

Analysis of airborne dust effects on terrestrial microwave propagation in arid area

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ABSTRACT

Sand and dust storms are environmental phenomena, during these storms optical visibility might be decreased, consequently, atmospheric attenuation is clearly noticed. Micro-wave (MW) and Millimeter-wave (mm) propagation is severely affected by dust and sand storms in considerable areas around the world. Suspended dust particles may directly cause attenuation and cross polarization to the Electromagnetic waves propagating through the storm. In this paper, a thorough investigation of dust storm characteristics based on measured optical visibility and relative humidity is presented. In addition, the dust storms effects of on Micro-wave and Millimeter-wave propagation have been studied based on data measured Received Signal levels (RSL) and dust storm characteristics synchronously. Analytical dust attenuation models predictions are matched to the measured attenuation data at 14 GHz and 21 GHz. It has been found that the measured attenuation is approximately ten times higher than the predicted attenuation for both frequencies.

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1. INTRODUCTION

The dust storm is a complex natural phenomenon characterized by strong winds and dust filled the air in an extensive area. Dust storm affects different parts of the world, including parts of China, India, United States of America and northeast Africa and the Middle East for a significant percentage of time annually [1]. Direct effects on wave propagation have been attributed to the complexity of the transmission medium especially at higher frequencies [2-5]. The transmission media in a dust storm is very complex compared to other transmission media.

Suspended dust particles effects on Microwave propagation has emerged as a field that attracted scholars interests recently [1-5]. Motivation to study dust storm effects stemmed from high data rates demand, quality improvement and availability of communication links. In addition, challenges to implement the emerging 5th generation make dust storm effects on microwave propagation an inevitable problem to be addressed.

When a microwave signal encounters precipitating particles (rain, snow, and dust) the signal gets attenuated due to two physical phenomenon, (A) scattering and (B) absorption of the energy of these particles. It has been realized that the scattering effect is more severe at frequencies higher than 10 GHz [4]. Calculation of the signal attenuation induced from dust particles has been done in two ways. Either by long-

term direct observations and statistical analysis of the measured data to articulate co-relations between the different variables [6-8] or by analysis of electrical properties of dust particles to come up with mathematical models.

All conventional methods for attenuation prediction have been based on solving Maxwell's equations either analytically or numerically. Numerical methods compute the scattering amplitude either by differentiation or integration using time/frequency domain, or volumetric integration of Maxwell's equations respectively [9]. On the other hand, analytical methods use certain approximations to ease such complicated calculations. Consequently, Rayleigh approximation and Mie scattering are the cornerstones of all recent analytical models [4]. Models based on numerical methods have emerged Recently, to calculate suspended dust particles effects on signal propagation [10]. Furthermore, a model has been developed as a result of a formulation of wave propagation constant based on equivalent complex permittivity [11]. Effective permittivity of dust storms has been calculated using Maxwell-Garnett formula.

Although analytical models have been developed theoretically, their depends on empirical inputs is clearly realized. Therefore, measured dust particles properties such as particle shape, size, dielectric constant, frequency, and visibility constitute main inputs of these models [12]. Consequently, variations in dust particle shape, size and dielectric constant from one place to another is a real challenge facing interested scholars [13, 14]. However, different approaches are used to estimate attenuation due to dust storms based on theoretical assumption, very limited efforts are devoted to measuring attenuation incurred from a real dust storm. Long-term measurements of dust storm parameters such as visibility, humidity, wind speed and the crosspending attenuation are very limited in the literature [9].

Therefore, this paper investigates dust storm characteristics from the presented results of measured optical visibility and relative humidity. Moreover, a comprehensive review of the available dust storm attenuation prediction models is included. In addition, the paper compares recent models predictions with the measured attenuation of two Microwave links of 2.6 km and 2.8 km operating at Ku and Ka bands (14GHz and 21GHz) respectively. This paper is organized as follows: the following section reviews the recent prediction models from the available resources. Section 3 presents measurement set up data collection and processing. Section 4 compares between measured results and dust storms models predictions. Finally, the paper is concluded in Section 6.

2. ATTENUATION PREDICTION MODELS

In this section, the previous works regarding the dust storm attenuation prediction models are presented. Recent mathematical models can be classified into four main categories based on their background as follows: Rayleigh approximation models, Mie scattering models, numerical models, and effective material property technique model. The coming subsections will provide a detailed review of these models.

