PREDICTION OF SIGNAL ATTENUATION DUE TO DUSTSTORMS USING MIE SCATTERING

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ABSTRACT: The present trend in radio design calls for the use of frequencies above 40 GHz for short links carrying wide-band digital communication signals. In order to utilize the new frequency band efficiently, signal attenuation studies due to duststorms is needed urgently for desert areas. This paper presents a mathematical model which has been developed to predict the signal attenuation due to duststorm. The proposed model enables the convenient calculation of the signal path attenuation based on Mie solution of Maxwell's equations for the scattering of electromagnetic wave by dust particles. The predicted values from the proposed mathematical model are compared with the measured values observed in Saudi Arabia and Sudan and show relatively close agreement.

Keywords: *Signal Attenuation, Duststorm, Mathematical Model, Duststorm Visibility.*

1. ABSORPTION AND SCATTERING BY THE ATMOSPHERE

When microwaves pass through the medium containing precipitations like rain, snow or dust particles, the signals get attenuated through two phenomena [1].
a) Absorption of energy by these particles.
b) Scattering of energy out of the beam by these particles.
Microwaves suffer absorption and scattering by the atmosphere especially at higher frequencies where the scattering effects become more severe [2]. The knowledge of these characteristics is essential to design reliable communications.

1.1 Theory of single-particle scattering

The basic theory underling mathematical model for attenuation is the theory for single-particle scattering [3]. The characteristics of these two phenomena, scattering and absorption, can be expressed most conveniently by assuming an incident plane wave. The total electromagnetic field around the scattering object is split into an incident and a scattered field as shown in Fig. 1 [4]:

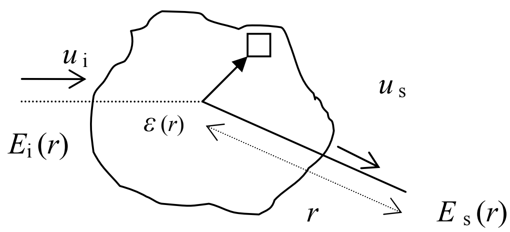

Fig. 1: Scattering configuration.

The total amplitude of the fields at any point on the surface of the sphere can be given as [5]:

$$H = H_i + H_s \tag{1}$$

$$E = E_i + E_s \tag{2}$$

where, E_i and H_i denote the incident electric and magnet field, and E_s and H_s denote corresponding scattered fields.

1.2 The total cross-section efficiency factors

The power density of the incident wave is uniform in space. Therefore, the power loss of the incident wave can be calculated by multiplying the uniform power density with a cross-section, having the dimension of the area. The total power removed from the incident field by absorption and scattering can be represented by the total or extinction cross-section [4].

When the problem is concerned with the flow of energy, poynting vector must be used. So the power density is represented by the averaged poynting vector $\bar{S}$. This poynting vector can be splitted into separate terms using the separation of the total field into the incident and scattered field (Eq. (1) and Eq. (2)), resulting in [4]:

$$\bar{S} = \bar{S}_i + \bar{S}_s + \bar{S}_d \tag{3}$$

where,

$$\bar{S}_i = \tfrac{1}{2}\mathrm{Re}(E_i \times H_i{}^*) \tag{4}$$

$$\bar{S}_s = \tfrac{1}{2}\mathrm{Re}(E_s \times H_s{}^*) \tag{5}$$

$$\bar{S}_d = \tfrac{1}{2}\mathrm{Re}(E_i \times H_s{}^* + E_s \times H_i{}^*) \tag{6}$$

and where, E_i and H_i denote the incident electric and magnet field, whereas E_s and H_s denote corresponding scattered fields.

The net power flow through the surface of this sphere can be calculated by integrating the radial component of $\bar{S}$ over the sphere. If the scatterer is a lossless dielectric, the power flow will be zero. If it is lossy (permittivity is complex), the net power flow will represent the absorption rate P_a of energy by the scatterer as shown in Fig. 2 and can be written as:

$$-P_a = P_i + P_s + P_d \tag{7}$$

where P_a represents the integral of the radial component of $\bar{S}$.

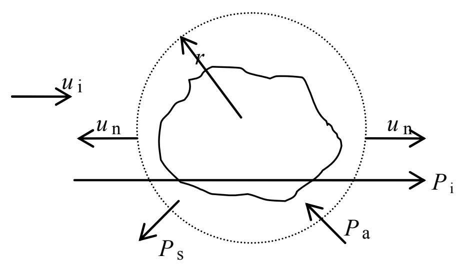

Fig. 2: Scattering points.

