Empirical Relations for Optical Attenuation Prediction from Liquid Water Content of Fog

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Abstract. *Simultaneous measurements of the liquid water content (LWC) and optical attenuation have been analyzed to predict optical attenuation caused by fog particles. Attenuation has been measured at two different wavelengths, 830 nm and 1550 nm, across co-located links. Five months measured data have been processed to assess power-law empirical models, which estimate optical attenuation from the LWC. The proposed models are compared with other published models and are demonstrated to perform sufficiently well to predict optical attenuation if the LWC values are available.*

Keywords

Free-space optical links, liquid water content, optical attenuation, drop size distribution, aerosols.

1. Introduction

Free-space optical (FSO) links are supposed to operate through atmosphere which contains fog, smoke, dust, rain, smog and charged particles. The terrestrial FSO links provide a viable last mile solution for high speed connectivity without the need of digging roads and streets which is necessary for laying the conventional fiber [1]. Atmospheric particles attenuate the optical beam, propagating through the line-of-sight FSO links. Among all these, fog is the most serious deterrent [2], [3]. Fog can be characterized by the liquid water content (LWC), optical visibility, drop size distribution and temperature [4]. The scattering and absorption of laser beam propagating through the atmosphere are associated with the size of fog droplets, their effective radii and the microphysical properties of fog, specifically the liquid water content [3], [5].

The LWC is the total mass of water per unit volume of the droplets in air and it is usually expressed in g/m^3. The LWC is used to characterize different types of fog/clouds. Higher amount of liquid water content decreases visibility and indicates dense fog [5], [6].

LWC varies for different types of fog and clouds. The variation of LWC for different fog stages (for a specific fog type) when the visibility is about 200 m has been provided in [17], see Tab. 1.

Fog stage	**LWC (g/m^3)**
ground fog	0.05
formation fog	0.075 - 0.173
mature fog	0.126 - 0.175
dissipation fog	0.162 - 0.166

Tab. 1. An example of variation of LWC for different fog types, from [17].

It is interesting to observe the built up of the LWC as the fog settles down. Closer analysis of Tab. 1 indicates that LWC of the fog particles is low during the formation phase but reaches higher values when the fog has settled in and matures. The LWC again starts to decline during fog dissipation.

For FSO technology, to mature and reach mass acceptability, there is the need to investigate different weather impairments on FSO links and predict the attenuation of transmitted laser beam caused by atmospherics aerosols [7]. The prediction of optical attenuation in lower atmospheric visibility ranges due to haze, fog, and clouds has been thoroughly investigated and researched [8], [9], [10]. At the moment, only few empirical relationships are available between the LWC and optical attenuation based on directly measured values of optical attenuation and the LWC simultaneously. Though several efforts have been made to estimate extinction coefficient (extinction coefficient is measured in km^{-1}) [5], [11], [12] and attenuation [13], [14] for FSO links on the basis of the LWC. The purpose of the current work is to use the real measured data of the optical attenuation and LWC which were measured simultaneously in Prague during 5 month period to predict optical attenuation from the LWC.

This paper is organized as follows. Section 2 describes the experimental setup used to collect the measurements. The microphysical properties of fog that help to determine the relationship between the LWC and optical attenuation are discussed in Section 3. Section 4 presents the analysis of the measured data and proposes models for estimating optical attenuation from the LWC. The assessment of the new models and a comparison with other existing empirical models is presented in Section 5. Finally, Section 6 draws conclusions.

2. Experimental Setup

The measurement campaign was carried out by the Department of Frequency Engineering, Czech Metrology Institute (CMI) Prague, Czech Republic, from 8 January 2009 till 31 May 2009. CMI is located at latitude 50° 05' 12" N, longitude 14° 24' 59" E, and at altitude of 191 m. Prague has continental weather and the air mean temperature of 10.4 °C since 1971 till 2000. Two FSO systems were installed at path length of 100 m at operational wavelength of 1550 nm and 830 nm. The technical specifications of the experimental installation in Prague are given in Tab. 2.

