

Dense Maritime Fog Attenuation Prediction from Measured Visibility Data

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Abstract. *The benefits of Free Space Optics (FSO) motivate to use it for future high data rate demanding communication applications. However, widespread growth of the technology has been hampered by reduced availability due to weather influences on the link. The fog has been analyzed as the most detrimental for FSO communication. There are some models that predict fog attenuation in terms of visibility. These models are compared with measured attenuation data of dense maritime fog. The comparison has been in terms of Sum of Square Error (SSE) and Root Mean Square Error (RMSE). A new model has been proposed that gives the least SSE and RMSE for the measured data.*

Keywords

FSO, attenuation, simulation, fog, model comparison.

1. Introduction

Free Space Optical communication has the tremendous potential to provide communication link for future high data rate demanding applications. FSO allows highest data rates due to high carrier frequency in the range of 20 THz to 375 THz. Among other advantages, license free communication, easy installation, avoiding electromagnetic pollution and wiretapping safety are few to name. This technology can provide solution to problems like first/last mile access connectivity, broadband internet access to rural areas, disaster recovery etc. Some of the envisioned implementation scenarios are delay free web browsing and data library access, electronic commerce, streaming audio and video, video on demand, video conferencing, real time medical imaging transfer, enterprise networking, work-sharing capabilities and high speed interplanetary internet links [1]. Recently FSO is being investigated for high speed data transfer applications involving links between fixed and mobile platforms e.g., High Altitude Platforms (HAPs), Unmanned Aerial Vehicles (UAVs), Geostationary (GEO) and Low Earth Orbits (LEO) satellite terminals. Famous optical wireless links experiments in last few years like Optical ground Station (OGS) – ARTEMIS,

JPL – OCTL, Altair UAV-to-Ground, Stratospheric Optical Payload Experiment – STROPEX, Airborne Laser Optical Link – LOLA, Optical Downlink Experiment – KIODO and TerraSAR-X LCT-ATM Laser Link are few good examples exhibiting the importance of such links for future broadband communication requirements.

However, FSO is highly weather dependent and fog is the major attenuating factor. Research studies have shown that attenuation has peak values of 480 dB/km under dense maritime fog [2]. Fog is the most critical attenuation factor among all atmospheric attenuating factors of FSO. The properties of fog were measured and modeled first at the beginning of the 20th century, for applications mainly in geodesy and meteorology. Mie scattering theory and the Koschmieder law [3], [4] are the examples of these research outcomes. The most accurate way to calculate attenuation in case of fog droplets is based on Mie scattering theory. However, it requires detailed information of fog parameters like particle size, refractive index, particle size distribution etc. which may not be readily available at a particular location of installation. Moreover it involves complex computations.

Another way is to use visibility data to predict specific attenuation. Research work was done to model and to study fog effect on light propagation in the visible and IR spectral range from empirical and theoretical points of view [5-7]. There are some models that predict specific attenuation in terms of visibility. However, when the predicted value by any model is compared with measured attenuation data, the measured attenuation data does not seem to follow any particular model predicted attenuation. In this paper a new model has been proposed. The measured attenuation and predicted attenuation by new model and existing models have been compared in terms of Sum of Square Error and Root Mean Square Error.

The remainder of this paper has been organized as follows: Section 2 presents the fog model predicting specific attenuation in terms of visibility. Section 3 discusses the experimental setup for attenuation measurement. Simulations for existing models are presented in Section 4. Section 5 presents the new proposed model and comparison of SSE. Concluding remarks finalize this paper in Section 6.

2. Fog Models Predicting Specific Attenuation in Term of Visibility

The increased interest in optical wireless communication led to exploring the propagation impairment of optical wireless signal. Fog consists of fine water droplets suspended in the air with diameters less than 100 μm [8]. Fog induces spontaneously decrease in visibility. It is admitted in theory that fog exists when visibility is decreased to less than 1 km and the relative humidity of the air reaches the saturation level (relative humidity close to 100%). A dense fog can induce extremely reduced visibility: to only a few meters sometimes. Fog is characterized by several physical parameters such as liquid water content, average particle size, particle size distribution and decrease in visibility. Due to lack of sufficiently detailed information at every installation site and complexity involved in Mie scattering theory, the models predicting the specific attenuation in terms of visibility were developed. The models Kruse, Kim and Al Naboulsi [9 - 12] use this approach and predict specific attenuation using visibility. The visibility parameter V (in kilometers) is defined as the distance to an object where the image contrast drops to 2% of what it would be if the object were nearby instead [9], [13]. The specific attenuation in dB/km for both Kim and Kruse model is given by

$$a_{\text{spec}} = \frac{10 \log V\%}{V(\text{km})} \left(\frac{\lambda}{\lambda_0} \right)^{-q}. \quad (1)$$

