Prediction of Attenuation using Visibility variations and other Meteorological Parameters in George, Western Cape, South Africa.

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Abstract: In this work, the impact of selected atmospheric parameters on attenuation of terrestrial and satellite signals over George, Western Cape in South Africa for the purpose of planning reliable and resilient free space optical communication links has been presented. The meteorological parameters data (visibility, temperature, rainfall rate, relative humidity, pressure, wind speed and wind direction) were obtained for ten years (2010 – 2019) from the South African Weather Service (SAWS). Total attenuation for the studied location was calculated from attenuation due to aerosol scattering, attenuation due to rain and attenuation due to scintillation. Three different wavelengths namely: 850 nm, 1200 nm and 1500 nm within the optical windows were used in calculating the wavelength dependent functions (attenuation due to aerosol scattering and attenuation due to scintillation). The result shows that attenuation due to rain was observed to account for 58% of the total attenuation and it is wavelength independent. Attenuation due to rain based on subtropic model was found to be about half of the calculated value based on temperate model. Further result shows total attenuation for worst visibility period (summer) throughout the year in the studied location is 7.7 dB/km (aerosol scattering: 0.53dB/km; rain: 4.5 dB/km and scintillation: 2.7 dB/km) at 850 nm. Overall results will be applicable in the area of the design and implementation of a reliable free space optical (FSO) links in the studied location.

1. Introduction

Over the years, free space optics has attracted a lot of attention because it has proved to be both a complimentary solution to optic fibre communication and also serves as an alternative to traditional RF technology for fast, reliable and feasible communication networks in providing high capacity transmission links [1] - [4]. It has been established that optical wave propagation in free space is affected by absorption, scattering and scintillation which results in attenuation of optical wave thus impacting negatively on the performance of free space optical communication link. The attractive features in the FSO communications include license-free operation, simple deployment, high data rate and high transmission security [5] - [8]. However, in order to take a full advantage of the remarkable bandwidth of free space optical communication, it is required to properly characterize the influence of various weather conditions in increasing signal attenuation [9] - [11]. In the present work, prediction of attenuation due to Mie scattering, rainfall and scintillation are the main focus based on evaluating the impact of meteorological parameters on free space optical communication link in George, Western Cape, South Africa. This in turn will be applied to Optisystem to calculate link budget at different wavelength.

The prediction of attenuation has been based on ten years (2010 – 2019) meteorological parameter data (Visibility, temperature, rainfall rate, relative humidity, pressure, wind speed and wind direction) obtained from the South African Weather Service (SAWS) [10], [12].
The research study is arranged as follows: Section 2 deals with critical attenuation that impact FSO communications links; Section 3 is on evaluation of attenuation under different wavelength with results and concluding remarks are presented in Section 4.

2. Theoretical Background
In the atmosphere, the signal is scattered, absorbed and attenuated as a result of atmospheric variations and turbulence. For the purpose of this work, total attenuation for the studied location will be a combination of attenuation due to scattering, rainfall and scintillation.

Several global models have been proposed to predict attenuation coefficients due to Mie scattering, scintillation and rainfall rate. In this work, we reviewed existing models by Kim, Kruse, Ijaz, Al Naboulsi (convection and advection), Rytov, Charbonneau [1, 3-5, 8-9, 11-12]. In order to develop the most appropriate attenuation coefficient for a reliable FSO link in George. The link distance under consideration is 6 km < V < 50 km. Table 1 presents the summary of the models considered.

Beers-Lambert described transmission of light in the atmosphere as:

\[ P_r = P_t e^{-\sigma z} \]  

(1)

where \( P_t \) is the transmitted power, \( P_r \) is the received power, \( \sigma \) is the atmospheric attenuation coefficient due to Mie scattering and \( z \) is optical ink distance.