2.1. Rayleigh approximation models

Rayleigh is a simple scattering approximation method which is valid when the particle is very small relative to the wave length [15]. Therefore, based on the above method a model has been proposed to estimate the suspended dust particles effects as follows [16].

$$\alpha = 566.97 \left(\frac{1}{V_0} \right) \left(\frac{r_e}{\lambda} \right) (G) \quad (1)$$

$$G = \left[\frac{\epsilon''}{(\epsilon' + 2)^2 + \epsilon''} \right] \quad (2)$$

where α is the attenuation, λ is the wavelength in meters

ϵ' , ϵ'' : the real and imaginary part of the dielectric constant of the dust particles. V_0 is optical visibility in kilometres. r_e is equivalent particle radius in meter.

In addition, Goldhirsh derived a mathematical model based on Rayleigh approximation for dust storm attenuation expressed by [17]:

$$A = \left[\frac{2.317 \cdot 10^{-3} \cdot \epsilon''}{(\epsilon' + 2)^2 + \epsilon''} \right] \cdot \lambda \cdot \frac{1}{V^\gamma} \text{ [dB/km]} \quad (3)$$

V visibility in kilometers, γ consistent value equals to 1.07 λ is the wavelength in meters.

2.2. Mie scattering models

Mie scattering is suitable at a higher frequency when the particle radius is comparable to the wave length [4]. Consequently, a model has been derived to calculate attenuation as follows [18]:

$$A = \frac{r_e f}{V} (x + y r_e^2 f^2 + z r_e^3 f^3) [\text{dB/km}] \quad (4)$$

where f is the frequency in GHz. r_e is the equivalent particle radius in meters, equal to 30 μm . x, y, z are constants depending on the particle dielectric constant ($\varepsilon = \varepsilon' + j\varepsilon''$).

In addition, a model based on Mie scattering has been proposed considering the variation of the dust particles dimensions as follows [4]:

$$A_p = \frac{1}{V^{1.07}} [c_1'' f + c_2'' f^3 + c_3'' f^4] [\text{dB/km}] \quad (5)$$

where A_p is the attenuation at a reference point. c_1'', c_2'', c_3'' are constants.

2.3. Numerical models

The numerical methods have been used to ease Maxwell equations complications especially for the boundary conditions [9]. A combination of two methods produced the following model [10]

$$A = 8.686 \times 10^3 \sum_{k=1}^K \sigma_{ext}(k\Delta r) N(k\Delta r) \Delta r [\text{dB/km}] \quad (6)$$

where K is an integer number of $r_{\max}/\Delta r$, r_{\max} and Δr are the maximum particle radius in the storm and the incremental radius, respectively. σ_{ext} is the extinction cross section.

2.4. Effective material property technique

Xiao-Ying developed a model by formulating the wave propagation constant based on the equivalent complex permittivity using the Maxwell-Garnett formula. Follows [11]:

$$\alpha = 8.686 \cdot \frac{2\pi}{\lambda} \left[\frac{\varepsilon_{eq}'}{2} \cdot \left(\sqrt{1 + \tan^2 \delta} - 1 \right) \right]^{\frac{1}{2}} [\text{dB/km}] \quad (7)$$

$$\tan \delta = \frac{\varepsilon_{eq}''}{\varepsilon_{eq}'} \quad (8)$$

where ε' and ε'' are the real and imaginary parts of ε_{eq}^* , and ε_{eq}^* is the complex relative permittivity of sand and dust.

3. MEASUREMENT SET UP AND DATA COLLECTION

The main objective of this paper is to compare the measured data with the recent dust storm prediction models based on different theories and techniques. Therefore, the experiment has been designed to consider all aspects such as Microwave link length, frequency, polarization, and meteorological parameters.

Measurement system constituted from two Microwave links, metrological station, and data acquisition and processing hardware. The microwave links under monitoring were operating at 14.4 GHz and 21.3 GHz with 2.6 km and 2.8 km lengths respectively. These links were located in North East Khartoum about 6 Km from Khartoum airport. Both links are not far from the Blue Nile; however, the radio links do not transverse the Blue Nile at any point. The links were installed in flat terrain.

Meteorological data was collected from an Automatic Weather Station (AWS), operating in Khartoum International Airport as an integrated weather observation system. Visibility was measured using Vaisala Transmissometer LT31, which can provide accurate and reliable measurements of the Meteorological

Optical Range (MOR) from 10 to 10,000 meters with 1 min integration time and accuracy of $\pm 3\%$. Rainfall rate is measured with 1 min integration time and accuracy of $\pm 1\%$ [19-20]. In addition, the automatic weather station was equipped with sensors of temperature (T), relative humidity (RH), wind speed and direction (WS, WD). Locations of the microwave links and the weather station are shown in Figure 1.

