wave length). A discussion concerning problems of the "clear air attenuation," atmospheric turbulences and sun shine impact, which was observed as a maximum 2 dB attenuation for a few minutes with a period of 24 hours is added.*

Keywords

Free space optics propagation, fog attenuation, wind turbulence attenuation, turbulent energy.

1. Introduction

The relationships between FSO link attenuation and visibility or between FSO link attenuation and wind turbulent energy is of a big interest and importance playing a role in the FSO planning. For this study we have used the experimental link of the Institute of Atmospheric Physics (IAP). This study is concerning only one FSO wavelenght which is 830 nm.

The optical link is installed on the mountain observatory placed on top of the Milesovka hill. This hill of 837 m a.s.l. is an isolated volcanic cone roughly by 400 m higher than the surrounding terrain. The top of the mountain is therefore almost not affected by the boundary layer and is exposed to strong winds, lightning etc. Low visibility due to low cloudiness and fog is also often observed.

The experimental optical link works as a simplex communication link with an optical transmitter and an optical receiver at a distance of 60 m. The link is slanted with the angle of approximately 30 degrees.

The transmitter head includes two separate optical sources using laser diode modules with wavelengths of 830 nm and 1550 nm. Both of these laser diodes are modulated and alternate switched by microprocessor. The measuring interval is 15 second for 830 nm and consequently 15 seconds for 1550 nm. The output laser beams comply with the Gaussian beam distribution with beam divergences of 6 mrad for the 830 nm and 12 mrad at 1550 nm wavelengths. The transmitter is located in the garden near the meteorological sensors.

The receiver head contains a photodiode module with preamplifier (including gain control), filter and a control unit for the evaluation and storage of the data measured. The diameter of the receiver lens is 60 mm. As a detector the InGaAs photodiode FGA10 was chosen for its wide spectral response. For signal processing, a logarithmic detector with a dynamic range of 90 dB was used. The receiver is located on top of the observatory tower. The configuration of the optical link as well as other measurement devices can be seen in Fig. 1.

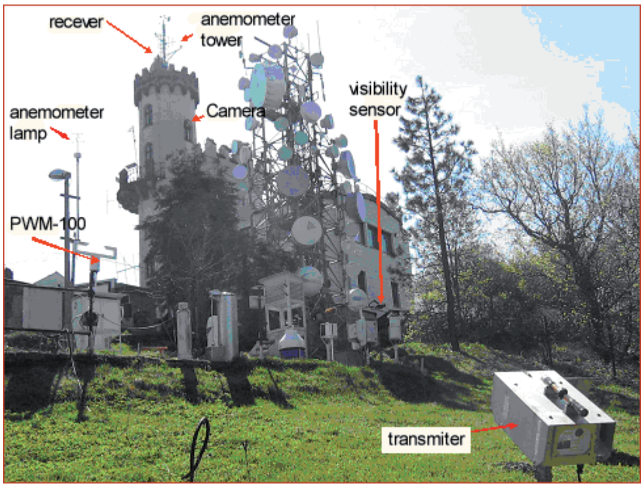

Fig. 1. The arrangement of the free-space optical link at the Milesovka observatory.

The attenuation measurements on the optical link are quasi-continuous and the average values on one wavelength are saved every 15 s while the average attenuation on the second wavelength are stored next 15 s. The optical set was made at the Department of Radio Electronics, Brno University of Technology (DREL).

The wind propably does not cause the transmiter vibrations as it is shadowed by high trees on one hand and the console is fixed in a huge concrete base on the other hand. The reciever is fixed in the 100 years old stone tower supposing no vibration impact.

The fluid convection can be laminar or turbulent one. In the second case we understand that the velocities vary randomly, however the law of conservation of matter and law of conservation of momentum are respected. The atmospheric turbulence is similar to the wind one but it respects not only wind parameters, but also air pressure, humidity and air density. All these parameters can be concentrated into the refractivity index.

2. Fog Attenuation Measurement and Modeling

The FSO link attenuation data collection is performed at the IAP observatory for nearly 3 years. Fig. 2 shows the example of attenuation A time course and estimated attenuation course from inverted visibility $1/V$ (through our empirical formula having been found more or less subjectively):

$$A = \frac{1350}{V} \quad \text{[dB/60m]} \tag{1}$$

where V is the visibility in [m]. The period of measurement is from the 120th to 152nd day of the 2009 year.

