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

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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 $A = 401.4V^{-0.5738} - 1.462\text{ dB/60m}$ ($V$ in meters) while for the attenuation due to the wind turbulent energy $E_T$ it holds $A = 2.112 - 2.213\exp(-0.2867E_T)\text{ dB/60m}$ ($E_T$ in m$^2$s$^{-2}$, it was derived for 830 nm wavelength). 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 wavelength 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 wind probably does not cause the transmitter 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 receiver 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):

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

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:

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

while for goodness of fit it holds: $R^2=0.9724$ (coefficient 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.
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:

\[ A = A_{\text{meas}} - \text{Threshold} \, [\text{dB}] \]  

(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 \( A_{\text{min}} \) in the chosen period (calendar month in our case). Then we search for the modus value among attenuation values from \( A_{\text{min}} \) to \( A_{\text{min}} + B \). For \( B \) we use an empirical value of 7 dB.

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).

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]:

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

(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 components 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 \((\text{m/s})^2\) are more unique (relatively small dispersions).
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.

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):

$$A = 2.112 - 2.213 e^{-0.2867E_T}$$  \hfill (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].

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 regularly 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.

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References


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