The medium surrounding the particle is assumed to be lossless, so the net flow of the energy of the incident field is zero for every closed surface ($P_i = 0$), and thus:

$$P_a + P_s = -P_d \tag{8}$$

and from Eq. 6;

$$P_a + P_s = -P_d = -\tfrac{1}{2}\mathrm{Re}\iint_s (E_i \times H_s {}^* + E_s \times H_i {}^*) \cdot u_n dS \tag{9}$$

where u_n is the unit vector normal to the surface S and directed outwards and the dot represent the inner product as shown in Fig. 2.

Using Maxwell equation the sum of absorbed and scattered energy can be expressed as [4]:

$$P_a + P_s = \frac{2\pi}{k}\left(\frac{\varepsilon}{\mu}\right)^{1/2} E_i \ \mathrm{Im}\left[u_e \cdot f\ (u_s, u_i)\right] \tag{10}$$

where,

k : wave number ($k = \omega\sqrt{\mu\varepsilon} = (2\pi)/\lambda$).

$\left(\frac{\varepsilon}{\mu}\right)^{1/2}$: characteristic impedance of the medium.

u_e : unit vector defining the polarization of the wave.

$f(u_s, u_i)$: the scattering amplitude function; it is a function of the direction of propagation u_i of the incident field and of the direction u_s from the object to the observation point.

The ratio of the rate of removal of energy ($P_a + P_s$) to the rate of the incident energy (P_i) on a unit cross-sectional area of the scatterer is defined as the extinction or total cross-section efficiency factors [4]:

$$\sigma_t = \frac{P_a + P_s}{P_i} = \sigma_a + \sigma_s = \frac{4\pi}{k}\,\mathrm{Im}\left[u_e \cdot f\,(u_s, u_i)\right] \tag{11}$$

2. ANALYTICAL MODELS FOR SCATTERING

Two models have been presented for an analytical solution of Maxwell's equations for the scattering of electromagnetic wave by dielectric spherical particles, Rayleigh approximation and Mie solution.

2.1 Rayleigh Approximation

The assumption for Rayleigh approximation is that ($ka < 1$), meaning that the radius a of the particle is small compared with the wavelength. For a dielectric sphere that is small compared with wavelength, the field inside the particle is chosen to be the solution of the equivalent dielectric electrostatic problem. In the Rayleigh approximation, the field inside the scattering particle is not modeled properly. For an exact solution the scattered field reflects all the properties of the object which is no longer true for an approximation solution [5].

The extinction or total cross-section efficiency factors by Rayleigh approximation expressed as [6]:

$$\sigma_t = \sigma_s + \sigma_a = \left[\frac{8}{3}\pi a^2 \left(ka\right)^4 + 12\pi a^2 \left(ka\right)\frac{\varepsilon''}{(\varepsilon'-1)^2 + (\varepsilon'')^2}\right]\left|\frac{\varepsilon - 1}{\varepsilon + 2}\right|^2 \tag{12}$$

where,

a : the particle radius

k : the wavenumber ($k = 2\pi/\lambda$)

ε' , ε'' : the real and imaginary contributions of the relative dielectric constant of the particles

2.2 Mie Solution

Mie solution is a complete analytical solution of Maxwell's equations for the scattering of electromagnetic wave by dielectric spherical particles. In contrast to Rayleigh scattering Mie solutions to scattering embraces all possible ratios of diameter to wavelength [7].

Mie solutions unlike Rayleigh scattering do not depend upon any such limitation and can be utilized to predict attenuation in microwave wave band with high reliability especially at higher frequencies used by new systems with larger bandwidth.

The extinction or total cross-section efficiency factors by Mie solutions can be expressed as [6]:

$$\sigma_t = \frac{\lambda^2}{2\pi}\left(ka\right)^3\left(c_1 + c_2\left(ka\right)^2 + c_3\left(ka\right)^3\right) \tag{13}$$

where,

a : the particle radius

k : the wavenumber ($k = 2\pi/\lambda$)