Description	**1550 nm Link**	**830 nm Link**
Wavelength	1550 nm	830 nm
Link distance	100 m	100 m
Transmitted Optical power	3.5 dBm	13 dBm
Lens Diameter	18 cm	15 cm
Fade Margin	13 dB	18 dB
Modulation Scheme	OOK Intensity modulation	OOK Intensity modulation

Tab. 2. Technical details of the FSO links.

The FSO systems were installed 26 meters above the ground level. The link margin of the two FSO systems allowed the measurement of specific attenuation up to 180 dB/km for 830 nm wavelength systems and 130 dB/km for 1550 nm system. Optical calibration was performed before deploying the FSO devices. A received power was obtained from the calibrated Received Signal Strength Indicator (RSSI) signal of the FSO link. Meteorological conditions were identified by means of a color video camera and an automatic weather observation system, located near the FSO receivers. The system used Vaisala sensors for the measurement of temperature, humidity, air pressure, velocity and direction of the wind. The VAISALA PWD 11 equipment measured the atmospheric visibility (5 % definition) values in the range from 50 m up to 2000 m using forward scattered light in an angle of 45°. The liquid water content of fog is measured by the device PVM-100, Gerber Scientific. The principle of the LWC measurement is, similarly as in the case of visibility, again based on optical scattering from small volume of air. The meteorological data were synchronized in time with the measurements of optical attenuation. The received FSO signal levels and the meteorological data were recorded synchronously on a PC's hard disk.

3. Microphysical Properties of Fog

Microphysical properties of fog such as the drop size distribution (DSD), the drop shape and the composition of particles are strongly influenced (both temporally and spatially) by the microclimate and by several environmental factors. To assess the performance of FSO links in terms of availability and reliability, the sensitivity of signal attenuation to microphysical quantities like the LWC, DSD, average particle size and the number concentration must be investigated well [3], [15]. In order to estimate the optical attenuations particularly in a fog environment, besides from the particle size distribution, LWC (mass of water droplets present per unit volume of air) is another important microphysical property. Within the fog particles LWC is highly influenced by fog particle's DSD and the number concentration.

Attenuation caused by fog particles is highly dependent upon the fog particle radii. For an optical beam propagating through fog, Mie resonance occurs at wavelengths comparable to the fog particle radii. The fog particle radii differ in different climatic regions and hence, optical wave propagating through fog conditions even at the same wavelength, face varying attenuation. Assuming spherical shape, fog particles can be categorized into following three classes based on their radii:

- Aitken particles and ultra-fine particles (nucleation mode): These are fine particles with the average size ranging between 0.001 and 0.1 μm. These particles contribute to the condensation and formation processes of fogs.

- Fine particles (accumulation mode): The range of these particles lie between 0.1 and 1 μm in size. Their number concentration is much higher than the one of ultrafine and and larger particles.

- The larger particles (coarse mode): The size of these particles goes from 1 and 100 μm. These particles mostly contribute to LWC.

The size distribution of fog particles is often modeled by a modified gamma distribution [16]:

$$n(r) = N_0 r^m \exp(\Lambda r^{\sigma}) \tag{1}$$

where $n(r)$ denotes the number of particles per unit volume per unit increment of the particle having radius r. N_0, m, Λ and σ are the four adjustable parameters that characterize this particle size distribution. Considering this distribution in case of fog (when usually $\sigma = 1$ is a good approximation), the liquid water content in g/m^{3}can be calculated as

$$LWC = \rho_w \frac{4}{3}\pi \int_0^{\infty} r^3 n(r) dr \tag{2}$$

where r is the fog particle radius and ρ_w(g/m^3) is the density of water.

