

Electromagnetic Waves Propagation in Dust Storms at Millimetre Wave Band

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Abstract

The effects of dust storms on propagation of electromagnetic wave at millimeter wave band are investigated. The propagation at millimeter wave band is affected by dust particles by way of signal attenuation. Formula for evaluating the wave attenuation at higher frequencies in a dusty medium is therefore developed in this work. The formula is based on the complex forward scattering amplitude of spherical dust particles using Rayleigh method. Three conditions are set to validate the suitability of the method for the model. It is shown that the Rayleigh approximation is valid for determining the scattering of spherical dust particles for the particle sizes and frequency range considered. The wave attenuation expression is proposed in terms of wavelength, visibility and complex permittivity. Attenuation results obtained are compared with some already published results. It is found that the attenuation by the proposed formula and the published formulae show close agreement. Attenuation in dry dust is only significant when the visibility becomes severe or at lower millimetric wave bands.

Keywords: attenuation, dust storms, electromagnetic wave, millimeter wave band, propagation, Rayleigh approximations

INTRODUCTION

Electromagnetic wave propagation in sand and dust storms has received some attention in the literature (Chu 1979; Ghobrial *et al* 1997; Elsheikh *et al* 2010 etc.) owing to the importance of satellite communication technology, remote sensing, radio relay etc. Large development of microwave links established in tropical, semi desert and desert regions is also a factor. Attenuation induced by storm particles can cause electromagnetic wave communication system outages during sand and dust storms (Goldhirsh 1982; Ghobrial *et al* 1997). These particles interfere with microwave or millimetre wave radio. Scattering and absorption by storm particles are largely responsible for the attenuation and cross polarization of microwave propagation in dust storms (Ansari *et al* 1982; Ahmed *et al* 1987). For accurate prediction of the impact of sand and dust storm on electromagnetic wave communication systems and for efficient design of the systems, it is necessary to consider and understand important propagation parameters.

A number of investigators have presented models to compute microwave attenuation in dust storms (Ansari *et al* 1982; Ghobrial *et al* 1987; Goldhirsh 2001). These investigators concluded that attenuation by dust storms is not serious except for very dense storms. It has also been shown (Yi 2004; Dong *et al* 2011) that complex permittivity and frequency have considerable influence on microwave propagation in

dust storms. Goldhirsh (1982), Bashir (2009) and many other investigators expressed wave attenuation induced by sand and dust storms in terms of mass of dust per unit volume of air. However, this parameter is difficult to measure accurately. Ahmed (1987) and Elsheikh *et al* (2010) dealt with the effects of particle size distribution on microwave propagation. Elabdin *et al* (2009) analysed the microwave attenuation based on Mie scattering theory. The model involves rigorous mathematical approach to predict wave attenuation in dust storms. YingXia *et al* (2003) and Srivastava *et al* (2003) also calculated the attenuation in sand and dust storms.

The previous studies conducted in this area barely treated the problem beyond the X-band and the attenuation expressions were given in terms of concentration number of particles or volume fraction which is difficult to measure or almost impossible. The present work considers the wave attenuation problem at millimetre wave (MMW) band and employs a more realistic dust storms characteristic to arrive at the attenuation expression. Since dust storms are meteorologically observed and majorly characterized using visibility, the paper explores the relation between the optical visibility and the volume fraction to simplify the complexity surrounding the problem involving randomly distributed sand and dust particles and the concentration number of particles per unit volume. Rayleigh approximation method is validated for solving the electromagnetic

wave scattering at MMW band. Thus, the effects of dust particles on electromagnetic wave attenuation are treated at MMW band by presenting formula that is suitable for different wavelength in terms of relative permittivity and visibility. The application of the proposed model is however limited to frequency of up to 85 GHz; a constraint due to the (Rayleigh) method used.

MODEL DEVELOPMENT

Rayleigh Approximation on Complex Scattering

Dust particles can cause attenuation of radio waves through scattering and absorption by the particles (Flock 1987). 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. However, the local field is generally unknown; hence, certain approximations like Rayleigh, Born, Wentzel-Kramers-Brillouin (WKB) etc. (Ishimaru 1978) are usually required to overcome the difficulty.

