Correlation of free-space optics link attenuation with sonic temperature

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Abstract. Our correlation analysis has shown promising and surprisingly good dependence of optical signal attenuation on sonic temperature, which is shown and discussed in this study. This discovered dependence is derived from measurements (periods with fog and rain events were excluded) and presented in the form of scatter plots. It is possible to express roughly that the attenuation decreases with the sonic temperature (negative correlation coefficient). Trying to understand our results, we added the explanation of the physical quantity sonic temperature in this contribution. © *2013 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.52.3.030503]

1 Introduction

One of modern telecommunication tasks is the estimation of the atmospheric attenuation of free-space optics (FSO) link operating in optical frequency bands. Even if fog and rain (and more or less wind turbulence) are subjects of the main interest,[1] we cannot forget the so-called "clear air" effects. The experimental activity of the Institute of Atmospheric Physics Prague (IAP) is also focused on the studies of the impact of wind parameters on the FSO link attenuation. The sonic anemometers are used for this purpose. Most modern sonic anemometers determine sonic velocity components [two-dimensional (2-D) or three-dimensional (3-D)] from measurement along a very short known path between two points of anemometer. The wind velocity component is derived from the time delay of acoustic pulse. In the case of 3-D anemometer there are three pulses sent in three perpendicular directions between two sensors (acoustic transmitter and receiver). Some sonic anemometers (including our ones) provide also sonic temperature as one of the output parameters,[2] and this parameter was also correlated with the measured FSO link attenuation. Surprisingly, the sonic temperature was well correlated with the FSO link attenuation. Chapter 3 deals with the sonic temperature in more details.

2 Description of Experimental Site

Our experimental activity is concentrated to the mountain meteorological observatory "Milesovka" (more information at http://www.ufa.cas.cz/html/meteo/mile.eng.html).

The Milesovka observatory (about 75 km northwest to Prague) is situated at the summit of an isolated, conically shaped mountain (837 m a. s. l.). The conditions on the top of Milesovka are close to free-space conditions. Book[3] deals with meteorological and climatic conditions on this hill in more detail. The experimental slant dual wavelength optical link has been operating for more than three years (since October 2008). The link length is 60 m while wavelengths being 830 and 1550 nm. Figure 1 is showing the profile of our FSO link. The data are sampled with a resolution of 15 s. Then they are averaged with the integration time being 1 min. The data are processed: a) to obtain the FSO link statistics of atmospheric attenuation; b) to compare attenuation with the meteorological models estimating the FSO link attenuation; c) to compare attenuation on both channels. More technically oriented description of our FSO experimental link was published in Ref. 4.

The wind measurements are performed by two Metek 3-D Ultrasonic anemometers USA-1. One of them is situated on top of the observatory tower very close to the optical receiver. The other one is located on a lamp post in the garden at the height of about 5 m above the surrounding terrain while the distance from the transmitter is about 12 m. The wind data are recorded every 0.1 s because these measurements are the primary source for wind turbulence calculations.

In this study, we focused on data processing during the period 1 January 2009–31 December 2011 at both lamp and tower site. The measured parameters are wind direction [°], wind speed in horizontal perpendicular axes x and y, and in vertical direction z [m/s] and sonic temperature.

3 Sonic Temperature: What Is It?

One of the available parameters measured by our METEK sonic anemometer is the sonic temperature T_s defined as:[2]

$$T_s = T\left(1 + 0,32\frac{e}{p}\right)[K]; \qquad e = \frac{rh e_s}{100}[hPa], \qquad (1)$$

where T is air temperature [K], p is air pressure [hPa], e is the pressure of water vapor [hPa], rh is the relative air humidity [%], and e_s is the pressure of saturated water vapor [hPa], which can be estimated from

$$e_s = 6.108 e^{\frac{7.5(T-273.15)}{237.3+(T-273.15)}\ln(10)}[hPa]. \qquad (2)$$

The sonic temperature is very close to the virtual temperature being defined as the temperature at which dry air has
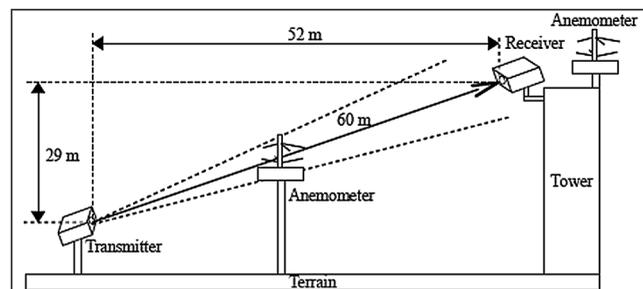

Fig. 1 Sketch of FSO link of the IAP Prague at Milesovka hill.

the same density as moist air at the same pressure.[5] The virtual temperature can be expressed approximately by[5]

$$T_v = T\left(1 + 0,378\frac{e}{p}\right) = T\left(1 + 0,61\frac{M_w}{M_w + M_d}\right) [\text{K}],$$

(3)

where M_w is the mass of water vapor and M_d is the mass of dry air, both in [kg] and in considered volume. The effect of the clear air atmosphere parameters on the speed of the sound v [m/s] can be approximated[2] as

$$v = \sqrt{c_t T\left(1 + 0.32\frac{e}{p}\right)} = \sqrt{c_t T_s}.$$

(4)

For the constant c_t it holds $c_t = 403 \text{ m}^2/(\text{s}^2 \text{ K})$. The virtual temperature [Eq. (3)] does not significantly differ from the sonic temperature given by Eq. (1). Our numerical tests generating all combinations of temperature, relative humidity and air pressure values proved that the relative difference is lower than 0.01%.