One can see that the attenuation reaches high values (35-40 dB related to 60m path). It is due to the extreme weather conditions at our Milesovka observatory. This “before time” suggested approximation (1) fits the measured values quite well but this approximation is not the ideal one. Also the integration time was 15 minutes in this case - so the resolution is small.

Now having more experimental data (one year) and after substraction of the threshold from attenuation we tested a few analytical approximations searching for appropriate relation between attenuation and visibility using the regression technique. The following approximation seems to be better than the previous one:

$$A = 401.4\,V^{-0.5738} - 1.462 \quad \text{[dB/60m]} \tag{2}$$

while for goodness of fit it holds: R^2=0.9724 (coeficient of determination), $RMSE$ = 0.45 dB (Root Mean Square Error). Visibility V should be given in meters.

Let us describe the technique for this approximate formula derivation now. It is flowing from alternated scatter-plot. For certain visibility intervals (0-100m, 100-200m,....) we evaluated mean value, median, standard deviation, minimum and maximum of measured attenuation within one year measurement. Each of these parameters was assigned to the middle of such visibility interval (see Fig. 3 and points in Fig.4).

In Fig. 4 we can see comparisons of measured attenuation with estimated ones using relations (1) or (2). There is also well known Kim’s relation [3] added. Fig. 4 was constructed as an alternated scatter-plot between visibility and median value of attenuation within 100m visibility intervals.

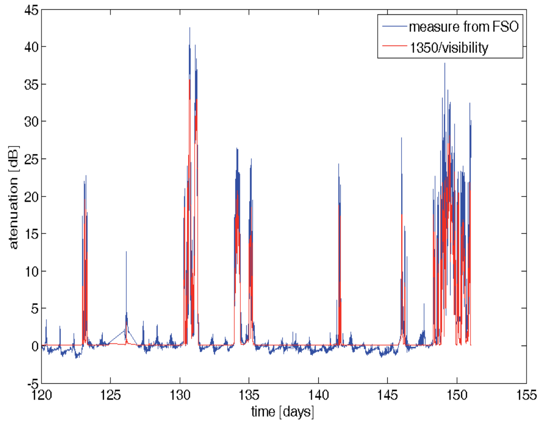

Fig. 2. Attenuation course on 830 nm (blue line) and estimated attenuation course (red line) for the 120th to 152nd days of the 2009 year. Estimation is based on (1).

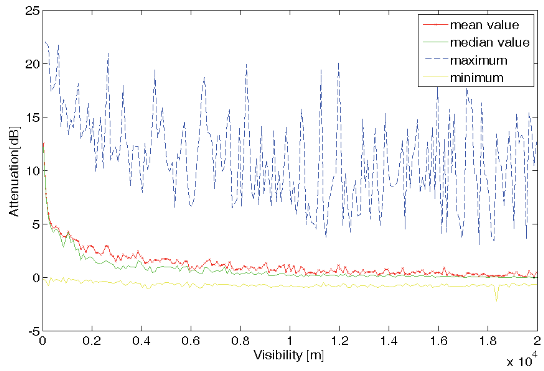

Fig. 3. Alternated scatter-plot of attenuation on 830 nm maximum (blue), minimum (yellow), mean value (red) and median (green) for visibility intervals of 100m length (derived from attenuation measurement at the IAP Milesovka observatory within period October 2008 - October 2009).

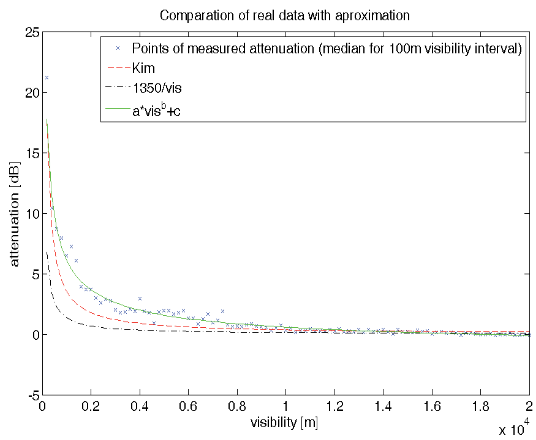

Fig. 4. Comparisons of measured attenuation on 830 nm with estimated ones from relations (1) or (3). This alternated scatter-plot is derived from one year attenuation and visibility measurement (October 2008 - October 2009).

