Electromagnetic Wave Attenuation and Phase Rotation by Charged Dust Particles

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Abstract

Electromagnetic wave propagating in dust storms is susceptible to attenuation and phase rotation by suspended charged particles. Considerable attention has therefore been paid to the development in the recent past by researchers. This paper presents a theoretical approach for predicting the attenuation and the phase rotation of an electromagnetic wave propagation in dust storms environment with charged particles. Mathematical model based on forward scattering amplitude Rayleigh theory is given in terms of monodisperse medium (equal sized distribution) and polydisperse medium (exponential size distribution). The attenuation and the phase rotation are calculated, and the results are analysed. The effect caused by the charged particles is notably significant. It is found that the attenuation and the phase rotation with charged dust particles are greater than where there is no charge. The coefficients of attenuation and phase rotation increase with the magnitude of charges carried by the dust particles depicted by the ratio of charge-to-mass. The results also show the variation of both attenuation and phase rotation with the charge distribution angles under different charge-to-mass ratios.

Keywords
Electromagnetic waves; attenuation; phase rotation; charged particles; dust storm.

1. Introduction

Propagation of electromagnetic waves in sand and dust storms has attracted much attention in the literature because the propagation is affected by means of signal attenuation and phase rotation. The mechanisms of absorption and scattering of dust or sand particles usually cause attenuation (Klačka et al., 2015). Studies have been conducted to investigate the impacts of dust storms on satellite communication (Harb et al., 2014) and predict attenuation and phase rotation in sand dust storms (Elabdin et al, 2009 and Musa & Bashir, 2013). In separate reviews carried out by Bashir & McEwan (1986) and Musa et al. (2014), Ryde was found to be one of the earliest researchers to pay attention to sand and dust storms effects on radar albedo. It was pointed out that at low frequency and in sand and dust storms with low visibility, radar signal is usually not significantly influenced. Thereafter, investigations (Musa et al., 2014a; Musa et al., 2014b; Dong et al., 2013 and Chiou & Kiang, 2016) showed that the physical characteristics of dust particles, such as permittivity, incident waves, particle sizes and particle shapes among others, have significant effects on electromagnetic wave propagation. Some measurements and theoretical works (Zheng et al., 2003) have also shown that sand and dust particles have charges that usually affect saltation of the particles. For a single spherical or ellipsoidal particle carrying charges, there is the forward scattering amplitude function of the charged dust or sand particle.

For this purpose, effect of charged dust particles on propagation of electromagnetic waves is investigated, and mathematical models to predict attenuation and phase rotation based on Rayleigh approximation approach by considering the charged particles are given in this paper. The models consider monodisperse and polydisperse media as well as variables which include charge distribution angle, charge-to-mass ratio and visibility during sand and dust storms. The models are suitable for calculation and analysis of microwave attenuation and phase rotation caused by charged dust particles of both spherical and ellipsoidal shapes in either monodisperse and polydisperse media.

After the introduction as contained in this section, other parts of this paper are arranged such that Section 2 presents a brief on the solutions of electromagnetic wave scattering. In Section 3, the electromagnetic wave attenuation and phase rotation models are developed, and the principle of chosen parameters are presented. Results prediction and discussions are presented in Section 4 where the models are implemented, and the attenuation and the phase rotation caused by charged dust particles are evaluated. Conclusion is then drawn in Section 5.

2. Solutions of Electromagnetic Wave Scattering

There are some widely used methods for solving problems associated with electromagnetic scattering. The scattering solutions techniques are usually by providing solution to Maxwell's equations analytically or numerically even though some numerical solutions often become or change to analytical solutions (Musa et al., 2014b). In numerical techniques, the integral equation methods are based on the surface or volume integral parts of the Maxwell's equations, while the differential equation methods compute the scattered field by providing a solution to the vector wave equation in the time or the frequency domain.