Here $V(\text{km})$ stands for visibility, $V\%$ stands for transmission of air drops to percentage of clear sky, λ in nm stands for wavelength and λ_0 as visibility reference (550 nm). For Kruse model [9]

$$q = \begin{cases} 1.6 & \text{if } V > 50 \text{ km} \\ 1.3 & \text{if } 6 \text{ km} > V > 50 \text{ km} \\ 0.585V^{1/3} & \text{if } V < 6 \text{ km} \end{cases} \quad (2)$$

Equation (2) implies that for any meteorological condition, there will be less attenuation for higher wavelengths. The attenuation of 10 μm is expected to be less than attenuation of shorter wavelengths. Kim rejected such wavelength dependent attenuation for low visibility in dense fog. The q variable in equation (1) for Kim model [10] is given by

$$q = \begin{cases} 1.6 & \text{if } V > 50 \text{ km} \\ 1.3 & \text{if } 6 \text{ km} < V < 50 \text{ km} \\ 0.16V + 0.34 & \text{if } 1 \text{ km} < V < 6 \text{ km} \\ V - 0.5 & \text{if } 0.5 \text{ km} < V < 1 \text{ km} \\ 0 & \text{if } V < 0.5 \text{ km} \end{cases} \quad (3)$$

Al Naboulsi et al. (France Telecom model) [11], [12] has provided relations to predict fog attenuation by characterizing advection and radiation fog separately. Generally radiation (convection) and advection fog are the most

usually encountered types in nature [14], [15]. Advection fog is formed by the movement of wet and warm air masses above colder maritime or terrestrial surfaces. It is characterized by liquid water content higher than 0.20 g/m^3 and a particle diameter close to 20 μm [8]. Al Naboulsi provides the advection fog attenuation coefficients as

$$\gamma_{\text{ADV}}(\lambda) = \frac{0.11478\lambda + 3.8367}{V} \quad (4)$$

Radiation fog is related to the ground cooling by radiation. It appears when the air is sufficiently cool and becomes saturated. This fog generally appears during the night and at the end of the day. Particle diameter is around 4 μm and the liquid water content varies between 0.01 and 0.1 g/m^3 [8]. Al Naboulsi provides the radiation fog attenuation coefficients as

$$\gamma_{\text{RAD}}(\lambda) = \frac{0.18126\lambda^2 + 0.13709\lambda + 3.7502}{V} \quad (5)$$

The specific attenuation in dB/km for both types of fog is given by Al Naboulsi as follows

$$a_{\text{spec}} \left(\frac{\text{dB}}{\text{km}} \right) = \frac{10}{\ln(10)} \gamma(\lambda). \quad (6)$$

In this paper the comparison of these models is done for in terms of sum of square error from the measured experimental data.

3. Experimental Measurement Setup

In 2004, the measurement campaign was carried out in La Turbie, France for dense maritime fog conditions [2]. The measurement setup at Nice, France near the village La Turbie consists of a transmissiometer to measure visibility at 550 nm center wavelength, an infrared link for transmission measurement at 850 and 950 nm and a PC based data logger to record the measured data along with temperature, humidity, and ambient light that were recorded in longer time intervals. It uses a lamp at 550 nm center wavelength and a receiver with optical band pass filter with 250 nm spectral width around the center wavelength. Transmitter and receiver were stable mounted in 3.5 m height to measure the transmission over a path of free air at 28.3 m distance. The measured transmittance was averaged over time and logged as one value per minute.

4. Simulation and Results

Simulations were performed to show the comparison between measurements and fog attenuation predicted by different models for the dense fog advection case (Fig. 1). It was concluded that it does not provide any reason to prefer any model over other [16].