To sum up this chapter, the sonic temperature is one of the important atmospheric parameters reflecting its state. The sonic temperature can be calculated through Eq. (1) by knowing air temperature T, relative humidity rh, and air pressure p or can be estimated by close virtual temperature [Eq. (3)] or measured by a sonic anemometer (considering the measured sound velocity v) using Eq. (4).

4 Results

We pointed at the problem of correlation coefficients between FSO link attenuation and sonic temperature. We calculated the correlations coefficients between these two characteristics excluding attenuation data being influenced by rain or fog (to be more specific, we excluded the data when the visibility was below 1350 m and rain rate was above 0 mm/h). The correlation coefficients are shown in Table 1. The correlation between attenuation and sonic temperature is negative and statistically significant for both wavelength channels. The explained variance amounts to about 14%.

The correlation coefficient value is about −38%, which indicates significant dependence of the attenuation on the sonic temperature. In order to visualize the dependence of the FSO link attenuation on the sonic temperature, we draw scatter plots for data from anemometer located on the lamp post and the tower, respectively. The attenuation

Table 1 Correlation coefficients between FSO link attenuation and sonic temperature (three year data).

Channel	Corr. coef.	Number of data	Critical value	Explained variance [%]
1550 nm	−0.3861	424377	−251.52	14.907
830 nm	−0.3627	802427	−324.90	13.155

Table 2 Derived coefficients k and q of equation $A = kT_s + q$, where A is attenuation [dB/60 m] and T_s is sonic temperature.

|	Tower		Lamp	
Wavelength	1550 nm	830 nm	1550 nm	830 nm
k	−0.028	−0.045	−0.026	−0.043
q	0.337	0.427	0.290	0.364

decreases with the increasing sonic temperature. The curve courses are similar in both cases (lamp and tower). For practical utilization, we formulated simple linear relationship between the attenuation A [dB/60 m] and the sonic temperature T_s [K], see Table 2. From the physical point of view, it is expected that the FSO link attenuation is proportional to the relative humidity (rh). To explain the negative correlation, we plotted the dependence of the relative humidity on the sonic temperature seeing that the rh decreases with increasing sonic temperature. This statement comes from Eqs. (1) and (2) supposing that water vapor pressure is more or less constant while the relative humidity changes with temperature through the saturated vapor pressure.

5 Conclusion

Studying the impact of wind turbulence, we were using many parameters provided by the 3-D sonic anemometers. One of those parameters—sonic temperature—shows good correlation with the FSO link attenuation. The sonic temperature does not correspond to the wind turbulence, but it describes—as shown in our contribution—the impact of water vapor on the FSO link attenuation.

We presented the dependence of measured FSO link attenuation on the sonic temperature, which was found to be decreasing. We acknowledged this fact by numerical simulation supposing that the attenuation is proportional to the air humidity.

Our conclusions are plausible also due to the fact that we obtained similar scatter plots (see Figs. 2 and 3) from the sonic temperature measurement on two distant places (tower and lamp post). Also the attenuation results on wavelengths
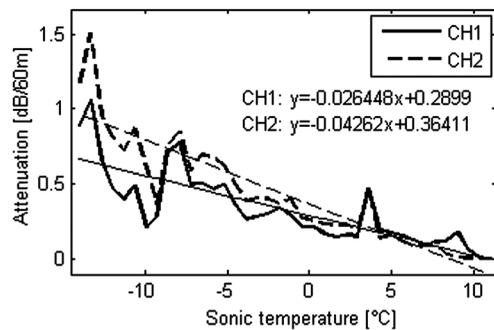
Fig. 2 Scatter plot between FSO link attenuation and sonic temperature measured on the lamp post; three-year measurement at the Milesovka observatory. The CH1 curve corresponds with the 1550 nm, CH2 to 830-nm wavelength.
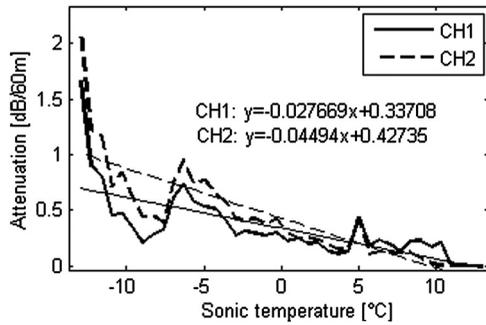
Fig. 3 Scatter plot between FSO link attenuation and sonic temperature measured on the observatory tower (receiver); three-year measurement at the Milesovka site. The CH1 curve corresponds with the 1550 nm, CH2 to 830-nm wavelength.

830 and 1550 nm are very similar, while the attenuation on 1550 nm is slightly lower (as expected). On the other hand, the attenuation being investigated as a function of the sonic temperature is of a quite low value (not exceeding 2 dB/60 m).

Our considerations have shown that sonic temperature expresses the status of atmosphere from the "clear air" point of view. It reflects the impact of the atmospheric gases (especially water vapor) on the FSO link attenuation. The sonic temperature was found to be an appropriate FSO link attenuation predictor at clear air conditions.

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