λ : the wavelength, and

C_1, C_2 and C_3: constants whose values depend on real (ε') and imaginary part (ε'') of the dielectric constant of the particles as:

$$C_1 = \frac{6\varepsilon''}{\left(\varepsilon'+2\right)^2 + \varepsilon''^2} \tag{14}$$

$$C_2 = \varepsilon''\left\{\frac{6}{5}\frac{7\varepsilon'^2 + 7\varepsilon''^2 + 4\varepsilon' - 20}{\left[\left(\varepsilon'+2\right)^2 + \varepsilon''^2\right]^2} + \frac{1}{15} + \frac{5}{3\left[\left(2\varepsilon'+3\right)^2 + 4\varepsilon''^2\right]}\right\} \tag{15}$$

$$C_3 = \frac{4}{3}\left\{\frac{\left(\varepsilon'-1\right)^2\left(\varepsilon'+2\right) + \left[2\left(\varepsilon'-1\right)\left(\varepsilon'+2\right) - 9\right] + \varepsilon''^4}{\left[\left(\varepsilon'+2\right)^2 + \varepsilon''^2\right]^2}\right\} \tag{16}$$

3. SIGNAL ATTENUATION DUE TO DUSTSTORM

The theory of attenuation due to sand and duststorm can be explained in terms of scattering and absorption cross section of a single particle. The methods to predict the signal attenuation due to rain effects can be applied for duststorm because the general model for scattering in sand and dust particle populations is essentially the same as that for a population of hydrometeors; both of them are discrete random medium [3].

The signal attenuation due to duststorm is estimated generally by solving the forward scattering amplitude function of a single particle [8,9,10]. The solution may be carried out using the Rayleigh approximation or Mie solutions. The method depends largely on the wave number and particle radius.

The attenuation of electromagnetic radiation (A_T) over a path of extent L through precipitating particles may be written as [11]:

$$A_T = \int_0^L A_p dx \quad \text{[dB]} \tag{17}$$

where A_p(*dB/km*) is the specific attenuation characterizing the precipitating particles.

The following expression has been used to calculate the attenuation due to rain [11,12,13]:

$$A_p = 4.343 \times 10^3 \int_{a_{\min}}^{a_{\max}} \sigma_t(a) \cdot N(a) da \quad \text{[dB/km].} \tag{18}$$

where,

$N(a)da$: the particles number per unit volume of air with particles radius between a and $a+da$,

σ_t : the total attenuation cross section efficiency factors of particle of radius a.

3.1 Duststorm Predicted Model

Starting from the above, we can expressed the attenuation of electromagnetic radiation (A_T) over a path of extent L through duststorm as:

$$A_T = \int_0^L A_d dx \quad \text{[dB]} \tag{19}$$

where A_d is the s pecific attenuation characterizing the duststorm which can be expressed as:

$$A_d = 4.343 \times 10^3 \int_{a_{\min}}^{a_{\max}} \sigma_t(a) \cdot N(a) da \quad \text{[dB/km].} \tag{20}$$

and where,

$N(a)da$: the dust particles number per unit volume of air with dust particles radius between a and $a+da$,

σ_t : the total attenuation cross section efficiency factors of dust particle of radius a.

a. Using Rayleigh Approximation

Goldhirsh [14], in using the Rayleigh approximation expression for the total cross-section efficiency factor (σ_t), expressed the specific attenuation due to duststorm A_d as:

$$A = \frac{2.317 \cdot 10^{-3} \cdot \varepsilon''}{\left[\left(\varepsilon' + 2 \right)^2 + \varepsilon''^2 \right] \cdot \lambda} \cdot \frac{1}{V^{\gamma}} \quad \text{[dB/km]} \tag{21}$$

where,

V : the visibility in kilometer,

λ : the wavelength in meter,

γ : constants that depend on the type of land from which the storm originated as well as the climatic conditions,

ε', ε'' : the real and imaginary part of the dielectric constant of the dust particles.

Goldhirsh formulation is applicable at wavelengths for which the Rayleigh condition is applicable which is equal to 48 GHz as a maximum frequency [14].

b. Using Mie solution

In order to derive a mathematical model that can predict the signal attenuation due to duststorm at higher frequencies, the Mie expression for total cross-section efficiency factors (σ_t) that appear in Eq. (13) was selected for substitution in Eq. (20). So the duststorm attenuation (A_d) can be written as:

$$A_d = 4.343 \times 10^3 \int_{a_{\min}}^{a_{\max}} \frac{\lambda^2}{2\pi} (ka)^3 \left(c_1 + c_2 (ka)^2 + c_3 (ka)^3 \right) \cdot N(a) da \quad \text{[dB/km]} \tag{22}$$

i. Dependence on Visibility

To calculate the attenuation by Eq. (22) requires data for the number of particles of dust *N*, which is difficult to measure accurately. On the other hand, statistical information on duststorm visibility is available. Goldhirsh [14] expresses the visibility in term of the particle density and the radius as:

$$V(km) = \frac{5.5 \times 10^{-4}}{N a_e^2} \tag{23}$$

where,

N : the dust particles number per unit volume,

a_e : the equivalent particle radius in meters.