2.1 Automatic Thresholding

The negative attenuation values obvious in Fig.2 must be understood as a result of data processing algorithm. The attenuation is computed from received power and its minimum corresponds to the recorded attenuation between 6 and 10 dB. We are searching for minimum attenuation values in calendar months subjectively calling this minimum "threshold." In fact, this is a reference level sometimes called "clear weather attenuation." This threshold varies month to month due to technical reasons. The considered attenuation is result of received power reduced by the found threshold value:

$$A = A_{meas} - Threshold \text{ [dB]}. \quad (3)$$

We are aware that our thresholding method is subjective one being not very comfortable. That's why we tried to perform the thresholding automatically. First of all we read the minimum attenuation value $A_{\min}$ in the chosen period (calendar month in our case). Then we search for the modus value among attenuation values from $A_{\min}$ to $A_{\min} + B$. For B we use an empirical value of 7dB.

3. Investigation of Relationships between Attenuation and Simple Wind Parameters

Our research of wind impact on FSO link attenuation is based on simultaneous measurement of attenuation and many wind parameters. To find out a relation between wind parameter and FSO link attenuation it is necessary to exclude the recorded fog attenuation and we did it. One can see that attenuation achieves expected fog attenuation values only for low visibility values while attenuation values are also disseminated for visibilities above 10 km (see, for instance, 25 dB values for visibility of 17 km in Fig. 5). Reason for this attenuation values cannot be fog, it must be wind (most probably).

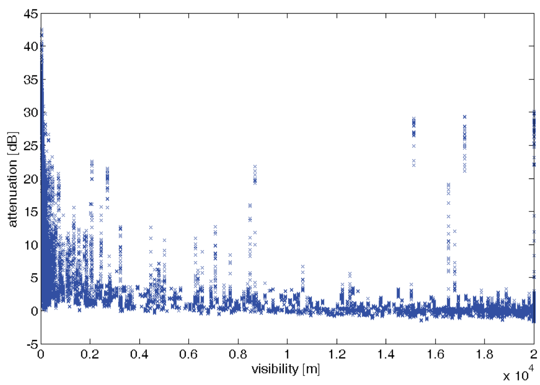

Fig. 5. Visibility-FSO 830 nm link attenuation scatterplot. This example is from May 2009 data.

To separate the fog attenuation we decided to neglect all attenuation data when the visibility was below 2700 m (it corresponds to the attenuation of about 3 dB after Kim model [3]).

We selected important wind parameters influencing the FSO link attenuation due to the optical energy redistribution. The quite good correlation between wind attenuation and turbulent energy of wind E_T was found in our research [1]. Formula for the turbulent energy E_T is taken from [2]:

$$E_T = 0.5\frac{1}{N}\sum_{i=1}^{N}\left[(u_i-\bar{u})^2+(v_i-\bar{v})^2+(w_i-\bar{w})^2\right] \quad (4)$$

where u, v and w are x-, y- and z (vertical) axis components of the wind speed vector $\mathbf{v}$; $\bar{u}, \bar{v}, \bar{w}$ are mean values of the wind velocity componets within integration interval. The integration time was 15 seconds so 150 samples (N=150) were obtained during one integration event (one wind velocity component is recorded every tenth of second). The turbulent energy represents the wind velocity standard deviation in fact.

Fig. 6 is showing the turbulent energy - FSO link attenuation scatterplot. We can see a great cumulation and dispersion of attenuation values close to small turbulent energy, on the other hand, attenuation values for turbulent energy above 6 $(m/s)^2$ are more unique (relatively small dispersions).