However, the process of solving the integral expression of scattering amplitude function is usually difficult. The function depends on permittivity and the local field inside the particle which is usually unknown. Therefore, approximations such as Rayleigh, Born and Wentzel-Kramers-Brillouin (WKB) are used. These approximations and analytical models make it possible to avoid difficult computations.

When the particle is electrically small, it is said to be a Rayleigh type scattering and is a function of the electric polarizability of the particles. With the aid of dielectric particles, the Rayleigh method presents an analytical solution of Maxwell's equations for electromagnetic waves scattering. Sand or dust particle is a composite dielectric containing dry and moistened sand or dust. Complex dielectric constant which changes along with frequency is a function of the dielectric constant of the sand/dust and moisture content (Musa et al., 2014a). In other words, the dielectric constant of the sand/dust particle depends on both frequency and water.

Using the forward scattering amplitude function under Rayleigh scattering theory and approximation therefore, models for electromagnetic wave attenuation and phase rotation due to charged dust particles can be developed for both spherical and ellipsoidal particle shapes.

3. Attenuation and Phase Rotation in Charged Dust Particles

To derive the electromagnetic wave attenuation and phase rotation caused by sand or dust particles, the complex refractive index of radar waves, $\overline{m}$, in a scattering medium given by Van De Hulst (1981) is defined.

$$\overline{m} = 1 - j2\pi k^{-3} NS(0) \qquad (1)$$

where k is the free space phase constant, N is the number of particles per cubic meter and $S(0)$ is the complex forward scattering amplitude function. The path is intersected by a slab containing many particles. The forward propagating wave is affected by scatterers in the active region of the slab. The region is referred to as the first few Fresnel zones.

It can be inferred from the Rayleigh scattering approximation theory and the work of He and Zhou (He & Zhou, 2005) that for a given charged dust particle, the scattering amplitude function (forward), $S_c(0)$ is:

$$S_c(0) = jk^3 G a^3 + jk^3 a^3 \cdot \frac{a\rho q(\varepsilon_m^* - 1)\sin^2\theta_0}{6\epsilon_0 E_0 (1-\cos\theta_0)} \qquad (2)$$

where a is the particle radius, ρ is the mass density of the particle (kgm^{-3}), ε_m^* is the complex dielectric constant of the particle, ($\varepsilon_m^* = \varepsilon' - i\varepsilon''$): ε' is the real part and ε'' is the imaginary part, θ_0 is the charge distribution angle (radian), q is the ratio of charge-to-mass ($\mu C\ kg^{-1}$), ε_0 is the vacuum permittivity, E_0 is the intensity of incident electric field (V/m) and G is a complex function when spherical particle shape is assumed.

Further, (2) can be rewritten as

$$S_c(0) = jk^3 a^3 \left(G + C_f\right) \qquad (3)$$

where

$$C_f = \frac{a\rho q(\epsilon_m - 1)\sin^2\theta_0}{6\epsilon_0 E_0 (1-\cos\theta_0)} \qquad (4)$$

where the parameters making up (4) are as defined earlier in (2).

Recall also that the attenuation and phase rotation of incident fields can be respectively expressed as:

$$A_{V,H} = kI_m(\overline{m})8.686 \times 10^3 \ [dB/km] \qquad (5)$$

and

$$\beta_{V,H} = kR_e(\overline{m})\left(\frac{180}{\pi}\right) \cdot 10^3 \ [deg/km] \qquad (6)$$

where I_m is the imaginary part, R_e is the real part of relative complex permittivity and k is the free space phase constant.

By substituting (3) into (1) and if the product is further substituted into each of (5) and (6), (7) and (8) are obtained respectively. This operation is performed to obtain the coefficients of attenuation and phase rotation caused by charged dust particles.

