Prediction of Electromagnetic Wave Attenuation in Dust Storms Using Mie Scattering

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***Abstract*—Electromagnetic wave propagation in arid and semi-arid regions is influenced by sand and dust storms. This phenomenon has received considerable interest in recent time with emphasis on signal attenuation. To this end, electromagnetic waves equation is proposed in this paper to compute and predict the attenuation of electromagnetic waves in dust storm, in which the propagating frequency, the dielectric constant of dust particles and the visibility during dust storm are accounted for. This was done based on modification of Mie theory. The proposed model enables convenient computation of electromagnetic waves attenuation using visibility, frequency and dust particles' characteristics such as permittivity and particle radius. Accuracy of this model, especially when the attenuation is a function of visibility, is verified and validated by using existing models. It can be found that attenuation increases when the visibility during dust storms gets severe.**

***Keywords*— Attenuation; sand and dust storm; Mie scattering; electromagnetic waves; particle concentration; visibility.**

I. INTRODUCTION

Dust storm - frequently observed in many areas around the world [1] - is a severe weather condition characterized by strong wind and dust-filled air over an extensive area. It occurs in the Middle East, North America, the arid parts of Asia and Africa. Dust storm may cause pollution, respiratory diseases, ecological disaster, low visibility, and interrupted traffic [2]. Different types of satellite based techniques have been proposed to monitor dust storms [3]. Typical parameters of dust storm which are significant in the study of electromagnetic wave propagation model formulation include visibility, land surface coverage, total number density (or particle concentration), moisture and permittivity and particle size distribution.

The dust particles affect communication links by degrading signal through attenuation along the propagation path and interference. Attenuation is caused, mainly, by two mechanisms known as scattering and absorption of the dust storm particles [4]. These two mechanisms have a relation with the dust particle dielectric constant, particle size, and few other dust particles characteristics [5].

Attention has recently been devoted to the attenuation of electromagnetic waves in dust storm [6], [7], [8]. Attenuation, phase shift, and fluctuations of microwave and millimeter-wave signals propagating through a dust storm have been studied [6], [7]. Using Mie scattering, mathematical models have been developed [8] for prediction of signal attenuation in dust storm. Attenuation was found to be related to the visibility, the frequency of the incident wave and the dust particle sizes. The Mie scattering solution is suitable for possible ratios of particle diameter and high frequency. It is however limited to spherical particles only.

While the effects of particle size distribution and particle shape [9] [10] have been dealt with, the concept of incorporating concentration number of particles and visibility relation, which are of great importance in the prediction of the attenuation effect, has however received little consideration thus far. Dust particle concentration in relation to visibility was investigated [11]. For this reason, the output of dust particle relation and visibility is incorporated into the proposed model in this paper for predicting the electromagnetic wave attenuation in dust storm. Besides, since dust storms are observed and characterized using visibility rather than particle concentration, the attenuation model is given in terms of visibility which is a more realistic dust storm parameter.

The organization of this paper is done such that in Section II, attenuation due to Mie scattering is presented. The attenuation effects of dust storm are discussed in Section III, the proposed model is presented in Section IV. The results are discussed in Section V, while some conclusions are drawn in Section VI.

II. MIE SCATTERING THEORY

Mie scattering theory is famous in today's research of scattering of electromagnetic waves by dielectric particles. The theory gives a complete analytical solution of the Maxwell's equations. The solution accommodates possible ratios of particle sizes and wavelength. This means that Mie solution is suitable for prediction of electromagnetic wave attenuation at high frequencies such as the microwave and the millimeter wave bands. However, unlike the Rayleigh method, its application appears to be limited by shape (spherical particles only). Besides, the theory apparently reduces to Rayleigh approximation as the size of the particles becomes smaller. The extinction or total cross-section efficiency factors by Mie solutions can be expressed as [12]:

$$\sigma_t = \frac{\lambda^2}{2\pi} (ka)^3 \left[c_1 + c_2(ka)^2 + c_3(ka)^3\right] \quad (1)$$