Rayleigh approximation method gives an analytical solution of Maxwell's equations for the scattering of electromagnetic waves by dielectric particles. The Rayleigh type of scattering occurs when the particle is electrically small. The scattering scatters energy with a radiation pattern like that of a dipole. It is a function of the electric polarizability of the particles. Polarizability is a property of matter and the measure of change in a molecule's electron distribution in response to changing electric interactions with solvents or ionic reagents.

The method is validated for solving electromagnetic wave scattering at MMW bands. Firstly, the approximation is valid when the external field is homogeneous and continuous, which occurs if the particle radius, a , satisfies the condition $a \leq 0.05\lambda$ (or $ka \ll 1$) where λ is the wavelength and k is the propagation constant. It should be noted that the particle radius and the wavelength must be of the same unit. Another condition is that the incident field penetrates so fast inside the particle that the static polarization is established in a short time compared to the wave period. That is $k|\bar{m}|a \ll 1$, where $\bar{m}$ is the particle refractive index (Ahmed 1987). Bashir *et al* (2012) added that the Rayleigh approximation is valid when the phase is also homogenous. Therefore for the phase to be the same inside and outside the particle, $\frac{2\pi a}{\lambda}|\epsilon - 1| \ll 1$; where ϵ is the permittivity.

The above three conditions are tested and implemented in this work. For instance, setting 0.5 as the limit in defining much less than 1 (McEwan *et al* 1985) and permittivity, $\epsilon = 3.8 - j0.038$ (Bashir 2009), the values of ka and $k|\bar{m}|a$ even at 100 GHz are of the order of 0.2 and 0.4 respectively. The third condition holds for only the millimetric wavelength

of the order of frequency less than 85GHz. In summary, these suggest the validity of Rayleigh approximation for dust particles up to 0.1 mm radius and 85 GHz frequency.

Electromagnetic Wave Attenuation in Dust Storms

The complex refractive index $\bar{m}$ of a scattering medium given by Van De Hulst (1957) can be referred to in deriving the electromagnetic wave attenuation in dust storms.

$$\bar{m} = 1 - j2\pi k^{-3} N S(0) \quad (1)$$

where $S(0)$ is the complex forward scattering amplitude function and k is the free space phase constant. In the definition of the complex refractive index, the path is considered to be intersected by a slab containing many particles. The field at a point will be influenced by scattering from all particles in the slab, but the forward propagating wave is coherently influenced only by scatterers in the active region of the slab which coincides with the first few Fresnel zones as seen from the observation point (Van De Hulst 1957). The complex forward direction scattering using Rayleigh approximation is

$$S(0) = jk^3 p_s \quad (2)$$

where p_s is the polarizability (of the dipoles of the particles).

Considering the shape of the particles as spheres, the complex polarizability is related to the complex permittivity and the volume of the particle, v , by the equation of Mosotti-Lorentz-Lorenz.

$$p_s = \frac{3v}{4\pi} \left(\frac{\epsilon - 1}{\epsilon + 2} \right) \quad (3)$$

where

$$v = \frac{4}{3} \pi a^3 \quad (4)$$

$$\text{If } G = \left(\frac{\epsilon - 1}{\epsilon + 2} \right) = G' - jG'' \quad (5)$$

and Equations (4) and (5) are substituted into Equation (3),

$$p_s = G a^3 \quad (6)$$

Equation (2) therefore becomes

$$S_f(0) = jk^3 G a^3 \quad (7)$$

Substituting Equations (5) and (7) into Equation (1), Equation (8) is obtained.