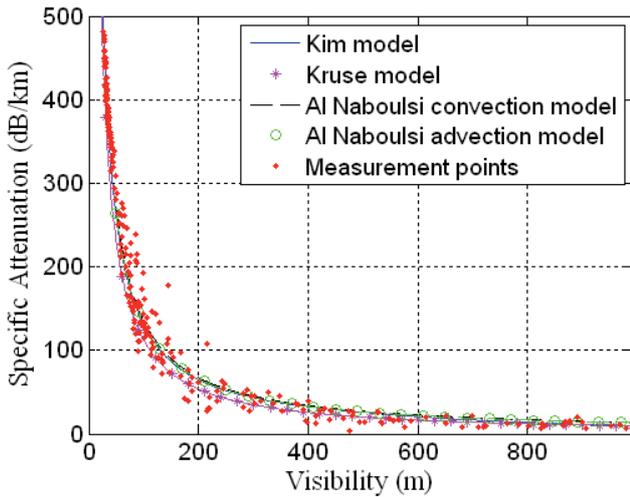


Fig. 1. Measured attenuation for 950 nm and fog attenuation predicted by different models [16].

The magnified view up to 250m visibility is presented in Fig. 2. But this magnified view also does not help in favoring any model over others [16].

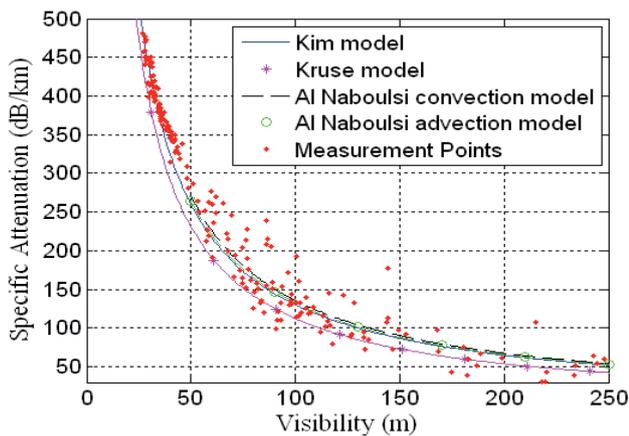


Fig. 2. Magnified view of comparing different models for measured attenuation data for 950 nm [16].

The attenuation measurement for 850 nm and corresponding predicted attenuation by different model is shown in Fig. 3. The magnified view is presented in Fig. 4.

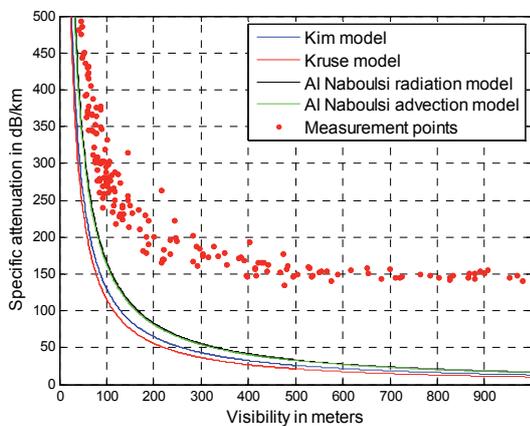


Fig. 3. Measured attenuation for 850 nm and fog attenuation predicted by different models.

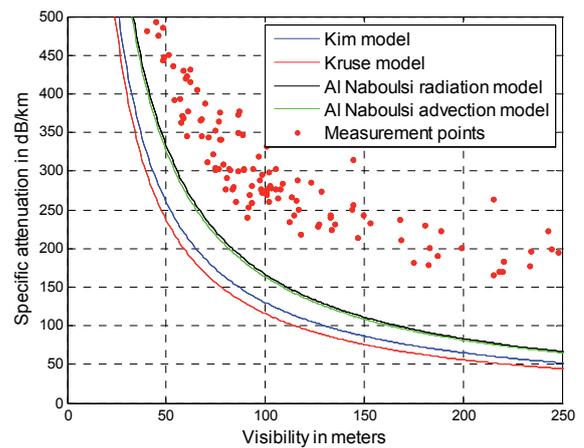


Fig. 4. Magnified view of comparing different models for measured attenuation data for 850 nm.

5. New Proposed Model and Comparison of SSE and RMSE

The simulation with measured data in previous section shows that any existing model cannot be preferred. This provokes the need to propose a model that can provide more accurate prediction of attenuation in terms of visibility.