where λ is the wavelength, k is the wavenumber, a is the radius of the dust particle and c_1, c_2 and c_3 are constants whose values depend on real (ε') and imaginary parts (ε'') of the dielectric constant of the dust particles given as:

$$c_1 = \frac{6\varepsilon_2}{(\varepsilon_1+2)^2+\varepsilon_2^2} \quad (2)$$

$$c_2 = \varepsilon_2 \left\{\frac{6}{5} \cdot \frac{7\varepsilon_1^2+7\varepsilon_2^2+4\varepsilon_1-20}{\left[(\varepsilon_1+2)^2+\varepsilon_2^2\right]^2} + \frac{1}{15} + \frac{5}{3\left[(2\varepsilon_1+3)^2+4\varepsilon_2^2\right]}\right\} \quad (3)$$

$$c_3 = \frac{4}{3}\left\{\frac{(\varepsilon_1-1)^2\ (\varepsilon_1+2)+[2(\varepsilon_1-1)(\varepsilon_1+2)-9]+\varepsilon_2^4}{\left[(\varepsilon_1+2)^2+\varepsilon_2^2\right]^2}\right\} \quad (4)$$

It is clear from (2) to (4) that to determine the scattering property of a dust particle, the complex dielectric constant needs to be known. Dielectric constant measurements of different frequency have been carried out [13], [14].

III. EFFECTS OF SAND AND DUST STORMS PARAMETERS ON ATTENUATION

Attenuation due to dust storm can be explained in terms of scattering and absorption cross section of a single particle. This is carried out by solving the forward scattering amplitude function (of a single particle). Methods for modeling of scattering in dust storm particle populations are essentially the same as that for a population of hydrometeors. This is so because they are all discrete random media. Suffice to state that all techniques for scattering computation are generally based on solving Maxwell's equations either numerically or analytically. However, some exact numerical solutions will in turn often reduce to an analytical solution. Solutions to the exact integral expression of scattering amplitude function are difficult. The function depends on the local field inside the particle and its permittivity. The local field is generally unknown and therefore, certain approximations like Wentzel-Kramers-Brillouin (WKB), Rayleigh and Mie solutions are usually employed to solve the problems.

The attenuation, A, of electromagnetic wave over a given path length in dust storm can be expressed as

$$A\ (dB) = \int_0^L A_d\ dx \quad (5)$$

where A_d is the specific attenuation in dust storm.

The specific attenuation can be expressed in (dB/km) as

$$A_d\ (dB/km) = 4.343 \times 10^3 \int_{a_{min}}^{a_{max}} \sigma_t\ (a).N(a)\ da \quad (6)$$

where σ_t defined in (1) is the total attenuation cross section efficiency factors of dust particle having radius a and $N(a)da$ is the dust particles number per unit volume of air with dust particles radius between a and $a + da$.

It is seen from (6) that to calculate attenuation, data on the dust particles number per unit volume of air, N, which are very difficult to obtain are required. Investigation has however shown that relation exists between the dust particles number and dust visibility. The visibility during dust storm is usually used to describe the dust particles concentration of the sand and dust, which can be expressed, empirically, by the number of the total dust particles per unit volume. In addition, statistical information on dust storm visibility are readily available unlike the dust particle number. This is to be incorporated in the development of the attenuation model to be discussed in the next section.

IV. THE PROPOSED MODEL

Recall the expression of extinction or total cross-section efficiency factors by Mie solutions in (1) and substitute it into (6), the following expression is obtained:

$$A_d = 4.343 \times 10^3 \int_{a_{min}}^{a_{max}} \left\{\frac{\lambda^2}{2\pi}\ (ka)^3\ [c_1 + c_2(ka)^2 + c_3(ka)^3].N(a)\right\} da\ [dB/km] \quad (7)$$

In the proposed model, effort is made to relate concentration number of particles per unit volume – sometimes referred to as volume fraction - with visibility. It is observed that the concentration number of particles per unit volume or volume fraction, v_f, is difficult to obtain or measure in dust storms. Dust storms are meteorologically and empirically observed using visibility. The visibility is directly related to the severity of dust storm and thus a measure of the severity of the storm. Visibility is often used to describe the distance at which a mark disappears against the background for terrestrial dust storm. The term visibility is also normally applied to denote the degree of dust storm density instead of the total number of dust particles [12]. This necessitated treating the prediction of electromagnetic wave attenuation during dust storms in terms of visibility.