Table 1. Review of the attenuation due to scattering models

| Models          | Valid                                                                 | Uncertainty                                      |
|-----------------|-----------------------------------------------------------------------|--------------------------------------------------|
| Kim             | Originally proposed for haze particles made up of small aerosols that have particle size smaller than wavelength in Visible and IR bands. Suitable for Visibility greater than 1-50 km, which covers our range of data, obtained for George. | When visibility is less than 1km, uncertainty exists. |
| Kruse           | Modification of Kim's model for Visibility less than 1km. Suitable for Visibility greater than 1-50 km, which covers our range of data, obtained for George. | Fog attenuation for visibility less than 50 m is considered wavelength independent. |
| Ijaz            | Valid for 15 m-1 km and wave length dependent                           | Mean of visibility data obtained is higher than 1km. |
| Advection       | Fog attenuation for wavelength between 0.69-1550 μm and valid for visibilities between 50 m-1km. Wavelength dependent | Mean of visibility data obtained is higher than 1km |
| Convection      | Fog attenuation for wavelength between 0.69-1550 μm and valid for visibilities between 50 m-1 km and is wavelength dependent. | Mean of visibility data obtained is higher than 1km |

2.1. Mie Scattering
Aerosol scattering is the most dominant scattering in free space optics, it occurs when the particle size of the object is of the same order of the transmitted wavelength (\( \lambda \)). In optics, it is mainly due to mist and fog. Attenuation is a function of frequency, but also of the visibility related to the particle size distribution. For the purpose of this work, visibility is measured by the Runway Visual Range (RVR) distance that a parallel luminous ray beam through the atmosphere until the intensity drops to 2% of its original value [3, 8, 13].

The coefficient of scattering due to aerosol can be expressed as

\[ \beta_{av}(\lambda) = 10 \log_{10} \left[ \frac{10 V T \left( \frac{\lambda (\mu m)}{550 \mu m} \right)}{2} \right]^{q(\lambda)} \]  

(2)

where \( T \) is the optical threshold for optical wireless communication system, \( q \) is the coefficient related to the particle size distribution in the atmosphere, \( \lambda \) is the wavelength and \( V \) is the visibility (meters). For the Kim and Kruse model, \( q = 1.3 \) because the visibility range falls between 6 km < \( V \) < 50 km [1, 3, 4-5, 8-9, 11-12].

[8] proposed expressions to predict the wavelength dependent fog attenuation coefficient for the convection and advection fogs for wavelengths from 0.69 to 1.55 μm and visibilities ranging from 50 m to 1 km. The expressions are given by:

\[ \alpha_{con}(\lambda) = 10 \log_{10} \left( \frac{0.11478 + 3.8367}{V} \right) \]  

(3)
\[
\alpha_{\text{atm}}(\lambda) = 10 \log \left( \frac{0.18126 \lambda^2 + 0.13709 \lambda + 3.7205}{\nu} \right)
\]

[3] proposed atmospheric attenuation for wavelength between 0.69 to 1.55 \( \mu \)m and is given by:
\[
\beta_{\text{atm}}(\lambda) = \frac{17}{V} \left( \frac{\lambda_{(\text{nm})}}{550 \text{nm}} \right)^{q(\lambda)}
\]
where \( V \) is in visibility in km, \( \lambda \) is wavelength in nm and \( q(\lambda) = 0.1428 \lambda - 0.0947 \) for fog.

### 2.2 Attenuation due to Rain

Due to the abundance of rainfall in George, this work considers the impact of non-selective or geometric scattering.

\[
\text{Att}_{\text{rain}} = a^* R^b
\]
Charbonneau proposed a model with \( a = 1.067 \) and \( b = 0.67 \) for temperate regions [8, 9] while [12] proposed a model with \( a = 0.3988 \) and \( b = 0.76 \) for sub-tropical regions.

### 2.3. Attenuation due to Scintillation

The atmospheric turbulence at a given location is never constant, it fluctuates both in temporal and spatial domains. This fluctuation is a function of the atmospheric wind speed and the atmospheric pressure. Every variation in the air temperature results in a spatial and temporal variation in the refractive index of the atmospheric optical channel [1], [5], [8], [9].