By solving N in the above formula we can express the particle density in term of the visibility and the radius as:

$$N = \frac{5.5 \times 10^{-4}}{V a_e^{\,2}} \tag{24}$$

ii. General Formula

By substituting the particle density expression which appear in Eq. (24) into Eq. (22), the specific attenuation characterizing the duststorm (A_d) may alternately be expressed as:

$$A_d = 4.343 \times 10^3 \int_{a_{\min}}^{a_{\max}} \left[\frac{\lambda^2}{2\pi} (ka)^3 \left(c_1 + c_2 (ka)^2 + c_3 (ka)^3 \right) \cdot \frac{5.5 \times 10^{-4}}{V a_e^{\,2}} \right] da \text{ [dB/km].} \tag{23}$$

A further approximation can be made in these calculations, assuming that every dust particle in a real storm may be replaced by an equivalent particle (a_e) whose radius is the mean radius for all dust particle. By this assumption the value of equivalent particle radius (a_e) considered as constant value and Eq. (23) may alternately be expressed as an algebraic expression:

$$A_d = 4.343 \times 10^3 \times \left[\frac{\lambda^2}{2\pi} (ka_e)^3 \left(c_1 + c_2 (ka_e)^2 + c_3 (ka_e)^3 \right) \cdot \frac{5.5 \times 10^{-4}}{V a_e^{\,2}} \right] \text{ [dB/km].} \tag{24}$$

and can be simplified to:

$$A_d = \frac{0.38 \times \lambda^2}{V} \left(c_1 k^3 a_e + c_2 k^5 a_e^{\,3} + c_3 k^6 a_e^{\,4} \right) \quad \text{[dB/km].} \tag{25}$$

By substituting $k = 2\pi / \lambda$ in Eq. (25):

$$A_d = \frac{0.38}{V} \left(c_1 \frac{8\pi^3}{\lambda} a_e + c_2 \frac{32\pi^5}{\lambda^3} a_e^{\,3} + c_3 \frac{64\pi^6}{\lambda^4} a_e^{\,4} \right) \text{ [dB/km].} \tag{26}$$

which can be simplified to:

$$A_d = 94.3 \times c_1 \frac{a_e}{V\,\lambda} + 3721.2 \times c_2 \frac{a_e^{\,3}}{V\,\lambda^3} + 23381 \times c_3 \frac{a_e^{\,4}}{V\,\lambda^4} \quad \text{[dB/km].} \tag{27}$$

Finally, we can express the specific attenuation due to duststorm A_d (dB/km) as:

$$A_d = \frac{X a_e}{V\,\lambda} + \frac{Y a_e^{\,3}}{V\,\lambda^3} + \frac{Z a_e^{\,4}}{V\,\lambda^4} \qquad \text{[dB/km].} \tag{28}$$

where,

a_e : the equivalent particle radius in meters,

V : the visibility in kilometer,

λ : the wavelength in meter and;

X, Y and Z: constants whose values depend on real (ε') and imaginary part (ε'') of the dielectric constant of the dust particles as:

$$X = \frac{565.8\varepsilon''}{(\varepsilon'+2)^2+\varepsilon''^2} \tag{29}$$

$$Y = 3.7\times10^3 \cdot \varepsilon'' \left\{ \frac{6}{5}\frac{7\varepsilon'^2+7\varepsilon''^2+4\varepsilon'-20}{\left[(\varepsilon'+2)^2+\varepsilon''^2\right]^2} + \frac{1}{15} + \frac{5}{3\left[(2\varepsilon'+3)^2+4\varepsilon''^2\right]} \right\} \tag{30}$$

$$Z = 3.12\times10^4 \left\{ \frac{(\varepsilon'-1)^2(\varepsilon'+2)+\left[2(\varepsilon'-1)(\varepsilon'+2)-9\right]+\varepsilon''^4}{\left[(\varepsilon'+2)^2+\varepsilon''^2\right]^2} \right\} \tag{31}$$

iii. The Formula in Term of Frequencies (*f*) in GHz

For more simplification of Eq. (31) it is better to express the wavelength (λ) in term of frequencies (f) in GHz which is easier to use by microwave network engineers. So the specific attenuation of duststorm A_d (dB/km) can be expressed as:

$$A_d = \frac{X a_e f}{(0.3)V} + \frac{Y a_e^3 f^3}{(0.3)^3 V} + \frac{Z a_e^4 f^4}{(0.3)^4 V} \quad \text{[dB/km]}. \tag{32}$$

and can be simplified to:

$$A_d = \frac{a_e f}{V}\left(x + y a_e^2 f^2 + z a_e^3 f^3\right) \quad \text{[dB/km]}. \tag{33}$$

where,

a_e : the equivalent particle radius in meters,

V : the visibility in kilometer,

f : the frequency in GHz, and

x, y and z: constants whose values depend on real (ε') and imaginary part (ε'') of the dielectric constant of the dust particles as:

$$x = \frac{1886 \cdot \varepsilon''}{\left(\varepsilon' + 2\right)^2 + \varepsilon''^2} \tag{34}$$

$$y = 137 \times 10^3 \cdot \varepsilon'' \left\{ \frac{6}{5} \frac{7\varepsilon'^2 + 7\varepsilon''^2 + 4\varepsilon' - 20}{\left[\left(\varepsilon' + 2\right)^2 + \varepsilon''^2\right]^2} + \frac{1}{15} + \frac{5}{3\left[\left(2\varepsilon' + 3\right)^2 + 4\varepsilon''^2\right]} \right\} \tag{35}$$

$$z = 379 \times 10^4 \left\{ \frac{\left(\varepsilon' - 1\right)^2 \left(\varepsilon' + 2\right) + \left[2\left(\varepsilon' - 1\right)\left(\varepsilon' + 2\right) - 9\right] + \varepsilon''^4}{\left[\left(\varepsilon' + 2\right)^2 + \varepsilon''^2\right]^2} \right\} \tag{36}$$

3.2 Determination of Attenuation at Different Bands

A further simplification can be made in this general formula (Eq. (33)) to more effective and become easier for use by microwave network designers and engineers. This can be achieved by subdividing the general formula into several formulas, each one can deal with specific microwave band suitable to calculate the signal attenuation due to dust particles at every microwave bands.

It is clear from the general formula that the signal attenuation due to dust particles depends on visibility, frequency, dust particles radius and dielectric constant. The dielectric constant values of dust particles are important components in the determination of attenuation. A number of investigators have measured the refractive index of sand and dust samples [9, 15, 16]. A further approximation can make in the new subdivided formulas, assuming that a single value of the refractive index can be fitted for all frequencies range in specific microwave band.

i. Attenuation at S-band

For S-band which is in the range between 2 – 4 GHz, the dielectric constants measured were ε'= 4.56, ε''= 0.251 [15]. The specific attenuation of duststorm A_d (dB/km) can be expressed as:

$$A_{dS} = 11 \cdot \frac{a_e f}{V} + 433 \cdot \frac{a_e^3 f^3}{V} + 2.46 \times 10^5 \frac{a_e^4 f^4}{V} \quad \text{[dB/km]}. \tag{37}$$

Figure 3 showed the signal attenuation (dB/km) versus frequency plot at S-bands for four different values of visibility at equivalent particle radius of 50 µm.

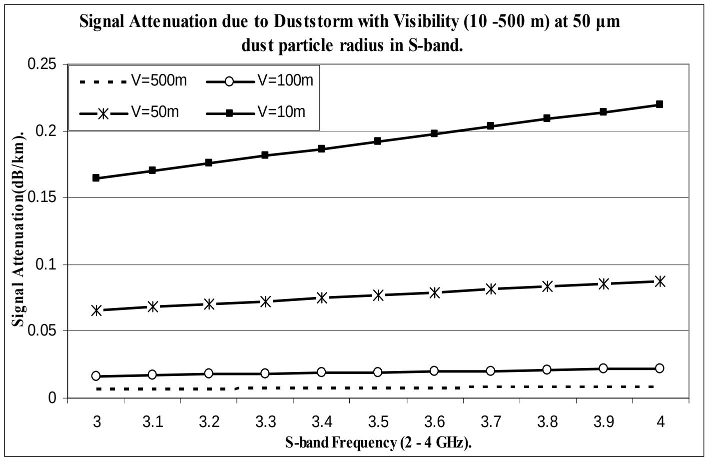

Fig. 3: Signal attenuation (dB/km) versus frequency at S-band.

ii. Attenuation at X-band

For X-band which is in the range between 8 – 12 GHz, the dielectric constants measured were $\varepsilon' = 5.73$, $\varepsilon'' = 0.415$ [8]. The specific attenuation of duststorm A_d (dB/km) can be expressed as:

$$A_{dX} = 13 \cdot \frac{a_e f}{V} + 702 \cdot \frac{a_e^3 f^3}{V} + 2.5 \times 10^5 \frac{a_e^4 f^4}{V} \quad \text{[dB/km]}. \tag{38}$$

The signal attenuation (dB/km) versus frequency plot at X-bands for four different values of visibility at equivalent particle radius of 50 µm is shown in Fig. 4.