A relation between dust concentration and visibility was given by [15], [16] and [17]. These relations provide ease of application to a different dust storms' characteristics. It also provides a means of estimating dust concentrations, ρ, from information on the visibility associated with a given dust storm. The relative mass of dust per cubic volume of air as defined by [15] is given as:

$$M = \rho_0 v_r\ [kg\ dust/m^3\ air] \quad (8)$$

where ρ_0 is the solid density of dust and v_r is the relative volume also known as the volume fraction, v_f.

The mass of suspending dust per unit volume of air was, similarly, related to visibility thus:

$$M = \frac{C}{V^\gamma} \quad (9)$$

where V is the visibility (km), C and γ are constants that depend on the land origin of the dust storm and the climatic conditions, and M is the dust mass (kg/m^3) of air. It is also referred to as dust concentrations denoted as ρ or the dispersed density in a medium. From (8) and (9), particle concentration which is to be denoted as volume fraction is expressed in terms of visibility in (10).

$$v_f = \frac{C}{V^{\gamma}\rho_0} \quad (10)$$

Equation (11) is the expression of the [16] relation between visibility and dust concentration. When the expression is divided by solid density of dust, $\rho_0 = 2650 \ kg/m^3$, (12) is obtained.

$$\rho = \frac{5.6 \times 10^{-5}}{V^{\gamma}} \ [kg/m^3] \quad (11)$$

$$v_f = \frac{2.113 \times 10^{-8}}{V^{\gamma}} \quad (12)$$

where the γ is a constant equal to 1.25.

[18] predicted that:

$$\rho = \frac{2.3 \times 10^{-5}}{V^{\gamma}} \ [kg/m^3] \quad (13)$$

and (13) thus produced the volume fraction represented in (14):

$$v_f = \frac{9.426 \times 10^{-9}}{V^{\gamma}} \quad (14)$$

where γ is 1.07. Equation (14) is noted to be the same expression also derived by [15] using different method and approach.

In relating the visibility during dust storm and the mass concentration of soil-derived aerosols, different values of C is generally applied depending on factors such as local erosion [17] or the distance from the source of the aerosol. It is observed that [16] recorded 5.6×10^{-5} and 1.25, respectively, as the values of C and γ while [18] had $C = 2.3 \times 10^{-5}$ and γ = 1.07. Also, the solid density, ρ_0, was approximately given as $2{,}440 \ kg/m^3$.

It is possible to analytically express attenuation coefficient in terms of visibility using (14). Also, the volume fraction for N equivalent dust particle scatterers, can be expressed as:

$$v_f = \frac{4}{3} \pi a^3 N \quad (15)$$

Thus, combining (14) and (15) and then making N the subject of the equation so obtained,

$$N(a) = \frac{2.25 \times 10^{-9}}{a^3 V^{\gamma}} \quad (16)$$

where a, in meter, is the equivalent particle radius.

The dust particles concentration or mean number density of dust particles of all sizes was derived by assuming an equivalent particle radius for all particles in dust storm. From (16), it is confirmed that the expression of the mean number density of particles of all sizes is like the expression derived by [19], albeit using different method. This is a further validation of the derivation obtained in this work as given in (16).

Substituting (16) into (7), A_d may alternately be expressed as given in (17).

$$A_d = 4.343 \times 10^3 \left\{ \frac{\lambda^2}{2\pi} (ka)^3 \left[c_1 + c_2 (ka)^2 + c_3 (ka)^3 \right] . \frac{2.25 \times 10^{-9}}{a^3 V^{\gamma}} \right\} [dB/km] \quad (17)$$

It is important to mention that (17) has been obtained under the assumptions that dust particles in dust storm may be replaced with an equivalent dust particle with mean radius. Other important assumptions made in the development of the proposed model are that the particles have spherical shape and are axially symmetrical, and that the medium surrounding the particles is a non-conducting one. Thus, effect of charges on the surface of the particle can be ignored.