$$\bar{m} - 1 = 2\pi a^3 N (G' - jG'') \quad (8)$$

$$= 2\pi a^3 N G' - j2\pi a^3 N G'' \quad (9)$$

From Equation (9)

$$\text{Re}(\bar{m} - 1) = 2\pi a^3 N [R_\epsilon(G)] \quad (10)$$

Multiplying Equation (10) through by the free space constant, k , the phase shift, β , is obtained thus

$$\beta = k \text{Re}(\bar{m} - 1)$$

$$= 2\pi k a^3 N [R_\epsilon(G)] \text{ [rad/m]} \quad (11)$$

$$= 39.478 \frac{\epsilon^3}{\lambda} N [R_\epsilon(G)] \left(\frac{180}{\pi} \right) \text{ [deg/m]}$$

$$= 2.2619 \times 10^6 \frac{N \epsilon^3}{\lambda} [R_\epsilon(G)] \text{ [deg/km]} \quad (12)$$

Similarly, the attenuation, α , is also obtained from Equation (9) as

$$\text{Im}(\bar{m}) = -2\pi a^3 N [I_m(G)] \quad (13)$$

$$\alpha = kI_m(\vec{m}) = -2\pi k a^3 N [I_m(G)] [Np/m] \quad (14)$$

$$= -39.478 \frac{a^3}{\lambda} N [I_m(G)] \quad (8.68) [dB/m]$$

$$= -3.427 \times 10^3 \cdot \frac{Na^3}{\lambda} [I_m(G)] [dB/km] \quad (15)$$

The phase shift and the attenuation coefficients for spheres at MMW in terms of number of particles, particle radius and wavelength are as derived in Equations (12) and (15) where N is the number of sand particles per cubic meter ($\#/m^3$), a is the radius (m), λ is the wavelength (m), $Re(G)$ is the real part of the complex permittivity and $Im(G)$ is the imaginary part of the complex permittivity defined in Equation (5).

As demonstrated in Equations (17) and (18), Equations (12) and (15) can be expressed in terms of volume fraction, v_f , defined as (Chu 1979)

$$v_f = \frac{4}{3} \pi a^3 N \quad (16)$$

Thus, the expressions for phase shift (deg/km) and attenuation (dB/km) encountered by the signal propagating through a dust medium when the particle shapes considered are as shown.

$$\beta = 5.4 \times 10^3 \cdot \frac{v_f}{\lambda} [Re(G)] [deg/km] \quad (17)$$

$$\alpha = -8.18 \times 10^4 \cdot \frac{v_f}{\lambda} [Im(G)] [dB/km] \quad (18)$$

However, the concentration number of particles per unit volume or volume fraction, v_f , is difficult to obtain or measure in dust storms. Meteorologically, dust storms are observed and characterized using visibility and this appears to be more realistic. Therefore, our method for evaluating phase shift and attenuation during dust storms is finally treated in terms of visibility. A relation between visibility and dust concentration was given by Goldhirsh (2001), Chepil (1957) and Gillett (1979). The relations provide ease of application to a range of dust storms characteristics. Goldhirsh (2001) defined the relative mass of dust per cubic volume of air and was given as

$$M = \rho_0 v_r [\text{kg of dust}/m^3 \text{ of air}] \quad (19)$$

where v_r is the relative volume (referred to as volume fraction, v_f), ρ_0 is the solid density of dust.

Similarly, the mass of suspending dust per unit volume of air was related to visibility (Goldhirsh 2001).

$$M = \frac{C}{V^y} \quad (20)$$

where V is the visibility (km), C and y are constants that depend on the climatic conditions and the type of land from which the storm originated. This clearly suggests why different values of C and y are employed by different investigators thereby leading to different value of M . Therefore, from Equations (19) and (20),

$$v_f = \frac{C}{V^y} \cdot \frac{1}{\rho_0} \quad (21)$$

If the values of C and y are taken as 3.44×10^{-4} and 1.25 respectively (Chepil 1957), substituted into Equation (21) and the resultant expression is divided by the value of solid density of dust ($2.65 \times 10^3 \text{ kg}/m^3$), volume fraction is obtained as expressed in Equation (22).

$$v_f = \frac{3.44 \times 10^{-4}}{2.65 \times 10^3} \cdot \frac{1}{V^{1.25}} \quad (22)$$

Finally, Equation (22) is substituted into Equations (17) and (18) and the obtained expressions are given below respectively.

$$\beta = \frac{3.44 \times 10^{-4}}{2.65 \times 10^3} \cdot [Re(G)] [deg/km] \quad (23)$$

$$\alpha = \frac{3.44 \times 10^{-4}}{2.65 \times 10^3} \cdot [Im(G)] [dB/km] \quad (24)$$

Thus, simple mathematical expressions are developed and proposed as contained in Equations (23) and (24) for predicting the phase shift (deg/km) and the attenuation (dB/km) encountered by the electromagnetic wave propagating through a dusty medium when the particle shapes are considered to be spherical.