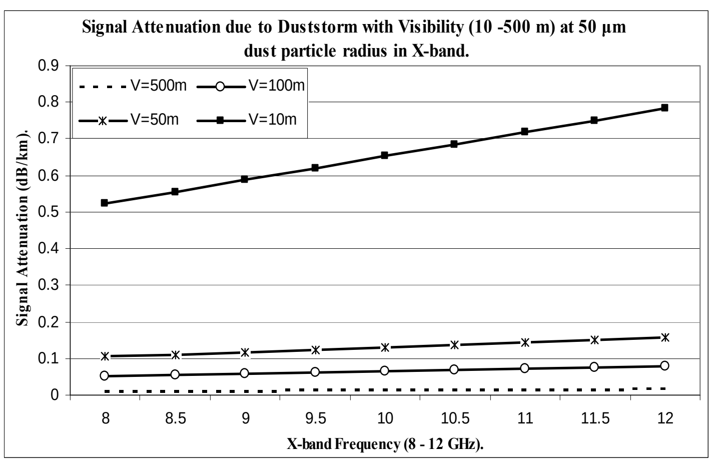

Fig. 4: Signal attenuation (dB/km) against frequency at X-band.

iii. Attenuation at Ku-band

For Ku-band which is in the range between 12 – 18 GHz, the dielectric constants measured were $\varepsilon' = 5.5$, $\varepsilon'' = 1.3$ [16]. The specific attenuation of duststorm A_d (dB/km) can be expressed as:

$$A_{dku} = 42 \cdot \frac{a_e f}{V} + 2806 \cdot \frac{a_e^3 f^3}{V} + 2.4 \times 10^5 \frac{a_e^4 f^4}{V} \quad \text{[dB/km]}. \tag{39}$$

Figure 5 showed the signal attenuation (dB/km) versus frequency plot at Ku-bands for four different values of visibility at equivalent particle radius of 50 μm.

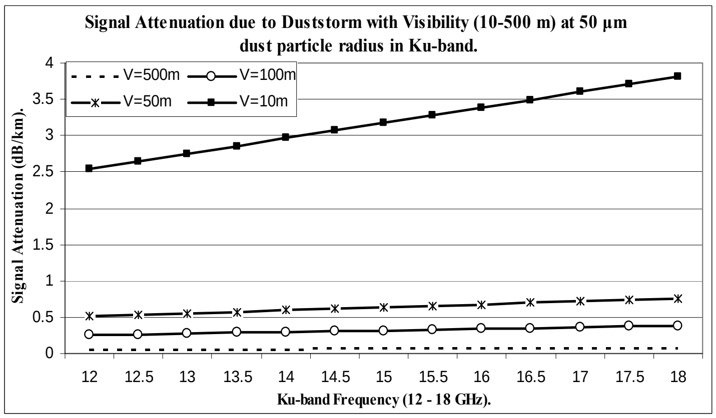

Fig. 5: Signal attenuation (dB/km) vs frequency at Ku-band.

iv. Attenuation at K-band

For K-band which in the range between 18 – 26.5 GHz, the dielectric constants measured were $\varepsilon' = 5.1$, $\varepsilon'' = 1.4$ [16]. The specific attenuation of duststorm A_d (dB/km) can be expressed as:

$$A_{dk} = 50 \cdot \frac{a_e f}{V} + 3368 \cdot \frac{a_e^3 f^3}{V} + 2.38 \times 10^5 \frac{a_e^4 f^4}{V} \quad \text{[dB/km]}. \tag{40}$$

The signal attenuation (dB/km) versus frequency plot at K-bands for four different values of visibility at equivalent particle radius of 50 μm is shown in Fig. 6.

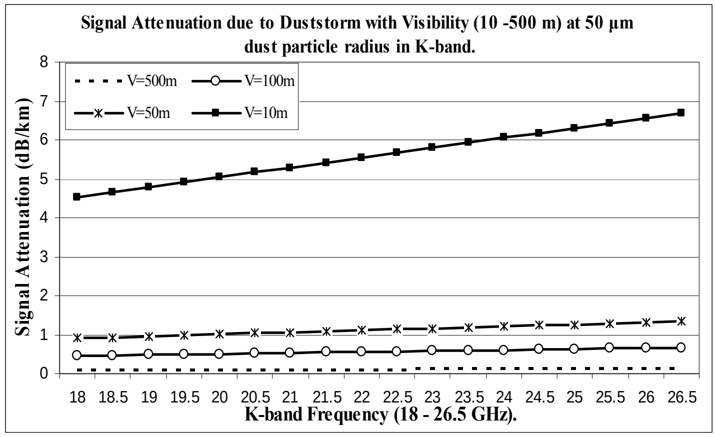

Fig. 6: Signal attenuation (dB/km) vs frequency at K-band.