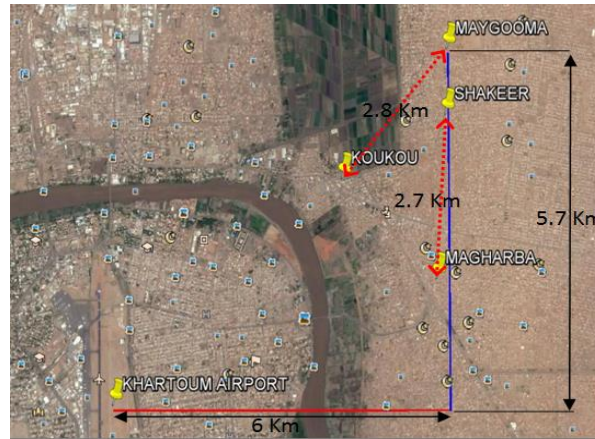


Figure 1. Locations of the microwave links and weather station in khartoum

During the experiment period from 1st June 2014 to 31 May 2015, more than 22 dust storms were experienced in the city of Khartoum. Metrological parameters, as well as transmitted and received signal levels were recorded during the storm events. The receive signal levels for the microwave links 14.4 GHz with 2.6 Km and 21.3GHz with 2.8 Km were collected at Khartoum, Sudan from 1st June 2014 to 31st May 2015 with 92 % availability. Visibility data was collected for 21 dust storm events, only one event was missed during the monitoring period.

4. ANALYSIS OF DUST STORM AND IT'S EFFECTS

Dust storms can generally be characterized by visibility and humidity parameters. The concurrently measured data on visibility and it's impacts on Shakeer- Magharba and MAYGOOMA-KOKOU microwave links are analyzed in the following subsections.

4.1. Optical visibility

Optical visibility has traditionally been used to measure the severity of the dust storm. It is considered such a realistic parameter that metrological observations of dust storms are based upon. Figure 2 shows the cumulative distribution function of the optical visibility based on the collected data using Vaisala Transmissometer LT31. The records include all events during which optical visibility was reduced below 10 km as a result of dust storms in Khartoum.

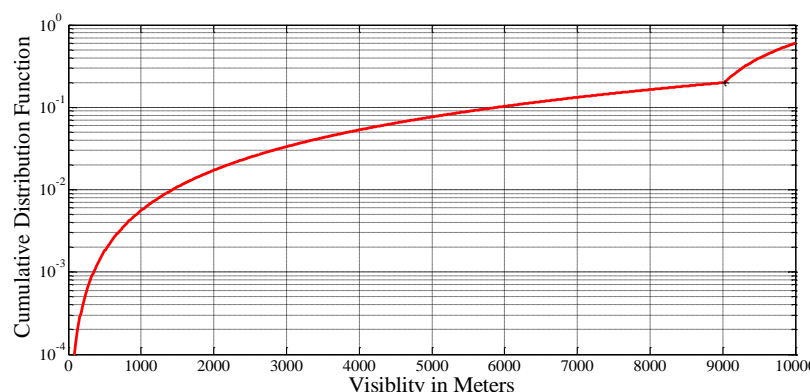


Figure 2. Cumulative distribution of measured visibility from June 1, 2014, to May 31, 2015, in Khartoum

4.2. Relative humidity

Figure 3 shows variation in relative humidity during a recorded dust storm on 6th June 2014. It can be noticed clearly that the relative humidity increased drastically from very low to 70% during the dust storm. Measurement has shown that dust can absorb 5.1% of moisture by weight in the air with 82% relative humidity [20]. Therefore, this rapid increase in the relative humidity can continuously affect the dielectric constant of the dust and consequently degrade the signal significantly, because of the changes in the dielectric characteristics of the dust particles.