A new model is proposed here that has the least SSE. The sum of square errors is the sum of square errors [17] between attenuation predicted by a model for a visibility and attenuation measured against that visibility. The model is given as follows for 850 nm wavelength. If f is the specific attenuation in dB/km and x is the visibility in meters

$$f(x) = a \exp(bx) + c \exp(dx).$$

Coefficients (with 95% confidence bounds):

$$\begin{aligned} a &= 946.8 \quad (917.5, 976.1), \\ b &= -0.02271 \quad (-0.02364, -0.02178), \\ c &= 170 \quad (164.6, 175.3), \\ d &= -2.916e-005 \quad (-4.127e-005, -1.706e-005). \end{aligned}$$

Goodness of fit is given by following parameters.

$$\begin{aligned} \text{SSE: } &1.987e+005, \\ \text{R-square: } &0.9847, \\ \text{Adjusted R-square: } &0.9846, \\ \text{RMSE: } &22.72. \end{aligned}$$

The model proposed for 950 nm wavelength is given as follows

$$f(x) = a \exp(bx) + c \exp(dx).$$

Coefficients (with 95% confidence bounds):

$$\begin{aligned} a &= 733 \quad (699.9, 766.1) \\ b &= -0.02824 \quad (-0.03108, -0.02541) \\ c &= 130.6 \quad (102.9, 158.3) \\ d &= -0.003764 \quad (-0.004569, -0.00296) \end{aligned}$$

The goodness of the fit is given by the parameters:

$$\text{SSE: } 1.012e+005,$$

R-square: 0.9892,
Adjusted R-square: 0.9892,
RMSE: 16.21.

The curve fitting by this model is given as follows.

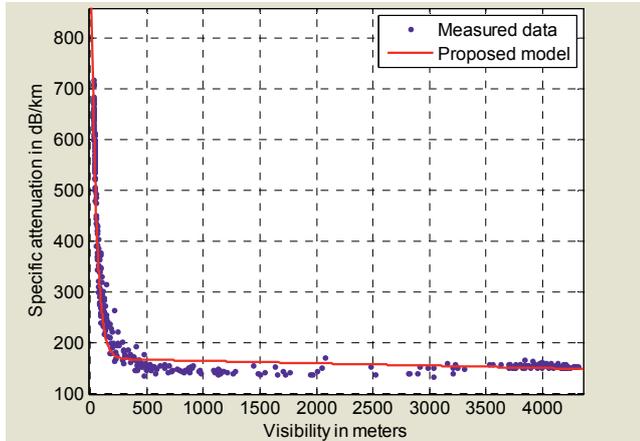


Fig. 5. Curve fitting by the proposed model for measured specific attenuation at 850 nm wavelength.

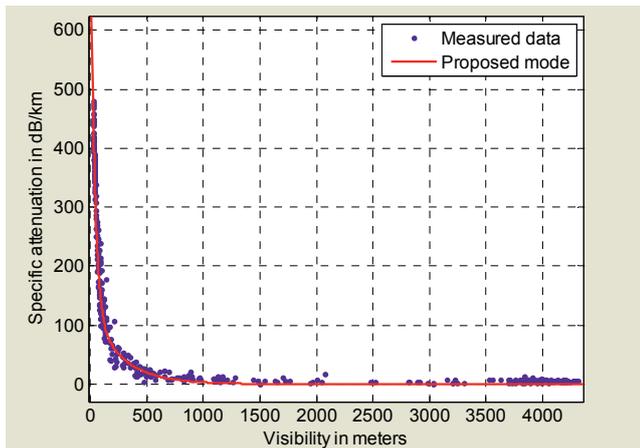


Fig. 6. Curve fitting by the proposed model for measured specific attenuation at 950 nm wavelength.

The sum of square error of 850 nm is shown in Fig. 7. The root mean square error of 850 nm is shown in Fig. 8. Fig. 7 and Fig. 8 show huge difference between the proposed model SSE, RMSE as compared to SSE and RMSE by other models.

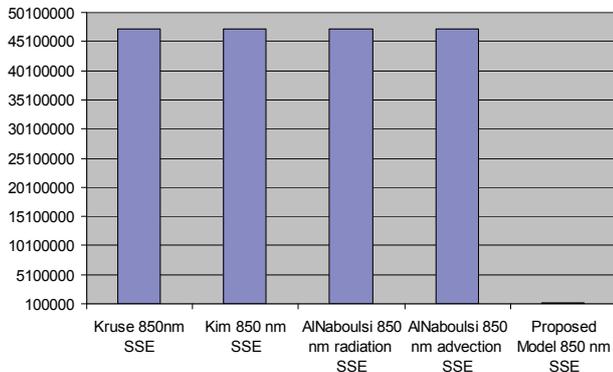


Fig. 7. Sum of Square Error of different models for 850 nm La Turbie data.