Simplifying (17) further, (18) is obtained.

$$A_d = \frac{1.555 \times 10^{-6} \lambda^2}{V^{\gamma}} \{ k^3 [c_1 + c_2 (ka_e)^2 + c_3 (ka_e)^3] \} [dB/km] \quad (18)$$

Further expansion of (18) and substitution of the propagation constant defined as $2\pi/\lambda$ reduce the expression into (19).

$$A_d = \frac{1.555 \times 10^{-6} \lambda^2}{V^{\gamma}} \left[c_1 (\frac{2\pi}{\lambda})^3 + c_2 (\frac{2\pi}{\lambda})^5 a_e^2 + c_3 (\frac{2\pi}{\lambda})^6 a_e^3 \right] [dB/km] \quad (19)$$

Equation (19) is further simplified as:

$$A_d = 3.86 \times 10^{-4} \left(\frac{c_1}{\lambda V^{\gamma}} \right) + 1.52 \times 10^{-2} \left(\frac{c_2 a_e^2}{\lambda^3 V^{\gamma}} \right) + 9.57 \times 10^{-2} \left(\frac{c_3 a_e^3}{\lambda^4 V^{\gamma}} \right) [dB/km] \quad (20)$$

The above equation can be further treated by letting

$$\alpha = 3.86 \times 10^{-4} . c_1 \quad (21)$$

$$\beta = 1.52 \times 10^{-2} . c_2 \quad (22)$$

$$\theta = 9.57 \times 10^{-2} . c_3 \quad (23)$$

Equations (21), (22) and (23) are then substituted into (20) to obtain (24).

$$A_d = \frac{\alpha}{\lambda V^{\gamma}} + \frac{\beta a_e^2}{\lambda^3 V^{\gamma}} + \frac{\theta a_e^3}{\lambda^4 V^{\gamma}} \ [dB/km] \quad (24)$$

where λ is the wavelength (m), V is the visibility (km), γ is a constant and the constants α, β and θ are as defined in (25), (26) and (27) respectively.

Equations (14), (15) and (16) can be written as (25), (26) and (27) respectively:

$$\alpha = \frac{2.32 \times 10^{-3} . \varepsilon_2}{(\varepsilon_1 + 2)^2 + \varepsilon_2^2} \quad (25)$$

$$\beta = 1.52 \times 10^{-2} . \varepsilon_2 \left\{ \frac{6}{5} . \frac{7\varepsilon_1^2 + 7\varepsilon_2^2 + 4\varepsilon_1 - 20}{\left[(\varepsilon_1 + 2)^2 + \varepsilon_2^2 \right]^2} + \frac{1}{15} + \frac{5}{3\left[(2\varepsilon_1 + 3)^2 + 4\varepsilon_2^2 \right]} \right\} \quad (26)$$

$$\theta = 1.28 \times 10^{-1}\left\{\frac{(\varepsilon_1-1)^2\,(\varepsilon_1+2)+[2(\varepsilon_1-1)(\varepsilon_1+2)-9]+\varepsilon_2^4}{[(\varepsilon_1+2)^2+\varepsilon_2^2]^2}\right\} \quad (27)$$

From (24)

$$A_d = \frac{f}{0.3V^\gamma}\left(\alpha + \frac{\beta a_e^2 f^2}{0.3^2} + \frac{\theta a_e^3 f^3}{0.3^3}\right)[dB/km] \quad (28)$$

where f is the frequency, α, β and θ are constants defined in (25), (26) and (27) respectively.