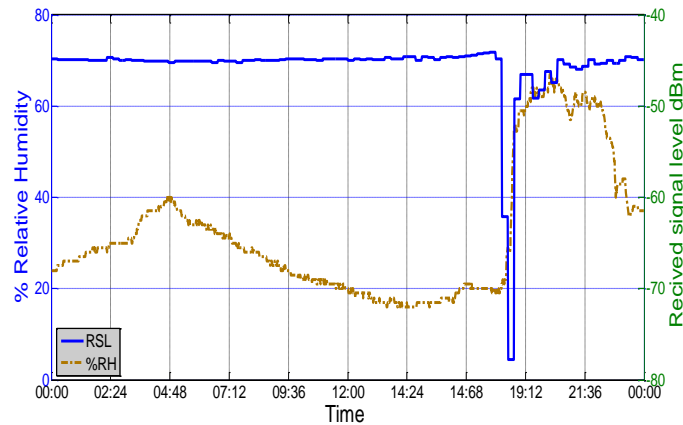


Figure 3. Received signal level and relative humidity on 6th June 2014

4.3. Attenuation due to dust storm

Figure 4 and Figure 5 present the cumulative distribution functions for the measured attenuation due to dust storm from 1st June 2014 to 31st May 2015, for the two microwave links with 2.6 km and 2.8 km path lengths operating at 14.4 GHz and 21.3 GHz, respectively. Measured total attenuation has been converted to dB/Km by assuming the intensity of dust storm is uniform over the entire link as follows:

$$\frac{dB}{km} = \frac{\text{Total Measured Attenuation at 14GHz \& 21.2GHz}}{\text{Length(2.6or2.8)}} \quad (9)$$

However, the two link lengths are almost the same, Figure 4 shows that the measured attenuation is approaching 12 dB at 0.0001 of measurement time for 21.3 GHz link, while in Figure 5 the second link attenuation for the same percentage of time is about 6.5 dB. Therefore, for same dust storm conditions clear effect of the frequency on attenuation can be noticed.

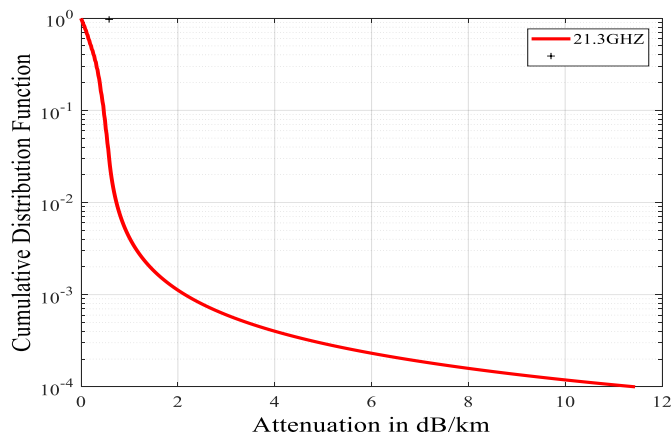


Figure 4. The cumulative distribution function of measured attenuation in dB/km at 21.3 GHz microwave link

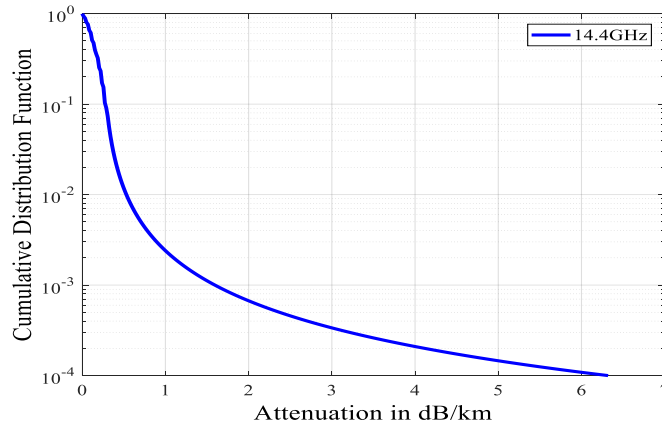


Figure 5. The cumulative distribution function of measured attenuation in dB/km at 14.4 GHz microwave link

5. DUST ATTENUATION PREDICTION VERSUS MEASUREMENT

Measured attenuation is compared at the same condition to the predicted attenuation obtained by Goldhirsh, A.S. Ahmed, Zain Elabdin, Xiao-Ying Dong Hsing-Yi Chen, and S. M. Sharif at 14 GHz and 21 GHz and is plotted in Figure 6 and 7, respectively. (1), (3),(4),(5),(6), and (8) are used to predict attenuation at 14 and 21 GHz.