The atmospheric turbulence loss caused by scintillation as proposed by Rytov and recommended by ITU is given as:
\[
\rho(L) = 2 \times \sqrt{23.17 \times 10^{-2} \times \alpha \times C^n \times L^{11}}
\]
where \( k \) is \( 2\pi/\lambda \), \( C \) is refractive index structure parameter and \( L \) is link distance.

#### 2.3.1 Rytov parameter for spherical waves

The Rytov parameter for the spherical waves is represented as:
\[
\sigma = 0.5C^n K^2 L^{11}
\]

#### 2.3.2 Refractive index structure parameter

Hufnagle- Valley (H-V) model defined the refractive index structure parameters as:
\[
C^n \left[ \frac{-2}{3} \right] = \left[ 0.00594 \left( \frac{\nu}{1500} \right)^2 \times (10^{-5} \nu)^{10} \times \exp \left( \frac{-h}{1000} \right) \right] + \left[ 2.7 \times 10^{-16} \times \exp \left( \frac{-h}{1500} \right) \right] + \left[ 1.7 \times 10^{-10} \times \exp \left( \frac{-h}{1000} \right) \right]
\]
where \( \nu \) is wind speed (m/s) and \( h \) is altitude (m).

### 3. Results and Discussion

#### 3.1. Monthly and Yearly variation of Atmospheric Parameters

Figure 1 depicts the monthly mean of atmospheric parameters (visibility, temperature, rainfall rate, relative humidity, pressure, wind speed and wind direction) over ten years. Seasonal variations are as stated in Table 2. Summer (December- February) recorded the least mean value for visibility and pressure while the period recorded the highest mean for wind speed, rainfall rate, temperature and relative humidity.

As presented in Figure 1, the mean of average monthly visibility for 10 years ranges from 17.91 km (March) to 18.89 km (June). With an average visibility greater than 18 km, attenuation due to scattering might not be due to fog, but more of rain, snow and precursors of secondary aerosol. The mean average monthly temperature recorded lowest value (7.70 °C) in July (winter) and the highest value (16.40 °C) in January (summer). The mean average monthly relative humidity recorded highest and lowest value of 79.43% and 69.38% in March and June respectively. Mean of average monthly pressure recorded highest and lowest value of 998.32 hPa and 990.95 hPa in July and February respectively. Mean of average monthly rainfall rate recorded highest and lowest value of 24.92 mm/hr.
and 18.76 mm/hr in February and July respectively. Wind speed recorded highest and lowest value of 4.13 m/s and 3.01 m/s in the months of December and May respectively, while the mean of average monthly wind direction recorded the highest and lowest value of 217.47 ° and 172.01 ° in June and December respectively. The significant peak and minimum values of most atmospheric parameters occur during the winter and summer.

Summary of the seasonal variations in mean of visibility (km), wind speed (m/s), rainfall rate (mm/hr), relative humidity (%), pressure (hPa), temperature (°C), wind direction (degrees) are presented in Table 2. This is to ascertain the influence and the impact of the studied parameters on different seasons in the studied locations.

Figure 2 depicts the yearly mean of atmospheric parameters (visibility, temperature, rainfall rate, relative humidity, pressure, wind speed and wind direction) over ten years. The result reveals that the yearly average visibility attained the peak in 2013 (18.94 km) and lowest in 2010 (17.83 km). The yearly average temperature was highest in 2019 (12.05 °C) and lowest in 2013 (11.44 °C), while the yearly average rainfall rate attained peak value in 2019 (22.44 mm/hr) and lowest in 2011 (21.20 mm/hr). Yearly average relative humidity was highest in 2015 (78.22%) and lowest in 2013 (70.67%), while the yearly average pressure was highest in 2016 (995.04 hPa) and lowest in 2011 (993.87 hPa).