Equation (28) is the expression for predicting the electromagnetic wave attenuation in dust storms using the Mie scattering theory. It is expressed as a function of visibility during the dust storms, the frequency of the incident electromagnetic wave, particle sizes and parameters that depend on dielectric constants. The expression in (28) can be further simplified and presented according to different frequency bands as will be treated in the next section.

A. Proposed Models at Different Frequency Bands

This sub-section is a presentation of the proposed model for determination and prediction of attenuation at different frequency bands. In other words, (28) can be further simplified and modified by substituting suitable and appropriate dielectric constants as provided [14]. The dust dielectric constant measured under different electromagnetic waves frequencies.

Table I shows the electromagnetic waves frequency bands using letter designation.

TABLE I. ELECTROMAGNETIC WAVES FREQUENCY BANDS USING LETTER DESIGNATION

Letter Designation	Frequency (GHz)	Wavelength
L-band	1 to 2	15 cm to 30 cm
S-band	2 to 4	7.5 cm to 15 cm
C-band	4 to 8	3.75 cm to 7.5 cm
X-band	8 to 12	25 mm to 37.5 mm
Ku-band	**12 to 18**	**16.7 mm to 25 mm**
K-band	**18 to 26.5**	**11.3 mm to 16.7 mm**
Ka-band	**26.5 to 40**	**7.5 mm to 11.3 mm**
Q-band	33 to 50	6.0 mm to 9.0 mm
V-band	50 to 75	4.0 mm to 6.0 mm
W-band	**75 to 110**	**2.7 mm to 4.0 mm**

The dielectric constants for Ku, K, Ka and W bands are respectively given as 5.5 + j1.3, 5.1 + j1.4, 4 + j1.33 and 3.5 + j1.64 [14]. Using the dielectric constant for Ku band and substituting into (25), (26) and (27), the following constants as expressed in (29) to (31) are obtained.

$$\alpha = 5.196 \times 10^{-5} \quad (29)$$

$$\beta = 3.073 \times 10^{-3} \quad (30)$$

$$\theta = 8.13 \times 10^{-3} \quad (31)$$

Thus, from (28), model for predicting the electromagnetic wave attenuation in dust storms at Ku band can be expressed as:

$$A_{dKu} = \frac{f}{0.3V^\gamma}(5.196 \times 10^{-5} + 0.034.a_e^2 f^2 + 0.301.a_e^3 f^3) \quad (32)$$

Similarly, using the dielectric constant for K band and substituting into (25), (26) and (27), the following constants as expressed in (33) to (35) are obtained.

$$\alpha = 6.191 \times 10^{-5} \quad (33)$$

$$\beta = 3.44 \times 10^{-3} \quad (34)$$

$$\theta = 8.047 \times 10^{-3} \quad (35)$$

Model for predicting the electromagnetic wave attenuation in dust storms at K band can then be expressed as:

$$A_{dK} = \frac{f}{0.3V^\gamma}(6.191 \times 10^{-5} + 0.038.a_e^2 f^2 + 0.298.a_e^3 f^3) \quad (36)$$

For Ka band, the constants are as expressed in (37) to (39), producing the prediction model as expressed in (40).

$$\alpha = 8.156 \times 10^{-5} \quad (37)$$

$$\beta = 3.658 \times 10^{-3} \quad (38)$$

$$\theta = 7.549 \times 10^{-3} \quad (39)$$

$$A_{dKa} = \frac{f}{0.3V^\gamma}(8.156 \times 10^{-5} + 0.0406.a_e^2 f^2 + 0.2796.a_e^3 f^3) \quad (40)$$

Lastly, using the dielectric constant for W band and substituting into (25), (26) and (27), the following constants as expressed from (41) to (43) are obtained.

$$\alpha = 1.153 \times 10^{-4} \quad (41)$$

$$\beta = 4.75 \times 10^{-3} \quad (42)$$

$$\theta = 7.09 \times 10^{-3} \quad (43)$$

The constants paved way for obtaining model for predicting the electromagnetic wave attenuation in dust storms at W band as expressed in (44):

$$A_{dW} = \frac{f}{0.3V^\gamma}(1.153 \times 10^{-4} + 0.0528.a_e^2 f^2 + 0.263.a_e^3 f^3) \quad (44)$$

V. RESULTS AND DISCUSSIONS

The signal attenuation (dB/km) versus visibility (km) graphs at different frequency values and bands are plotted and presented in Fig. 1 (Ku band), Fig. 2 (K band), Fig. 3 (Ka band) and Fig. 4 (W band).

