VOL. 14, NO. 1, JANUARY 2019 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

MICROWAVE ATTENUATION AND PHASE ROTATION IN SAND AND DUST STORMS - PART II

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ABSTRACT

Microwave propagation suffers attenuation and phase rotation by suspended dust particles where occurrence of sand and dust storms (SDS) is predominant especially in arid and semi-arid regions. The SDS phenomenon has received considerable interest in recent times with emphasis on signal attenuation and phase rotation effects. To this end, mathematical models of dust induced complex scattering are developed and proposed using Rayleigh method to compute attenuation and phase rotation of electromagnetic waves by considering dust particle shapes and best fit ellipsoids. This part II of Microwave Attenuation and Phase Rotation in SDS also presents a new expression for the relation between visibility and dust concentration. The expression was included in the proposed models whose simulated results, when compared with some published results, show close agreement. Attenuation and phase rotation in dry dust are found to be significant only when visibility becomes severe or at increased microwave bands.

Keywords: attenuation, phase rotation, microwave propagation, dust concentration, ellipsoidal shape, visibility.

1. INTRODUCTION

In Part I of this work, sand and dust storms (SDS) have been noted to be weather phenomena known with strong wind blowing dust over an area. It was also established that SDS occur in Africa, Asia and Middle East, and that their particles do have some effects on telecommunication systems. This include degradation of signal through attenuation along the propagation path. The effects of SDS on microwave (MW) propagation can be estimated when the forward scattering amplitude function of a single particle is solved using analytical or numerical methods as explained in Part I. Using Rayleigh approximation method and integrating a new expression for the relation between visibility and dust concentration, this Part II assumes ellipsoidal particle shapes in developing models for microwave (MW) attenuation and phase rotation under both equal sized distribution and exponential size distribution conditions.

Microwave attenuation in SDS have attracted investigators' attention [1], [2] and [3]. This is due to the expansion in the application of electromagnetic wave systems and spectrums with very high frequency [4]. [5] calculated the attenuation of the electromagnetic waves in SDS using Mie theory. Based on the predicting model adopted, the phase rotation component of the SDS's effect was, however, not calculated. [6] and few others have shown that scattering of MW by SDS is a function of visibility during SDS, dust particle shape, size and dielectric constant, and the wave frequency.

Dust particles have complex or irregular shapes. They are unlike hydrometeor such as rain which have clearly defined and relatively known shapes. However, ellipsoidal shape is often applied as an approximate dust particle [7]. This means that in a medium with ellipsoidal dust particles, the attenuation and the phase rotation can be determined if the ellipsoid axes ratios are given.

This part of the paper, therefore, tackles the problems associated with attenuation and phase rotation of ellipsoidal particles. The report of this work is organized such that introduction is given in section 1, the relation between visibility and particle concentration is presented in section 2, formulation of the scattering coefficients' models, i.e. attenuation and phase rotation, in different media using ellipsoid shape is detailed in section 3. In section 4, the attenuation and the phase rotation during SDS are determined using the proposed models. The results are analysed and benchmarked with some existing results. Conclusions are drawn in section 5.

2. VISIBILITY IN DUST STORMS AND PARTICLES CONCENTRATION

Visibility in SDS is related with number of concentration of dust particles per unit volume in this section. This is to allow for solving the problems of dust storms' attenuation and phase rotation in terms of visibility instead of concentration number of particles which is also known as volume fraction. This is more realistic because the volume fraction has been observed to be very difficult to measure or obtain in dust storms. In addition, the dust storms phenomenon is observed and usually characterized by using visibility, in practice.

A mass of dust per volume of air was defined by [8]:

$$M = \rho_0 v_r \; [kg \; of \; dust/m^3 of \; air] \qquad (1)$$

where

ρ_0 = the solid density of dust
v_r = the relative volume or volume fraction to be denoted as v_f.

Mass of a suspending dust particle per volume of air relative to visibility can also be defined as:

$$M = \frac{C}{V^{\gamma}} \qquad (2)$$

where

VOL. 14, NO. 1, JANUARY 2019 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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V = the visibility (km)
C and γ = constants dependent on climatic conditions and origin of the storms
M = the dust mass in kg/m^3 of air.