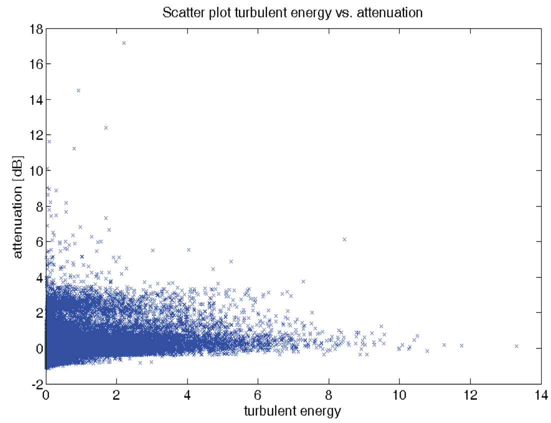

Fig. 6. Scatterplot turbulent energy – 830 nm FSO link attenuation; fog attenuation is excluded (data from July 2009).

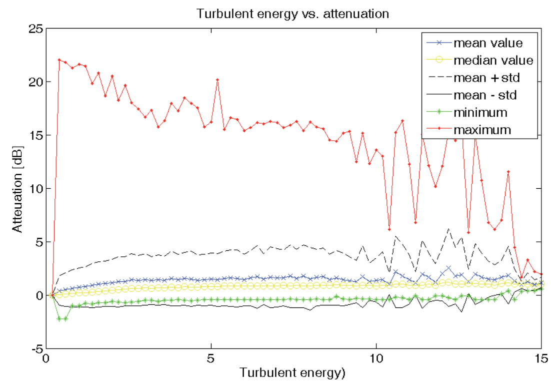

Fig. 7. Alternated scatterplot of attenuation on 830 nm: turbulent energy dependence (minimum, maximum, mean value, mean value +/- standard deviation, median). For details see Fig. 8.

Fig. 7 shows alternated scatter-plot between the turbulent energy and FSO link attenuation (fog attenuation was excluded), i.e. the mean value, standard deviation, median, maximum and minimum were evaluated for certain turbulent energy interval of the 0.2 $(m/s)^2$ span. One can see that the extreme values are decreasing with the increasing turbulent energy. Fig. 8 shows details resulting in the attenuation - turbulent energy (A-E_T) dependence.

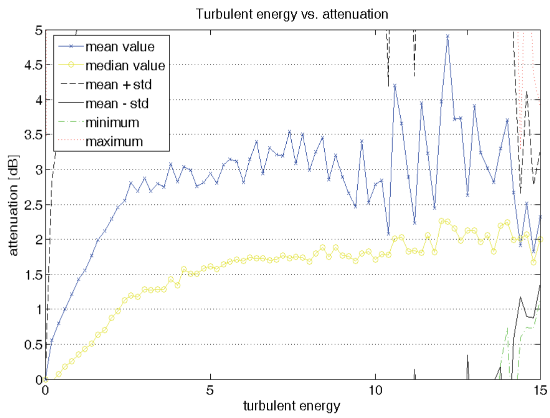

Fig. 8. Attenuation on 830 nm - turbulent energy (A-E_T) dependence (detail of Fig. 7). Blue line is the interval mean value, yellow line represents the median.

As the A-E_T relation seems to be clear, a numerical approximation of this would be welcome. We found a quite good one for median value due to regression (see Fig. 9):

$$A = 2.112 - 2.213\, e^{-0.2867 E_T} \tag{5}$$

For goodness of fit it holds: $R^2 = 0.94$, $RMSE = 0.85$ dB. In the future we intend to consider also turbulence of index of refraction [4].

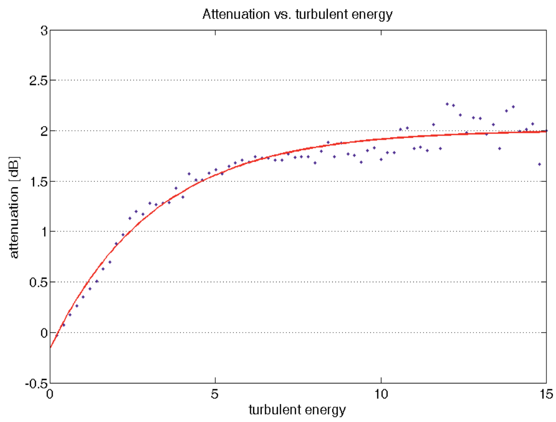

Fig. 9. Attenuation on 830 nm - turbulent energy (A-E_T) dependence. Red line represents the found numerical approximation of the A-E_T relationship (4). The used data are from the IAP's Milesovka observatory derived from the October 2008 - October 2009 period.