It has been shown that in Figure 6 measured attenuation is greater than 6 dB/km at the lowest measured visibility 0.08 km, respectively, while for the same visibility highest analytical model prediction is approximately 0.6 dB/km which is just one-tenth of the measured attenuation. On the other hand, Figure 7 shows that the values of the measured attenuation were approaching 11.5 dB/km, 2.7 dB/km and 1 dB/km at visibility 0.083 km, 0.279 km and 0.936 km respectively. On the contrary, analytical models predictions are close to 0.9 dB/km, 0.28 dB/km, and 0.08 dB/km at the corresponding visibility levels 0.083 km, 0.279 km, and 0.936 km respectively. It can be clearly noticed that predicted attenuation is at its best is less than one-tenth of the measured attenuation at the same dust storm circumstances.

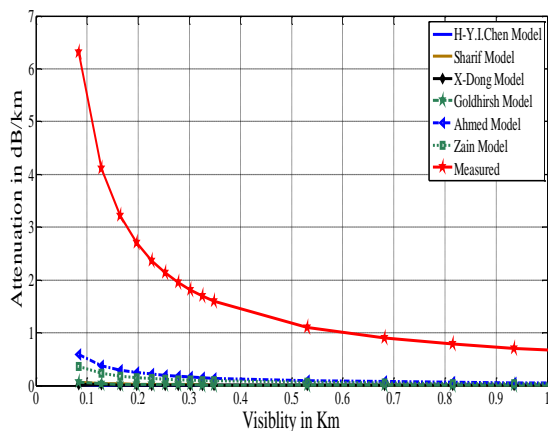


Figure 6. Measured and predicted attenuation at 14 GHz

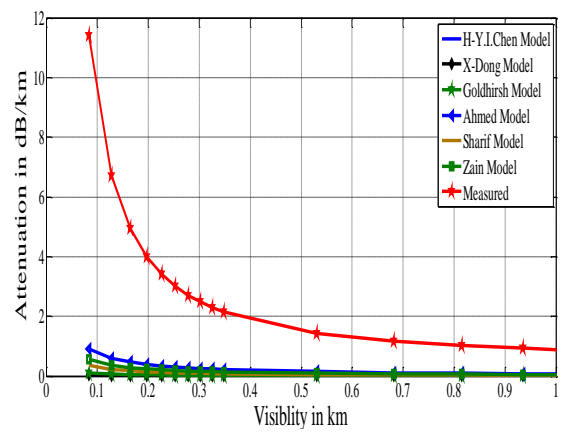


Figure 7. Measured and predicted attenuation at 21 GHz

6. CONCLUSION

Metrological parameters such as visibility and humidity and their effects on 14 and 21 GHz microwave propagation were measured concurrently for a one-year period in Khartoum, Sudan. Prediction models proposed by Ahmed, Goldhirsh, Elabdin, Sharif, Dong, and Hsing to predict dust storms attenuation on Microwaves and Millimeter waves are available in the literature. Measured attenuation has been matched with analytical models predictions. It can be concluded that predicted attenuation is at its best is less than one-tenth of the measured attenuation at same dust storm circumstances for both studied frequencies.

Therefore, analytical models fall away from measured attenuation for frequencies under study especially at low visibilities with the high particle concentrations. From thoroughly study it can be observed that the dust particle characteristics (i.e particle shape, size, and moisture content) are the main source of errors. Hence, improving the analytical models' accuracy is one of the challenges facing researchers in this field, innovative ideas to encompass all dust particles properties, dust storm characteristics, and external environment dynamic changes are required to provide reliable predictions.