As can be seen from Fig. 1 to Fig. 4, the signal attenuation increases as the severity of the dust storm increases. In other word, attenuation increases as the visibility decreases. The signal attenuation also increases as the frequency of the incident electromagnetic wave increases and vice versa. At frequency Ku band, results show that attenuation varies from 0.024 dB/km to 0.43 dB/km for dust particles with equivalent radius of $50\ \mu m$ and dust storms visibility between 10 m and 100 m.

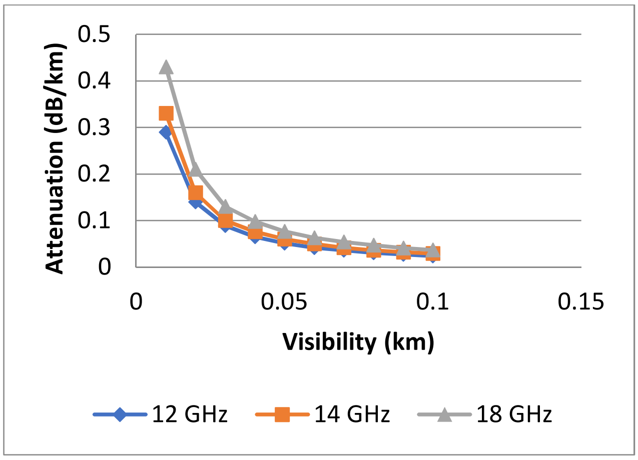

Fig. 1. Attenuation at Ku band (12 GHz, 14 GHz and 18 GHz frequency): (32).

In Fig. 5, the signal attenuation was plotted against the visibility during dust storms showing the different frequency bands. Results show that attenuation varies from 0.024 dB/km to 5.4 dB/km for dust particles with effective radius of $50\ \mu m$ and visibility between 0.01 km and 0.1 km. Suffice to mention that this present good agreement with the signal attenuations obtained by [8].

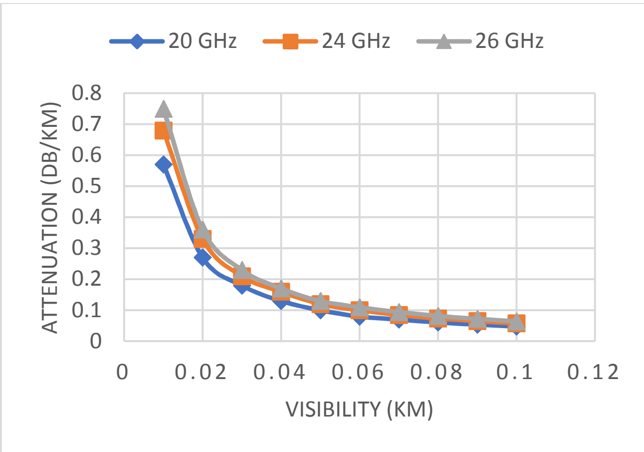

Fig. 2. Attenuation at K band (20 GHz, 24 GHz and 26 GHz frequency): (36).

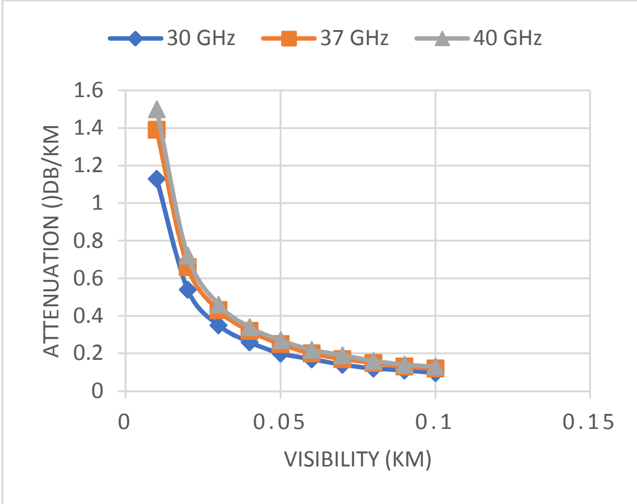

Fig. 3. Attenuation at Ka band (30 GHz, 37 GHz and 40 GHz frequency): (40).