RESULTS AND DISCUSSIONS

To validate the proposed model for predicting phase shift and attenuation in storms with dry dust concentration, the following parameters are employed; $\epsilon = 3.8 - j0.038$ [18] and $\lambda = 0.03 \text{ m}$. The proposed attenuation model (Equation 24) is calculated and then verified by comparing the obtained results with those obtained by Alhaider (1986), Ahmed (1987) and Goldhirsh (2001) formulae as clearly illustrated in Figure 1. There is an excellent agreement in the attenuation obtained by our proposed model and the published formulae especially those of Ahmed's (1987) and Alhaider's (1986).

Among the attenuation models, the proposed model, Alhaider (1986) and Ahmed (1987) models produce a higher value of wave attenuation apparently at lower visibilities. A significant difference is observed in the wave attenuation between the Goldhirsh's formula and other formulae (i.e. the proposed model, Ahmed's (1987) and Alhaider's (1986) models) at lower visibility. However, this difference becomes almost negligible as the visibility increases. An interesting result is noted at such stage. It is found that the wave attenuation obtained by all the models decreases sharply as the visibility improves.

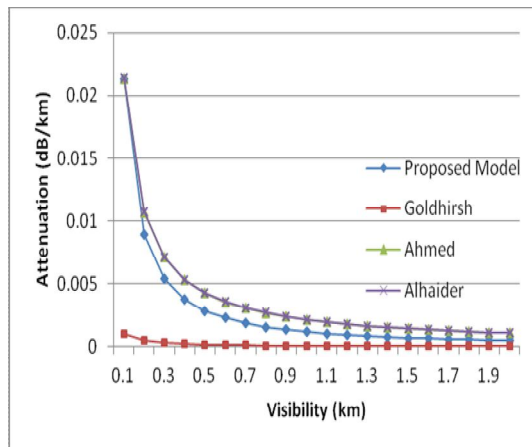


Figure 1. Validation of the proposed model with attenuations obtained by Goldhirsh, Ahmed and Alhaider formulae.

Having validated the proposed model, it is used to investigate electromagnetic wave attenuation during dust storms in different situations as shown in Figures 2 and 3. It is confirmed that wave attenuation is negligible except in severe dust storms with very low visibility and for higher frequencies. It is found that in dust storms, the attenuation increases as the visibility decreases. Thus a linear relation exists between attenuation and visibility. Similarly, more attenuation is encountered at higher frequencies.

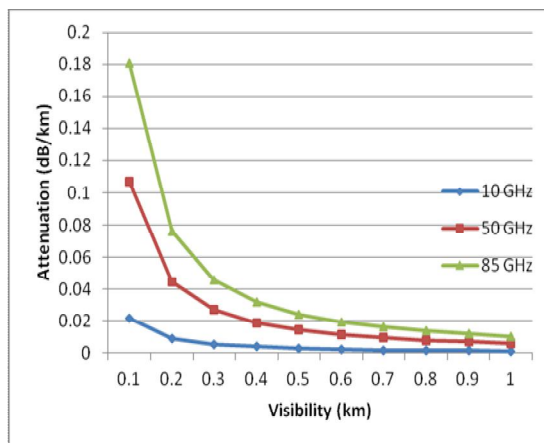


Figure 2. Attenuation with visibility at 10 GHz, 50 GHz and 85 GHz ($\epsilon = 3.8 - j0.038$ (Bashir 2009))

Furthermore, attenuation with different moisture content at 10 GHz is also checked using the complex permittivity of Ansari *et al* (1982). Results are obtained for 0% moisture content where the permittivity recorded was $\epsilon = 2.53 - j0.0625$ as well as moisture content at 10% when the permittivity was $\epsilon = 4.0 - j0.1325$ as shown in Figure 3. Moisture content has a significant impact on attenuation. Increase in attenuation is observed at higher moisture content. In other word, attenuation is relatively negligible in dry dust.