4. Analysis of Measurements

The LWC is the mass of water in a fog/cloud in a specified volume of air and it is usually given in g/m^3. Small amounts of the LWC (< 0.05 g/m^3) usually result in light fog, while large values (> 0.1 g/m^3) result in the formation of thick or dense fog (approximate visibility range of 50 m) [6].

In the measurement campaign, we sampled data at a rate of one sample per minute. We selected the data set for analysis where the visibility was less than 2 km. Fig. 1 shows the reduced data set (from January 2009) of optical attenuation and the corresponding variation of the LWC. The LWC is plotted in blue, whereas, optical attenuation is in red for 1550 nm and in green for 830 nm, respectively. Note also that the time axis in the Fig. 1 is not continuous calendar time, but instead several observed fog events are put in order.

The scaling constant 65 for LWC in Fig. 1 was chosen considering a theoretical relation $A = 4.34 \times 1500\ LWC/r_e$ ([3]) where A (dB/km) is specific attenuation and r_e (µm) is the effective radius of drop size distribution; during dense fog conditions its value was observed to be about 10 µm in Prague [3]. From Fig. 1 a direct correspondence between optical attenuation and the LWC can be observed. Attenuation is clearly increasing with increasing LWC. This dependence is usually modeled by a power law relationship. A linear regression analysis of the logarithms of attenuation and of LWC was applied to obtain parameters of the power law models for wavelengths 830 and 1550 nm. The results are shown in Figs. 2 and 3. A relatively wide range of LWC values is covered in our analysis, from 0.001 till about 0.3 g/m^3, which is comparable with other studies, e.g. [20].

The following model parameters were obtained by regression:

$$A_{0.83\mu\mathrm{m}} = 318.16(LWC)^{0.5274}, \tag{3}$$

$$A_{1.55\mu\mathrm{m}} = 289.51(LWC)^{0.4876} \tag{4}$$

where A (dB/km) represents specific optical attenuation and LWC (g/m^3) represents the corresponding liquid water content. Hereafter, (3) and (4) would be referred to as Model A_{830} and A_{1550}.

5. Model Comparison

The above empirical models were derived using all data collected during all fog events observed when atmospheric visibility was lower than 2000 m. Therefore these models represent long-term averages that may be more or less different from individual fog events. It is interesting to demonstrate this fact on the examples. For this purpose, two fog events recorded on 20-21 January 2009 and 07 February 2009 have been selected for further detailed comparison of

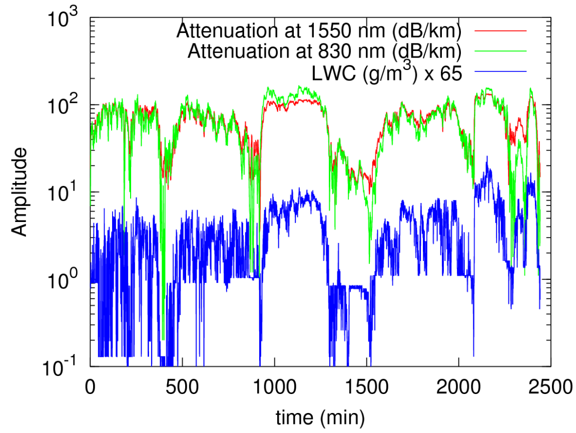

Fig. 1. Optical attenuation along with LWC [18].

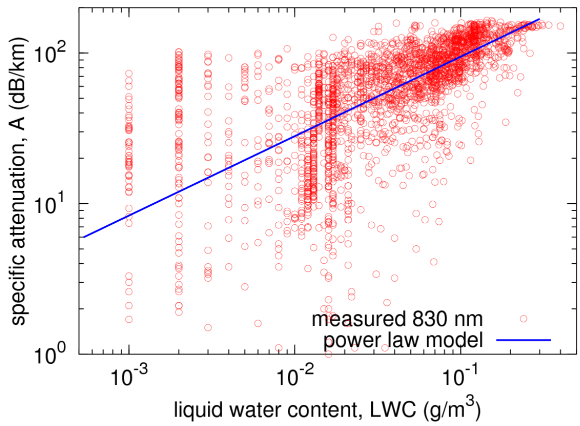

Fig. 2. Optical attenuation and LWC measured in Prague, January - May 2009, wavelength 830 nm; fitted power law model (3).