3.1 Attenuation and Phase Rotation by Charged Spherical Particles

In this sub-section, the charged dust particle is considered as spherical shape, and mono-dispersive medium i.e. a medium with equal particle radius is also assumed. The attenuation and the phase rotation are, respectively, expressed in (7) and (8).

$$A = 2.57 \times 10^{-3} \cdot \frac{f}{V^\gamma}. I_m(G + C_f) \ [dB/km] \qquad (7)$$

$$\beta = 1.70 \times 10^{-2} \cdot \frac{f}{V^\gamma}. R_e(G + C_f) \ [deg/km] \qquad (8)$$

where f is the frequency, V is the storms' visibility and γ is a constant.

The attenuation and the phase rotation for a spherical particle but in a particle size distribution (PSD) or poly-dispersive medium can also be obtained as:

$$A = 1.54 \times 10^{-2} \cdot \frac{f}{V^\gamma} \cdot I_m(G + C_f) \ [dB/km] \qquad (9)$$

$$\beta = 1.02 \times 10^{-1} \cdot \frac{f}{V^\gamma} \cdot R_e(G + C_f) \ [deg/km] \qquad (10)$$

Suffice to mention that when the charge distribution angle, $\theta_0 = 0$, C_f in Eq. (4) becomes zero. This implies that (3) reduces to

$$S(0) = jk^3a^3(G) \qquad (11)$$

Equation (11) is the same result as that of the propagation coefficient due to uncharged dust particles based on the Rayleigh approximation (Musa & Bashir, 2013).

3.2 Attenuation and Phase Rotation by Charged Ellipsoidal Particles

For charged dust particles with ellipsoidal shape, the scattering amplitude (forward), $S_c(0)$ becomes:

$$S_c(0) = jk^3a^3\left(\frac{\psi_i}{3} + C_f\right) \qquad (12)$$

where ψ is a complex function when ellipsoidal particle shape is assumed and other parameters are as expresses or defined earlier.

Further, by following the approach adopted in this research work as highlighted above, the coefficients of attenuation and phase rotation of charged ellipsoidal dust particles in each of mono and poly dispersive media are obtained, respectively, as presented in (13) to (16).

$$A_{V,H} = 8.57 \times 10^{-4} \cdot \frac{f}{V^{\gamma}} \cdot I_m(\psi_i + C_f)\ [dB/km] \quad (13)$$

$$\beta_{V,H} = 5.65 \times 10^{-3} \cdot \frac{f}{V^{\gamma}} . R_e(\psi_i + C_f)\ [deg/km] \quad (14)$$

$$A_{V,H} = 5.14 \times 10^{-3} \frac{f}{V^{\gamma}} \cdot I_m(\psi_i + C_f)\ [dB/km] \quad (15)$$

$$\beta_{V,H} = 3.39 \times 10^{-2} \cdot \frac{f}{V^{\gamma}} \cdot R_e(\psi_i + C_f)\ [deg/km] \quad (16)$$

where f is the frequency, V is the storms' visibility, γ is a constant, ψ is a complex function as ellipsoidal particle shape is assumed, I_m is the imaginary part, R_e is the real part of relative complex permittivity and C_f is as expreseed in (4) with its parameters as defined earlier in (2).

The attenuation and the phase rotation expressed in (13) and (14) are those of charged ellipsoidal dust particles in mono dispersive media, while the attenuation and the phase rotation for charged ellipsoidal dust particle in poly-dispersive media or particle size distribution (PSD) are as expressed in (15) and (16).

As pointed out earlier, when the charge distribution angle, $\theta_0 = 0$, C_f in (4) becomes zero. This implies that the the forward scattering amplitude i.e. (12) reduces to

$$S(0) = jk^3a^3\left(\frac{\psi_i}{3}\right) \quad (17)$$

where k is the free space phase constant, a is the particle radius and ψ is a complex function for ellipsoidal particle shape.

Equation (12) is the same result as that of the propagation coefficient due to uncharged ellipsoidal dust particles based on the Rayleigh approximation (Musa & Bashir, 2013).