Also, the yearly average wind speed attained peak value in 2013 (3.70 m/s) and lowest in 2015 (3.32 m/s), while the yearly average wind direction was highest in 2016 (200.34 °) and the lowest in 2010 (183.16 °).

| Season         | Mean visibility (km) | Mean wind speed (m/s) | Mean wind direction (°) | Mean Rainfall rate (mm/hr) | Mean Temp (°C) | Mean Relative humidity (%) | Mean Pressure (hPa) |
|----------------|-----------------------|-----------------------|-------------------------|-----------------------------|----------------|---------------------------|---------------------|
| Winter (June-Aug) | 18.68                 | 3.49                  | 214.16                  | 19.06                       | 7.90           | 70.00                      | 997.14              |
| Summer (Dec-Feb)  | 18.24                 | 3.86                  | 173.99                  | 24.43                       | 15.55          | 77.27                      | 991.40              |
| Autumn (Mar-May)  | 18.27                 | 3.16                  | 188.91                  | 22.84                       | 12.34          | 76.42                      | 994.09              |
| Spring (Sep-Nov)  | 18.42                 | 3.75                  | 188.70                  | 20.58                       | 10.88          | 75.61                      | 994.83              |
3.2. Evaluation of attenuation due to Aerosol scattering at different wavelength

Based on a review carried out in Table 1, Kim and Kruse models are most relevant for the range of visibility under consideration (6 km < V < 50 km), different wavelengths (1550 nm, 1200 nm, 850 nm) were applied to estimate attenuation due to aerosol scattering in this work. Attenuation decreases with increase in wavelength with the highest value (0.54 dB/km) at 850 nm in the month of March and October as shown in Figure 3. With monthly average visibility of over 18km, weather is largely made of rain or drizzle and snow based on weather codes from SAWS. Figure 3 shows attenuation due to aerosol scattering at different wavelengths for different months of the year based on Kim and Kruse model.

3.3. Evaluation of Attenuation due to Rain rate

Two models were reviewed for the purpose of this work as shown in Figure 4. Attenuation due to rainfall rate is independent of wavelength as it depends on rainfall rate, power law constants a and b which vary on a geographical basis and are functions of temperature, frequency and microstructure of rain. The sub-tropical model returned values which are about half of values obtained from temperate model.

![Figure 2. Yearly mean of Visibility (km), Wind Speed (m/s), Rainfall rate (mm/hr), Relative Humidity (%), Pressure (hPa), Temperature (°C), Wind direction (degrees) for George, Western Cape, South Africa.](image)

![Figure 3. Attenuation due to Aerosol scattering at 1550 nm, 1200 nm and 850 nm](image)
Figure 4. Attenuation due to rain based on temperate and subtropic models

3.4 Evaluation of Attenuation due to Scintillations
Attenuation due to scintillation was evaluated for different wavelengths and was observed to be inversely related to wavelength. Attenuation due to scintillation for the studied location was observed to vary from 1.89 dB/km, 2.2 dB/km and 2.7 dB/km/km for 1550 nm, 1200 nm and 850 nm wavelengths respectively. Refractive index structure parameter $[C_n]$ was estimated to be $2.9 \times 10^{-15}$ [m$^{-2/3}$] at a height of 197 m and monthly average wind speed of about 4 m/s which depicts moderate turbulence for the city.

4. Conclusion
In order to design and implement a very robust free space optical link in studied location, average visibility for the different seasons should be taken into consideration with the worst being in summer (December–February) at 18.24 km which means that highest attenuation that will be observed during this period should form part of the basis for the total attenuation for the city. Total attenuation for the worst visibility period (summer) throughout the year in the studied location is 7.7 dB/km (aerosol scattering: 0.53dB/km; rain: 4.5 dB/km and scintillation: 2.7 dB/km) at 850 nm. This will aid further planning while using Optisystem to calculate link budget at different wavelength in the studied location.

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