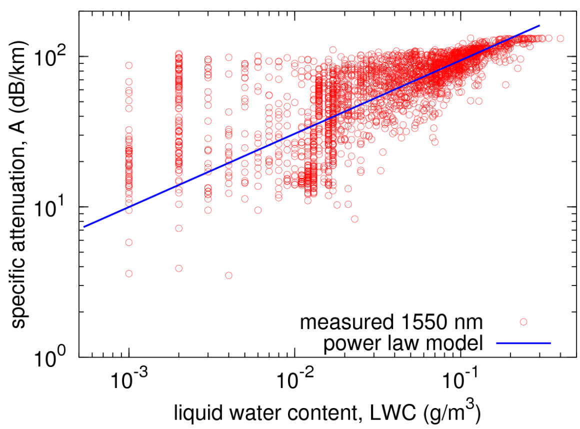

Fig. 3. Optical attenuation and LWC measured in Prague, January - May 2009, wavelength 1550 nm; fitted power law model (4).

proposed models at wavelengths 830 and 1550 nm with measured data. Furthermore, the comparison will be made with three other models available in the open literature to calculate optical attenuation from the LWC. These models are given in following equations,

$$A_{0.785\mu\mathrm{m}} = 238(LWC)^{0.86}. \tag{5}$$

Hereafter, (5) would be referred to as Model B for further analysis. Model B [13] can perform well under light fog conditions (attenuation level below 40 dB/km) but may not be suitable for moderate, thick or dense fog conditions because the higher attenuation levels (attenuation higher than 40 dB/km) have been extrapolated [13]. Two other models are given in [14]:

$$A_{0.63\mu\mathrm{m}} = 360(LWC)^{0.64}, \tag{6}$$

$$A_{10.6\mu\mathrm{m}} = 610(LWC). \tag{7}$$

Equations (6), (7) would be referred to as Model C and Model D respectively for further discussion. Notice that Model D is included in our analysis merely for interesting comparison of near and middle infrared wavelengths. Optical attenuation at wavelengths around 11 μm is known to be linear with LWC according to the principles of scattering theory [21]. The models' predictions along with the measured data of the fog event recorded on 20 - 21 January 2009 at a wavelength of 1550 nm are provided in Fig. 4.

The models' predictions along with the measured data of the fog event recorded on 07 February 2009 at 1550 nm wavelength are provided in Fig. 5. Similar comparison with the measured data of all observed fog events at 1550 nm wavelength is shown in Fig. 6.

It is obvious from Figs. 4, 5, 6 that there is a close match of measured data with Model A_{1550} for all ranges of optical attenuations, whereas measured data is deviated from Model B and Model D. Model C predicts slighly lower attenuation for lower LWC values. A median percentage error criterion is used to assess the models with respect to measured data quantitatively. The percentage error is given as

$$\Delta(\%) = 100 \left| \frac{M_d - P_d}{M_d} \right| \tag{8}$$

where M_d is measured data and P_d is predicted data. Then the median value is calculated of the above given percentage errors. The resulting median percentage errors of the fog attenuation at 1550 nm are shown in Tab. 3. The last row in the table shows the errors computed using data of all observed fog events together.

It is seen in Tab. 3 that our proposed model has the lowest error when all fog events are taken into account, but the Model C exhibits slightly lower error when only the 7 February fog event is considered.

Let us compare the models with attenuation at 830 nm. The models' predictions along with the measured data of fog event recorded on 20-21 January 2009 at wavelength of 830 nm are provided in Fig. 7. The simulation results along with the measured data of selected fog event recorded on 07 February 2009 are provided in Fig. 8. Similar comparison with the measured data of all observed fog events at 830 nm wavelength is shown in Fig. 9.