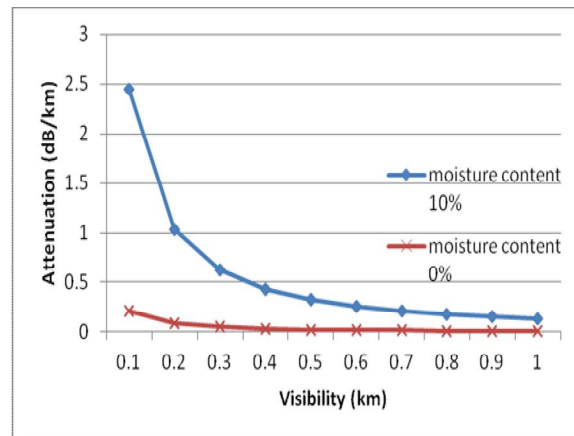


Figure 3. Attenuation with different moisture content at 10 GHz ($\epsilon = 2.53 - j0.0625$ at 0% moisture content and $\epsilon = 4.0 - j0.1325$ at 10% moisture content Ansari *et al* (1982)).

Phase shift (deg/km) with visibility (km) is also plotted in Figure 3 at frequencies of 10 GHz and 50 GHz using Equation (23). The result shows that phase shift shares some level of similar characteristics with attenuation. The phase shift decreases with an increase in visibility and increases with a decrease in visibility.

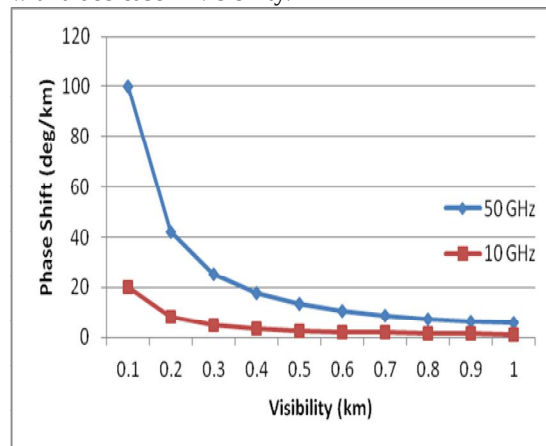


Figure 4. Phase shift with visibility at 10 GHz and 50 GHz. ($\epsilon = 3.8 - j0.038$ (Bashir 2009))

CONCLUSION

This work investigates the electromagnetic wave propagation in dust storms at MMW band. Mathematical model for evaluating propagation parameter is successfully developed and used to calculate the wave attenuation and the phase shift in dust storms. The proposed model suitable for MMW band and different visibility range is based on the method of Rayleigh approximation. The model shows that attenuation and phase shift are found to be dependent on visibility, wavelength and complex permittivity. They are also observed to be dependent on the moisture content of the dust particles in the storms and this explains the higher values recorded

for dust storms with moisture when compared to dry dust concentration.

A validation of the results of this research shows excellent agreement with some already published models. Having compared the proposed model with published results with very close conformity, it can be concluded that the proposed model is valid, very reliable and applicable to frequency of up to 85GHz. Attenuation and phase shift are inversely related to visibility as they increase with a decrease in visibility. Attenuation is found to be 0.02 dB/km at 100 m visibility but 0.0012 dB/km when the visibility is at 1 km. Similarly, at 10 GHz frequency, the phase shift value ranges between 1.13 deg/km and 20 deg/km when the visibility is respectively between 1 km and 100 m. From the research finding, it is concluded that the wave attenuation in dust storms is negligible except during severe dust storms with very low visibility and at higher frequencies.

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