This is also referred to as dust concentrations denoted as ρ or dispersed density in a medium. From (1) and (2), particle concentration or volume fraction can be expressed in terms of visibility as shown.

$$v_f = \frac{C}{V^{\gamma}\rho_0} \tag{3}$$

Another expression between dust particle concentration and visibility is given in (4).

$$\rho = \frac{5.6 \times 10^{-5}}{V^{\gamma}} \; [kg/m^3] \tag{4}$$

If (4) is divided by solid density of dust ($\rho_0 = 2650 kg/m^3$), (5) can be obtained.

$$v_f = \frac{2.113 \times 10^{-8}}{V^{\gamma}} \tag{5}$$

where
1.25 = the value of the constant, γ.

The dust storms situation in Sudan was used by [10] to give the expression:

$$\rho = \frac{2.3 \times 10^{-5}}{V^{\gamma}} [kg/m^3] \tag{6}$$

and thus, produce volume fraction as expressed:

$$v_f = \frac{9.426 \times 10^{-9}}{V^{\gamma}} \tag{7}$$

where
$\gamma = 1.07$.

It is interesting to observe that (7) is the same expression also derived by [8].

It was also observed that no single value of C can be generally applied to relate the mass concentration and the visibility in dust storms, because C may depend on factors earlier mentioned. Although [9] reported 5.6×10^{-5} and 1.25 as C and γ respectively, but [10] reported C and γ to be 2.3×10^{-5} and 1.07 respectively. 2,440 kg/m^3 was used as the value of solid density, ρ_0. Eq. (7) is applied in this research work to analytically express attenuation and phase rotation coefficients in terms of visibility.

The volume fraction can be expressed for N equivalent dust particle scatterers as:

$$v_f = \frac{4}{3}\pi a^3 N \tag{8}$$

Solving for N, while combining (7) and (8), produces the following expression.

$$N = \frac{2.250 \times 10^{-9}}{a^3 V^{\gamma}} \tag{9}$$

where
a = the equivalent dust particle radius (m).

The concentration number of dust particles was derived by assuming an equivalent dust storm's particle radius. It can be confirmed that the expression of the concentration number of dust particles in (9) is the same expression derived by [11], albeit, using another method. This has led credence to and further validates the derivation of (9) as well as its subsequent application in the models developed in this work for evaluating MW attenuation and phase rotation during dust storms.

7.2 - 15.3 µm was recorded as the equivalent or average particle radius for eight log-normal particle size distributions [12]. Where necessary, 11.25 µm is retained as average equivalent particle radius.

3. ATTENUATION AND PHASE ROTATION BY ELLIPSOIDAL PARTICLES

In Part I, Rayleigh scatterer technique has been discussed and validated for solving electromagnetic wave scattering even at microwave bands. This was carried out to ensure veracity and accuracy of the proposed models. This section, therefore, deals with development of attenuation and phase rotation models in ellipsoidal particles medium.

Let the attenuation for horizontally and vertically polarized incident fields be expressed, respectively, as:

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

Similarly, the phase rotation is also expressed as:

$$\beta_{V,H} = kR_e(\overline{m}) \left(\frac{180}{\pi}\right) \cdot 10^3 [deg/km] \tag{11}$$

Definition of complex refractive index of a scattering medium [13] is referred to for derivation of attenuation and phase rotation models in SDS.

$$\overline{m} = 1 - j2\pi k^{-3} N S(0) \tag{12}$$

where
k = the free space phase constant
N = the number of particles per cubic meter
$S(0)$ = the complex forward scattering amplitude function.

Using Rayleigh approximation, the complex forward direction scattering can be expressed as:

$$S(0) = jk^3 p_s \tag{13}$$

where
p_s = the particles' dipole complex polarizability.

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The propagation constants depend on the scattering particles' shape and the orientation in relation to the polarization of the wave. If the particle shape is considered as ellipse and the orientation is such that the field is applied along one of the axes (i = 1, 2, 3), the polarizability (p_i) is expressed as:

$$p_i = \frac{1}{3}\psi_i a^3 \tag{14}$$

where

$$\psi_i = \left[l_i + \left(\frac{1}{\varepsilon-1}\right)\right]^{-1} = \psi_i' - j\psi_i'' \tag{15}$$

From (15), l_i can assume three factors such that $l_1 + l_2 + l_3 = 1$. Eq. (14) may be expressed as:

$$p_i = \frac{v}{4\pi\left[l_i + \left(\frac{1}{\varepsilon-1}\right)\right]} \tag{16}$$