4. Results Prediction and Discussion

The developed models for theoretical prediction and analysis of electromagnetic waves attenuation and phase rotation in a propagation medium with charged dust particles are applied and computed in this section. The results obtained are presented and discussed. Using (7) to (10) and (13) to (16), the electromagnetic wave attenuation and phase rotation introduced by charged dust particles can be computed and analysed. This is demonstrated in this section. To show variations of attenuation and phase rotation with visibility, the parameters applied are as follows: frequency $f = 10GHz$ and $37GHz$, dielectric constant $\varepsilon = 3.8 - j0.038$ with 0% moisture content (Bashir & McEwan, 2012a) and (Bashir & McEwan, 2012b). The ratio of charge-to-mass, $q = -0.1\mu C/kg$, angle of charge distribution, $\theta_0 = 1.5\ rad$ and intensity of the incident electric field, $E_0 = 0.5V/m$.

Figure 1 and Figure 2 show the variations of attenuation and phase rotation with visibility during storms using (7) and (8) respectively. A proportionate inverse relationship exists between the attenuation and the visibility as shown in Figure 1. A similar relationship exists between the phase rotation and the visibility in Figure 2. It is observed that both the attenuation and the phase rotation decrease as the visibility increases. For instance, when visibility increases from 10m to 100m, the attenuation decreases from 144dB/km to 12dB/km (at q = -0.1µC/kg and f = 10GHz).

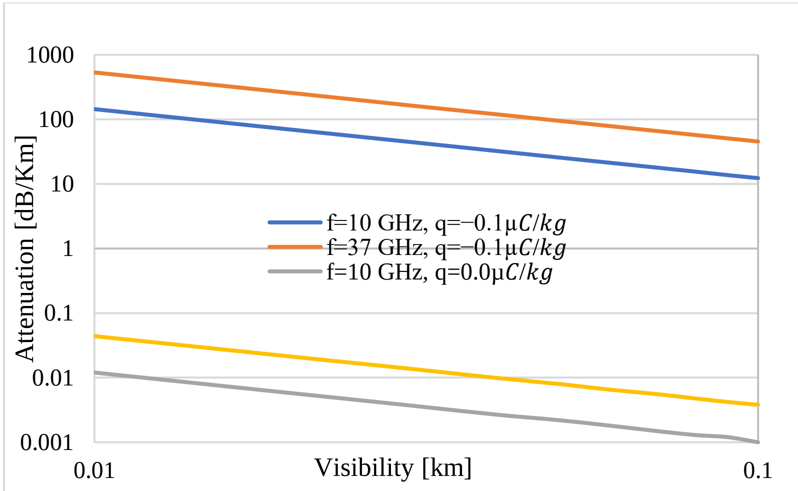

Figure 1. Variation of attenuation with visibility

Furthermore, it can be observed that the attenuation for charged dust particles is higher than that of dust particles that have no charges. This is also true for the microwave phase rotation as shown in Figure 2. Lastly, the results also show that the higher the frequency, the higher the attenuation and the phase rotation. The results show that at 10GHz, the attenuation is 12dB/km. But when the frequency increases to 37GHz, the attenuation increases to 45dB/km (at q = -0.1μC/kg and visibility of 100m).