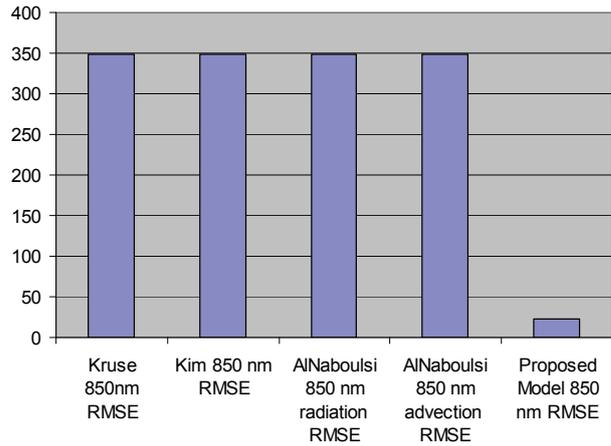


Fig. 8. Root Mean Square Error of different models for 850 nm La Turbie data.

The sum of square error of 950 nm is shown in Fig. 9. The root mean square error of 950 nm is shown in Fig. 10. Fig. 9 and Fig. 10 show huge difference between the Proposed model SSE, RMSE as compared to SSE and RMSE by other models. The comparison of proposed model with other model suggests to use the proposed model for the specific attenuation prediction by using visibility data for 850 nm and 950 nm wavelengths.

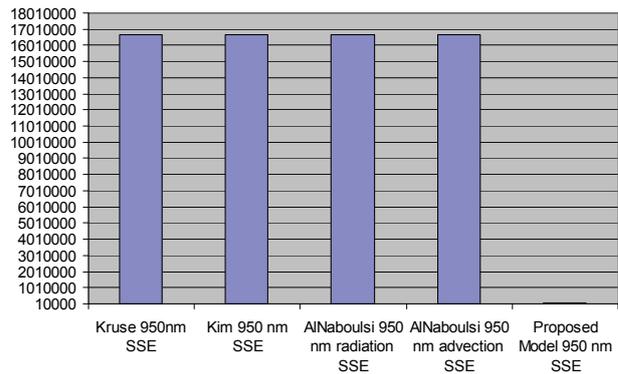


Fig. 9. Sum of Square Error of different models for 950 nm La Turbie data.

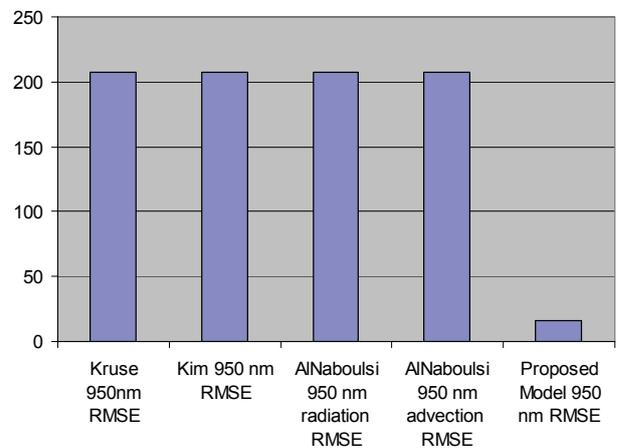


Fig. 10. Root Mean Square Error of different models for 950 nm La Turbie data.

The RMSE for 850nm wavelength for the already existing models is in the range of 348 whereas the RMSE of the proposed models is 22.72. The RMSE for 950nm wavelength for the already existing models is in the range of 207 whereas the RMSE of the proposed models is 16.21. This comparison also shows that the proposed model performs better than other models.

6. Conclusion

The measured attenuation and visibility data has been used to propose a new model that predicts attenuation in terms of visibility. The new and existing attenuation predicting models using visibility have been compared with attenuation measured in La Turbie (France). The comparison has been performed in terms of Sum of Square Error and Root Mean Square Error. It has been found that the new proposed model supersedes in accuracy of prediction. This inspires to use this model for the prediction of attenuation suffered by optical wireless communication under dense maritime fog conditions. However as the measured data was for the wavelengths of 850 nm and 950 nm, the model can be used for these two wavelengths.

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