v. Attenuation at Ka-band

For Ka-band which in the range between 26.5 – 40 GHz, the dielectric constants measured were $\varepsilon' = 4$, $\varepsilon'' = 1.325$ [16]. The specific attenuation of duststorm A_d (dB/km) expression can be written as:

$$A_{dka} = 66 \cdot \frac{a_e f}{V} + 3712 \cdot \frac{a_e^3 f^3}{V} + 2.2 \times 10^5 \, \frac{a_e^4 f^4}{V} \quad \text{[dB/km]}. \qquad (41)$$

Figure 7 showed the signal attenuation (dB/km) versus frequency plot at Ka-bands for four different values of visibility at equivalent particle radius of 50 µm.

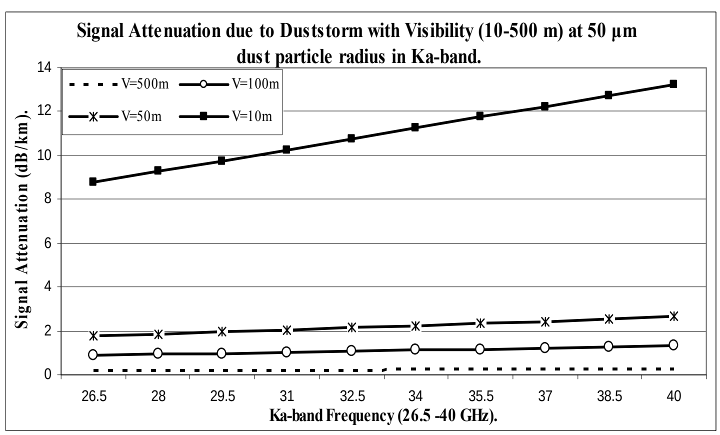

Fig. 7: Signal attenuation (dB/km) against frequency at Ka-band.

vi. Attenuation at W-band

For W-band which in the range between 56 – 100 GHz, the dielectric constants measured were $\varepsilon' = 3.5$, $\varepsilon''= 1.64$ [16]. The specific attenuation of duststorm A_d (dB/km) expression is;

$$A_{dW} = 94 \cdot \frac{a_e f}{V} + 6232 \cdot \frac{a_e^3 f^3}{V} + 2.1 \times 10^5 \frac{a_e^4 f^4}{V} \quad \text{[dB/km]}. \tag{42}$$

The signal attenuation (dB/km) versus frequency plot at W-bands for four different values of visibility at equivalent particle radius of 50 µm is shown in Fig. 8.

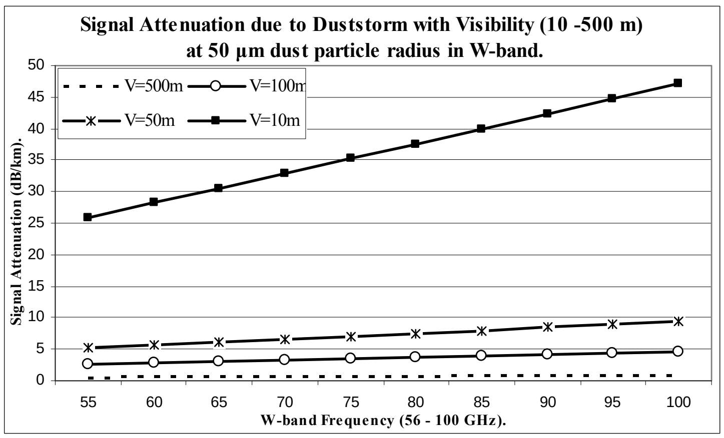

Fig. 8: Signal attenuation (dB/km) versus frequency at W-band.

4. VALIDITY OF THE MATHEMATICAL MODEL

In order to verify the validity of the proposed mathematical model for prediction of signal attenuation due to duststorm, a comparison run between the results obtained from the mathematical model and field measurements were made. At the same time a comparison run between the proposed model and one of the current models was also investigated.