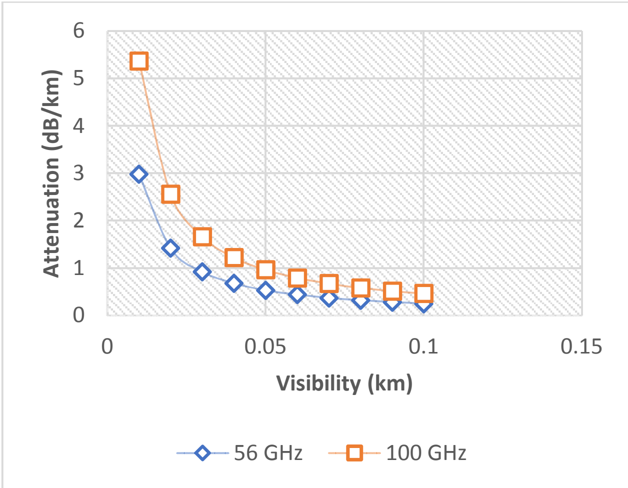

Fig. 4. Attenuation at Ka band (56 GHz and 100 GHz frequency): (44).

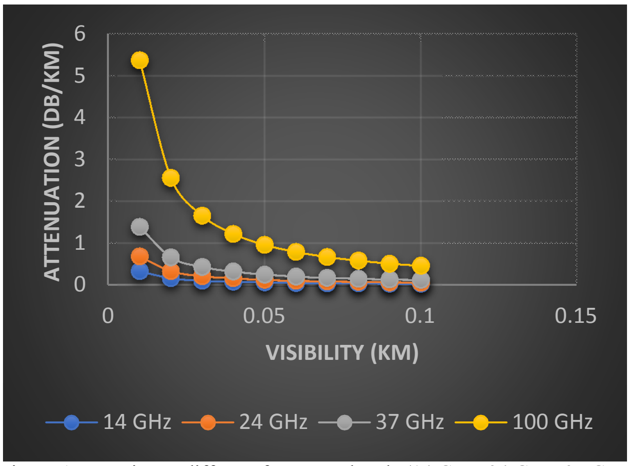

Fig. 5. Attenuation at different frequency bands (14 GHz, 24 GHz, 37 GHz and 100 GHz).

VI. CONCLUSION

In this research work, taking the Mie scattering theory and solution of Maxwell's equations, the dielectric constant of dust particles at different frequency bands and the relation between dust particle concentration and visibility into consideration, the attenuation of the electromagnetic waves propagating across dust storms using newly developed prediction model was calculated. The derivation was premised on the spherical shape assumption of dust particles and uniformly distributed particle size along the propagation path.

The proposed models expressed for attenuation of electromagnetic waves were derived in terms of the wavelength or incidence frequency, equivalent particle radius and visibility. Formulas are presented for electromagnetic wave propagation in dust storms, suitable for different frequency bands. The study has been made for different visibilities and frequencies especially at millimetre wave and sub- millimetre wave.

The results obtained show that attenuation is directly proportional to frequency, but inversely proportional to the dust storms visibility. Thus, one of the conclusions that can be drawn is that the signal attenuation increases as the severity of the dust storm increases. Another definite conclusion is the fact that signal attenuation increases as the frequency of the incident electromagnetic wave increases.

Taking both the frequency, dielectric constants and visibility into account, it was also found that the calculated attenuation is comparable to those obtained using available existing models.

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