4. Conclusion

From our measurement at the Milesovka observatory the empirical attenuation-visibility relations were found for wavelength 830 nm and due to the RMSE and correlation coefficient tested, see (1) and (2). Equation (2) fits the attenuation estimation based on the visibility much better because it is based on regression technique. On the other hand, equation (1) yields results being more similar to the Kim's formula [3].

A progress was performed in the research of the wind impact on the optical signal attenuation. First relation between the attenuation and turbulent energy E_T was formulated (5). The standard deviation for intervals of turbulent energy of absolute values above 11 $(m/s)^2$ is decreasing with the turbulent energy. It is obvious that in these cases the A-E_T dependence is more unique with the tendency to be constant (see Fig. 4). On the other hand, the standard deviations in E_T intervals for low turbulent energy values is big so the attenuation estimation could be ambiguous and equation (5) can be understood as a statistical estimation.

Of course the question whether to consider median or mean value within the E_T intervals in the wind impact investigation is to be discussed. We incline to prefer median as it omits random extreme attenuation values which can occur during the measurement campaign.

It was observed that the sun shine regulary influences the FSO signal fluctuation once per 24 hours for a few minutes. The sun shine causes maximum 2 dB attenuation.

The data sampling as well as processing is continuing. We plan to focus on the wind turbulence research on both wavelengths at our disposal.

Acknowledgements

The authors thank to Prof. Otakar Wilfert and Prof. Zdeněk Kolka both from the Brno University of Technology (DREL) for the useful cooperation on the experimental FSO link performance. This study was thankfully supported by the GAČR grant Nr. 102/08/0851 and MŠMT grant Nr. OC09027 (project COST IC0802).

References

[1] FISER, O. et al. Attenuation measurement on dual-wavelength optical free-space link. In *Proc. of SPIE, session Atmospheric Optics: Models, Measurements and Target-in-the-Loop propagation III*. San Diego (USA), 3-4 August 2009, pp. 7463-1 - 7463-11.

[2] STULL, R. B. *An Introduction to Boundary Layer Meteorology*. Kluwer Academic Publisher, 1991.

[3] KIM, I., MCARTHUR, B., KOREVAAR, E. Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications. In *Proc. of SPIE – vol. 4214 Optical Wireless Communications III*. Ed. Eric J. Korevaar, February 2001, pp. 26-37.

[4] ANDREWS, L. C., PHILLIPS, R. L. *Laser Beam Propagation through Random Media*. SPIE Press, June 1998

About Authors …

Jiří PEŠEK received his MS from the Faculty of Electrical Engineering, Czech Technical University in Prague in 2009. Now he is Ph.D. student of the Faculty of Electrical Engineering and Informatics, University of Pardubice focusing on FSO link communication and computer networks.

Ondřej FIŠER received his M.S. degree (1977) in Electrical Engineering and his Ph.D. degree (1986) in Electronics, both from the Czech Technical University in Prague. He works as a scientific researcher at the Inst. of Atmospheric Physics, Academy of Sciences of the Czech Republic, focusing on the atmospheric radiowave and FSO propagation research and radar meteorology (http://www.ufa.cas.cz/html/meteo/lide/ fiser.html). He also teaches electrical engineering at the University of Pardubice.

Jaroslav SVOBODA studied meteorology and climatology at the Faculty of Mathematics and Physics, Charles University in Prague (graduated in 1967) where he defended also his Ph.D. theses (1980). He has worked at the Institute of Atmospheric Physics, Academy of Sciences of the Czech Republic since 1968. Professional interests: physical design of mathematical models of the atmospheric boundary layer over a complex terrain, development of numerical codes of the boundary layer models, comparison of model outputs with measurements.

Vladimir SCHEJBAL graduated from the Czech Technical University in Prague in 1970. He received the PhD degree from the Slovak Academy of Science, Bratislava in 1980. He was with the Radio Research Inst. Opocinek, Antenna Department. from 1969 to 1993. From 1983 to 1986, he was on a leave with the Higher Inst. of Electronics (Microwave Department) Beni Walid, Libya as a lecturer. He has been with the University of Pardubice since 1994, now as a full professor and a head of the department. He is interested in microwave antennas and propagation.