4.1 Saudi Arabia Measurements

During the course of measurements, Alhaider and Ali recorded several duststorms during 1987 in the city of Riyadh, Saudi Arabia [17]. The duststorm was observed both by the meteorological sensors and by the radio links. Visibility reduction was measured by using the known marked distance method. For most of the events, the cell size of the storm exceeded 20 km. The measurements run over 14 km microwave link at 40 GHz (Ka-band). The millimeter wave transmitters and receivers are placed at 100 m and 25 m above ground, respectively.

4.2 Sudan Measurements

Measurement in Khartoum-Sudan on September 1, 2007 shows attenuation 0.67 dB per kilometer observed by the author on 15 km link at 13 GHz (Ku band) [18]. The duststorm produced a visibility smaller than 5 m. The predicted value found by proposed model using the Ku-band specific attenuation formula is 0.55 dB per kilometer for the same visibility which is quite close to measured value of 0.67 dB/km.

4.3 Comparison of Measured and Calculated Values

Calculated attenuation values for different values of visibility at 40 GHz are given in Table 1 together with attenuation measured values observed in Saudi Arabia. The predicted values calculated by the proposed Ka-band specific attenuation formula (Eq. 41) and Goldhirsh model (Eq. 21). The following values are considered in calculation:

- Visibility from less than 1 km to more than 5 km.
- Equivalent dust particle radius (a_e) = 30 µm.
- The dielectric constants (ε'=4, ε''=1.325).
- Frequency = 40 GHz.

Table 1: Result of Measurements and Calculations of Signal Attenuation due to Duststorm for Different Value of Visibility at 40 GHz.

Calculated Value (dB/km)		Measured Value (dB/km)	
A_c (Goldhirsh Model)	A_c (Proposed Model)	A_m	Visibility (km)
0.02	0.13	0.14	0.625
0.01	0.064	0.1	1.25
0.007	0.06	0.071	1.42
0.003	0.021	0.05	3.75
0.002	0.014	0.036	5.56

The signal attenuation (dB/km) versus different values of visibility plot at frequency equal to 40 GHz for measured and calculated values is shown in Fig. 9. Unlike the predicted values from Goldhirsh model the attenuation values calculated by the proposed model show close agreement to measurements.

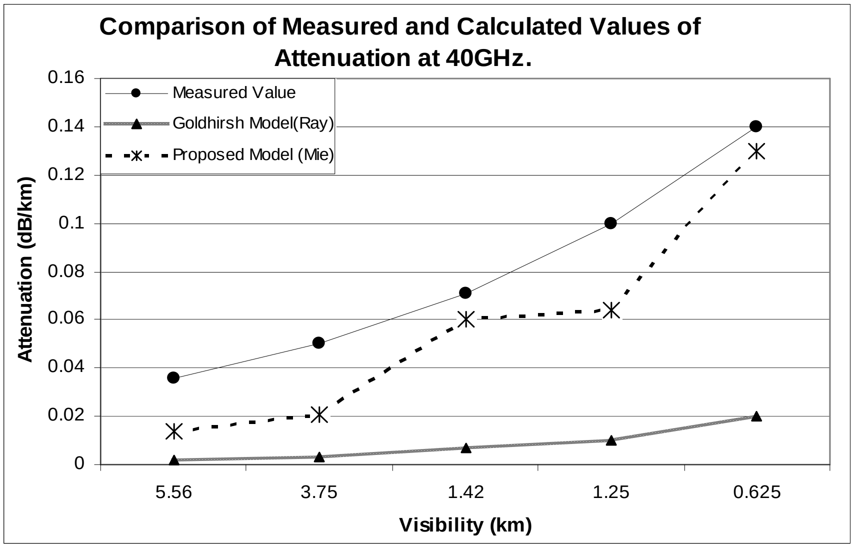

Fig. 9: Comparison between Measured and Calculated Attenuation.

5. CONCLUSION

A model has been developed to predict microwave attenuation due to dust particles using Mie solution of Maxwell's equations for the scattering of electromagnetic wave. In this proposed model the term visibility (*V*) is applied to denote the degree of duststorm density instead of total number of dust particles (*N*).

The predictions show that the attenuation varies from 13 dB/km to 0.2 dB/km at 40 GHz for dust particle radius equal to 50 μm and the visibility varies from 10 m to 500 m. At higher frequency of 100 GHz, the attenuation varies from 47 dB/km to 2dB/km for dust particle radius equal to 50 μm and the visibility varies from 10 m to 500 m.

The predicted values from the mathematical model are compared with the measured values observed in Saudi Arabia and Sudan. The proposed model predicts the measured data more accurately than existing model. The accurate prediction is useful to design higher frequency links at areas affected by duststorms.

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