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REFERENCES

- [1] N'tchayi Mbourou, G., J. J. Bertrand, and S. E. Nicholson, "The diurnal and seasonal cycles of wind-borne dust over Africa north of the equator," *Journal of Applied Meteorology*, Vol. 36, PP.868–882, 1997.
- [2] E. A. A. Elsheikh, et al., "A proposed vertical path adjustment factor for dust storm attenuation prediction," in *Proc. (ICOM)*, 2011, pp. 1-3.
- [3] M. R. Islam, et al., "Proposing a horizontal path adjustment factor for microwave link's attenuation prediction based on the analysis of dust storm behavior," in *Proc (MICC)*, 2011, pp. 44-48.
- [4] Z. E. O. Elshaikh and M. Islam, "Mathematical model for the prediction of microwave signal attenuation due to dust storm", *Progress In Electromagnetics Research M*. vol.6,pp.139-153,2009.
- [5] M. R. Islam, E. A. A. Elsheikh, A. F. Ismail, S. O. Bashir, and J. Chebil, "Development of an Empirical Dust Storm Attenuation Prediction Model for Microwave Links in Arid Area-A Proposed Framework," in *proceeding of International Conference on Computer and Communication Engineering (ICCCE)*, pp. 224-227. 2014
- [6] E. A. A. Elsheikh, I. M. Rafiqul, A. F. Ismail, M. H. Habaebi and J. Chebil, "Dust storms attenuation measurements at 14GHz and 21 GHz in Sudan," *2015 International Conference on Computing, Control, Networking, Electronics and Embedded Systems Engineering (ICNNEE)*, Khartoum, 2015, pp. 11-16.
- [7] E. A. A. Elsheikh, M. R. Islam, M. H. Habaebi, A. F. Ismail and A. Zyoud, "Dust Storm Attenuation Modeling Based on Measurements in Sudan," in *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 8, pp. 4200-4208, Aug. 2017.
- [8] Abdulwaheed Musa , et al., "Review and Assessment of Electromagnetic Wave Propagation in Sand and Dust Storms at Microwave and Millimeter Wave Bands-Part II" *Progress In Electromagnetics Research M*, Vol. 40, pp.101–110, 2014.
- [9] H. Chen and C. Ku, "Calculation of Wave Attenuation in Sand and Dust Storms by the FDTD and Turning Bands Methods at 10–100 GHz," in *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 6, pp. 2951-2960, June 2012.
- [10] X. Dong, H. Chen and D. Guo, "Microwave and Millimeter-Wave Attenuation in Sand and Dust Storms," in *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 469-471, 2011.
- [11] S. Ghobrial and S. Sharief, "Microwave attenuation and cross polarization in dust storms," in *IEEE Transactions on Antennas and Propagation*, vol. 35, no. 4, pp. 418-425, April 1987.
- [12] E. A. A. Elsheikh, M. R. Islam, et al "The effect of particle size distributions on dust storm attenuation prediction for microwave propagation," in *proceedings of International Conference on Computer and Communication Engineering (ICCCE 2010)*, pp. 1-5. 2010.
- [13] A. J. Ansari and B. G. Evans, "Microwave propagation in sand and dust storms," in *IEE Proceedings F-Communications, Radar and Signal Processing*, vol. 129, no. 5, pp. 315-322, October 1982.
- [14] Vishvakarma, B. R., & Rai, C. S. Limitations of Rayleigh scattering in the prediction of millimeter wave attenuation in sand and dust storms. in *Proc. (IGARSS)1993*, vol.1, pp. 267-269.
- [15] B. R. Vishvakarma and C. S. Rai, "Limitations of Rayleigh scattering in the prediction of millimeter wave attenuation in sand and dust storms," *Proceedings of IGARSS '93 - IEEE International Geoscience and Remote Sensing Symposium*, Tokyo, Japan, 1993, pp. 267-269 vol.1.
- [16] A. S. Ahmed, A. A. Ali and M. A. Alhaider, "Airborne Dust Size Analysis for Tropospheric Propagation of Millimetric Waves into Dust Storms," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. GE-25, no. 5, pp. 593-599, Sept. 1987.
- [17] J. Goldhirsh, "Attenuation and backscatter from a derived two-dimensional duststorm model," in *IEEE Transactions on Antennas and Propagation*, vol. 49, no. 12, pp. 1703-1711, Dec. 2001.
- [18] S. M. Sharif. "Attenuation properties of dusty media using Mie scattering solution." *Progress In Electromagnetics Research M*. Vol. 43, pp. 9-18. June 2015,.
- [19] Vaisala "Vaisala Transmissometer LT31 RVR with New Eyes," Vaisala., Helsinki, FINLAND, Tech. Rep. Ref. B210416en-C ,Vaisala 2010.
- [20] E. A. A. Elsheikh, et al., "Air Born Dust Particles Effects On Microwave Propagation In Arid-Area" in *proc. of 7th International Conference on Computer and Communication Engineering (ICCCE 2018)*.PP.412-415, 2108.
- [21] Sharief, S.M.. "Backscatter properties of dusty medium at X band." in *Proc. of Sixth International Conference on Antennas and Propagation, ICAP 89*, vol.422. pp. 424-427, 1989.

- [22] A. Basahel, Md. Rafiqul Islam, Mohamed Hadi Habaebi, S. Ahmad, "Availability prediction methods for terrestrial free-space-optical link under tropical climate," *Indonesian Journal of Electrical Engineering and Computer Science (IJECS)*, 10(1), pp. 224-229, 2018.

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