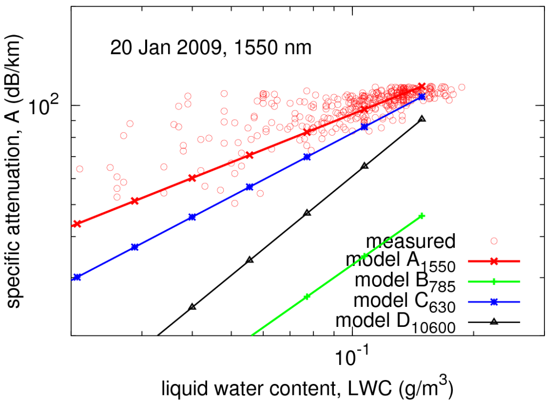

Fig. 4. Comparison of the models with measured data, 20-21 January 2009, wavelength 1550 nm.

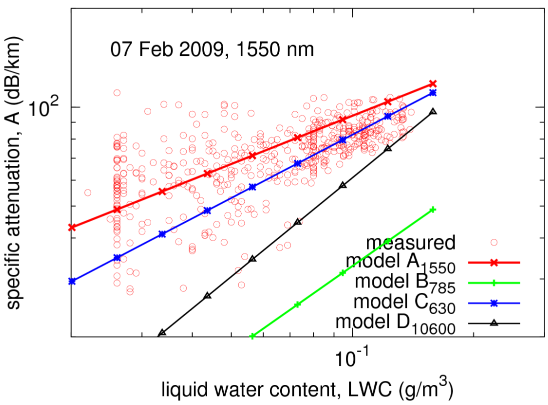

Fig. 5. Comparison of the models with measured data, 7 February 2009, wavelength 1550 nm.

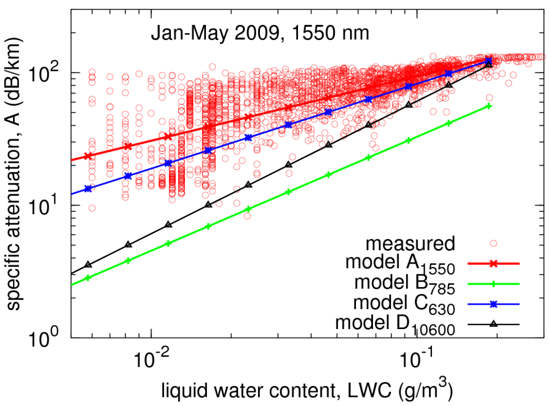

Fig. 6. Comparison of the models with measured data, January-May 2009, wavelength 1550 nm.

Median percentage error of attenuation				
Fog event	**Model A**	**Model B**	**Model C**	**Model D**
20-21 Jan	5.5	63.9	12.0	31.8
7 Feb	15.8	66.1	15.2	39.4
all events	18.4	71.4	24.8	53.6

Tab. 3. Median percentage error for considered fog events, wavelength 1550 nm.

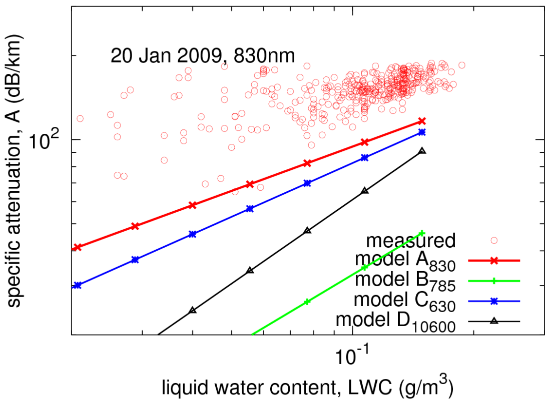

Fig. 7. Comparison of the models with measured data, 20-21 January 2009, wavelength 830 nm.