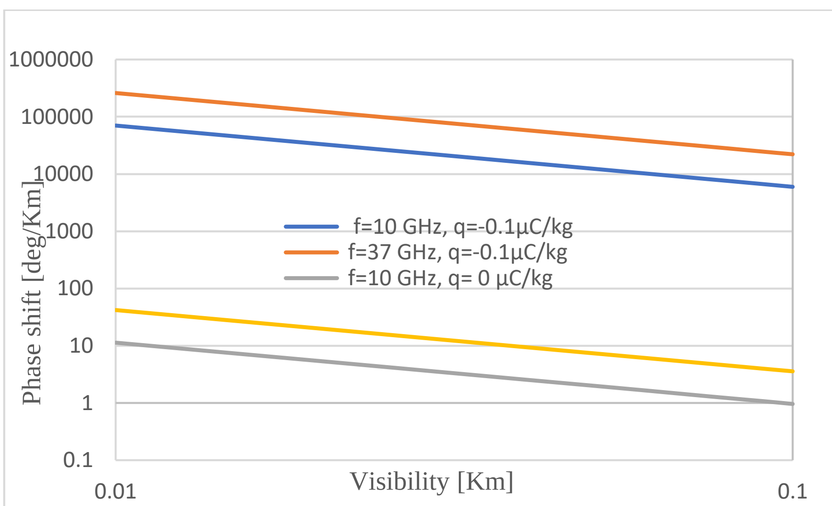

Figure 2. Variation of phase rotation with visibility

Results showing the variation of attenuation with charge distribution angle are presented in Figure 3, while the relationship between phase rotation and charge distribution angle is shown in Figure 4. Using (9) and (10) i.e. attenuation and phase rotation equations for dust particle size distribution or poly-dispersive media, the attenuation and the phase rotation are calculated for different charge distribution angles from 0 rad to 3 rad when other parameters are such that frequency, $f = 10GHz$, visibility, $V = 0.1km$ and the charge-to-mass ratio q is varied between $q = -0.1\ \mu C/kg, q = -0.15\ \mu C/kg$ and $q = -0.03 \mu C/kg$.

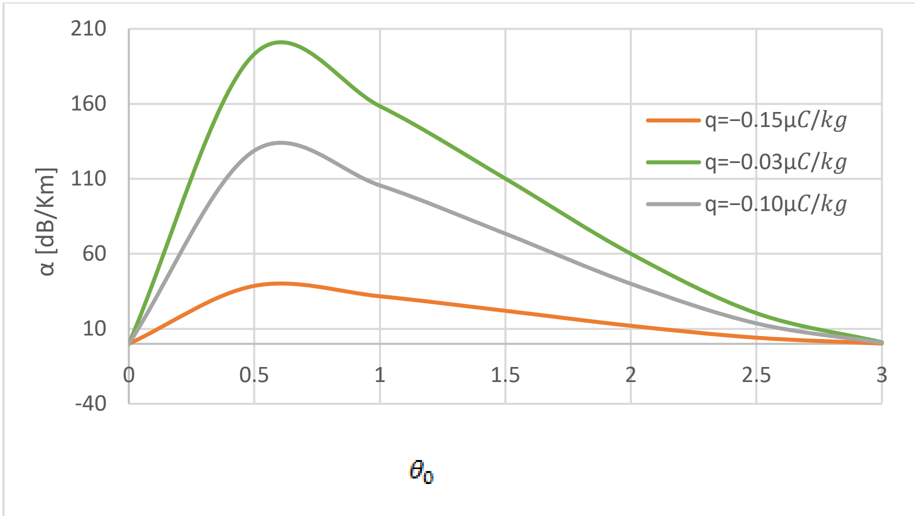

Figure 3. Variation of attenuation with charge distribution angle (9)

Results obtained show that for the same value of charge-to-mass ratio, the attenuation and the phase rotation values begin to decrease with an increase in the charge distribution angle, after an initial proportionate increase in the attenuation and the phase rotation as shown in Figure 3 and Figure 4. This is a pointer to the fact that the more dispersive the charges carried by dust particles are, the lesser is the influence on both the attenuation and the phase rotation. In other words, as the distribution area of the charges on the surface of dust particle increases, the attenuation and the phase rotation begin to decrease, showing a somewhat sinusoidal distribution function. It can be observed in Figure 3 that the attenuation decreases from 31.7dB/km to 4dB/km when the charge distribution angle increases from 1rad to 2.5rad (when q = -0.03).

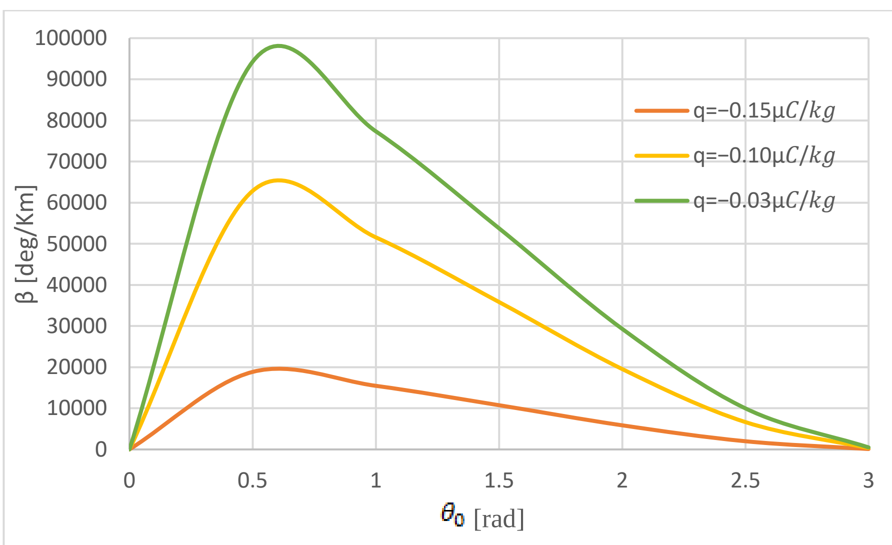

Figure 4. Variation of phase rotation with charge distribution angle (10)

Generally, the effect of the charged dust particles on electromagnetic wave attenuation as well as phase rotation is apparently higher than the ones with no charges. This is clear from the theoretical models of attenuation in a medium with charged particles expressed in (7), (9), (13) and (15). It can also be seen in (8), (10), (14) and (16) for the phase rotation component. The coefficients of attenuation and phase rotation increase as the magnitude of charges carried by the dust particles, given in terms of ratio of the charge and mass, increases. The higher the concentration of the charges carried by the dust particles, the higher the effect of electromagnetic wave attenuation. Whenever the angle of charge distribution, $\theta_0 = 0$, it means that the particle is with no electric charge on its surface. Conversely, when $\theta_0 = \pi$, it implies that the electric charges are distributed over the whole surface of the dust particles.

From the formulated models, it can be concluded that the attenuation decreases as the intensity of the incident electric field and the visibility increase. Also, attenuation increases as the particles sizes increases. Finally, it is found that the effect of the ellipsoidal charged particles on electromagnetic wave attenuation and phase rotation is obviously higher than a situation where the particles are without charges.

5. Conclusion

In this paper, theoretical models to predict attenuation and phase rotation due to charged dust particles have been developed and proposed. Different scenarios and conditions have been assumed. The mathematical models as expressed in (7) and (8) – spherical shape of mono-dispersive charged dusty medium, (9) and (10) - spherical shape of poly-dispersive charged dusty medium, (13) and (14) - ellipsoidal shape of mono-dispersive charged dusty medium, (15) and (16) - ellipsoidal shape of poly-dispersive charged dusty medium, were developed to predict and evaluate electromagnetic wave attenuation and phase rotation.

Predictions consistent with the experimental result of scattering wave attenuation in reference (Zheng et al., 2003) are made with the assumption that charges are partially and uniformly distributed on the dust particle's surface. The results show the importance of the influence of dust with charges on the attenuation and the phase rotation of electromagnetic waves. The rules of microwave attenuation and phase rotation varying with the distribution area of charges, incident electric wave intensity, charge-to-mass ratio, frequency, radius of dust particles and visibility are given.

Finally, for a simplification of the description of the influence of charges on electromagnetic wave attenuation and phase rotation in charged dust particles, a new parameter, C_f, involving charge distribution angle, intensity of incident waves and charge to mass ratio, is introduced. This allows for prediction and discussion of electromagnetic waves attenuation and phase rotation by charged dust particles.

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