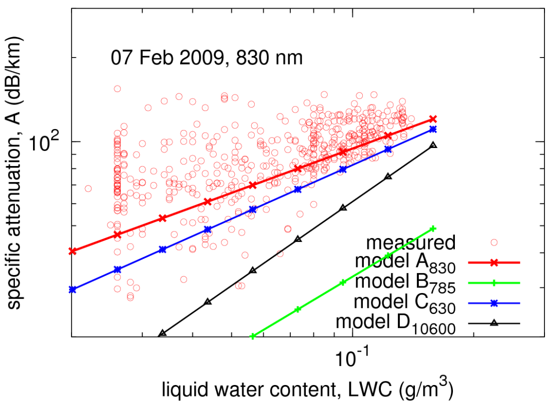

Fig. 8. Comparison of the models with measured data, 7 February 2009, wavelength 830 nm.

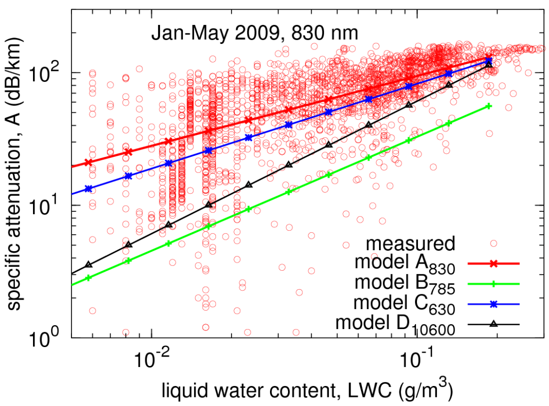

Fig. 9. Comparison of the models with measured data, January-May 2009, wavelength 830 nm.

The median percentage error of the fog attenuation at 830 nm is provided in Tab. 4. It is obvious from Tab. 4 that our proposed model with the least value of median percentage error is performing better as compared to the other models at wavelength of 830 nm. The results in Figs. 4 - 9 suggest that on average, optical attenuation due to fog does not exhibit significant dependence on wavelengths ranging between 800 and 1600 nm (taking into account uncertainties due to spread of measured data).

Median percentage error of attenuation				
Fog event	**Model A**	**Model B**	**Model C**	**Model D**
20-21 Jan	33.9	75.8	41.4	54.1
7 Feb	17.3	72.5	27.7	50.6
all events	27.5	71.8	33.2	53.3

Tab. 4. Median percentage error for considered fog events, wavelength 830 nm.

6. Conclusions

Five months measurement of optical attenuation the liquid water content have been used to obtain model parameters of a power law model for direct estimation of optical attenuation from the LWC. A comparison with other existing models shows that our proposed models perform better and can provide sufficiently accurate estimates of optical attenuation on our experimental paths. The analysis has also shown that taking into account the significant spread of measured data, it is generally difficult to establish any clear wavelength dependence of the relation between attenuation and the LWC in the range of 800 - 1600 nm. In this respect however, the model D valid for 10.6 μm has to be treated separately and it was included only for comparison with standard FSO operational wavelengths as mentioned in Section 5.

Though there may be some variation of the optical attenuation in the classical optical windows, the proposed models can be used conveniently in the range of wavelengths around 830 and 1550 nm for estimation of optical attenuation due to dense fog based on LWC with reasonable accuracy. Disadvantage of the models is that they are completely empirical and thus related to particular measured data. Furthermore one can see from the presented results that acuracy of the models is compromised for lower values of LWC because of significant measurement errors (relative) in this region. On the other hand, due to a limited fade margin (see Tab. 2), the highest attenuation results are also distorted by an “attenuation saturation” effect that is not physical, but it is only an artifact of measurement. Therefore it is recommended to use the relations (3) and (4) only in the interval $0.01 < LWC < 0.2$ (g/m^3).

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