Substituting (16) into (13) and replacing p_s with p_i, the forward complex scattering based on ellipse particle shape assumption is expressed as:

$$S(0) = jk^3 \cdot \frac{1}{3}\psi_i . a^3 \tag{17}$$

Equation (17) is substituted into (12). The output of the substitution can also be substituted into (10) and (11) to obtain the following set of equations:

$$A_{V,H} = 3.810 \times 10^5 \cdot Na^3 \cdot f \cdot I_m(\psi_i)\ [dB/km] \tag{18}$$

$$\beta_{V,H} = 2.513 \times 10^6 \cdot Na^3 \cdot f \cdot R_e(\psi_i)\ [deg/km] \tag{19}$$

To obtain attenuation and phase rotation of ellipsoidal particles in a monodisperse medium, (9) is substituted into (18) and (19) to obtain

$$A_{V,H} = 8.573 \times 10^{-4} \cdot \frac{f}{V^{\gamma}} \cdot I_m(\psi_i)\ [dB/km] \tag{20}$$

$$\beta_{V,H} = 5.654 \times 10^{-3} \cdot \frac{f}{V^{\gamma}} \cdot R_e(\psi_i)\ [deg/km] \tag{21}$$

For ellipsoidal dust particles in a polydisperse medium, the propagation coefficient, K, given in Part I is recalled with a suitable modification as shown in (22):

$$K_e = \frac{k}{3}\left[1 + \frac{12\pi N}{\beta^3}(\psi_i)\right] \tag{22}$$

Equation (22) is substituted into (10) and (11) to obtain the following equations, respectively.

$$A_{V,H} = 6.858 \times 10^5 \cdot \frac{N}{\lambda\beta^3} \cdot I_m(\psi_i)\ [dB/km] \tag{23}$$

and

$$\beta_{V,H} = 4.524 \times 10^6 \cdot \frac{N}{\lambda\beta^3} \cdot R_e(\psi_i)\ [deg/km] \tag{24}$$

Finally, (9) and the mean value a (given as $1/\beta$) are substituted into (23) and (24) to obtain attenuation and phase rotation in polydisperse medium as expressed:

$$A_{V,H} = 5.144 \times 10^{-3} \frac{f}{V^{\gamma}} \cdot I_m(\psi_i)\ [dB/km] \tag{25}$$

$$\beta_{V,H} = 3.393 \times 10^{-2} \cdot \frac{f}{V^{\gamma}} \cdot R_e(\psi_i)\ [deg/km] \tag{26}$$

4. RESULTS AND DISCUSSIONS

This section presents and discusses the results. The microwave attenuation and phase rotation models are implemented and validated with existing similar works. The results obtained are discussed and analyzed.

4.1 Proposed models validation

The formulated models expressed in (20), (21),(25) and (26) are validated against other established models using the following parameters: $\varepsilon = 3.8 - j0.038$ at 0% moisture content and $\lambda = 0.03m$; except where it is otherwise stated. Eq. (20) is validated using vertical component of existing models of [8], [12] and [14]. The results, using (20), show some agreement and high consistency (see Figure-1). The vertical component was computed using $l_i = 0.44$ and γ = 1.07.

Similarly, the proposed attenuation model in polydisperse medium expressed in (25) is also confirmed and substantiated using [15] as shown in Figure-2.

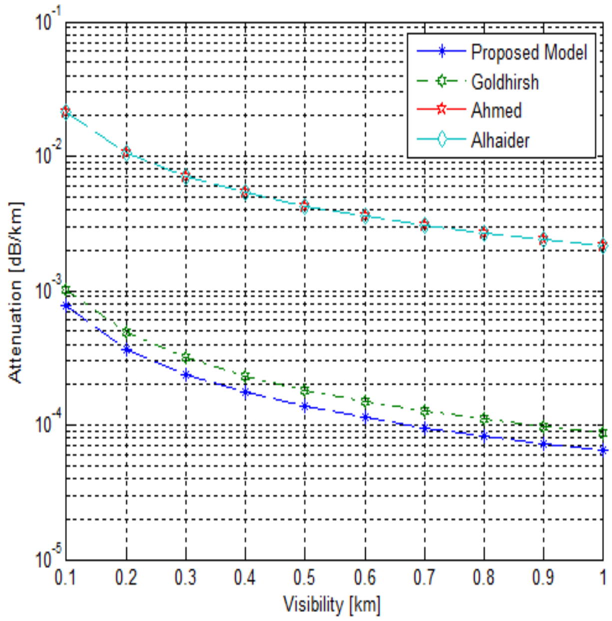

Figure-1. Validation of the proposed model (attenuation against visibility - monodisperse medium).

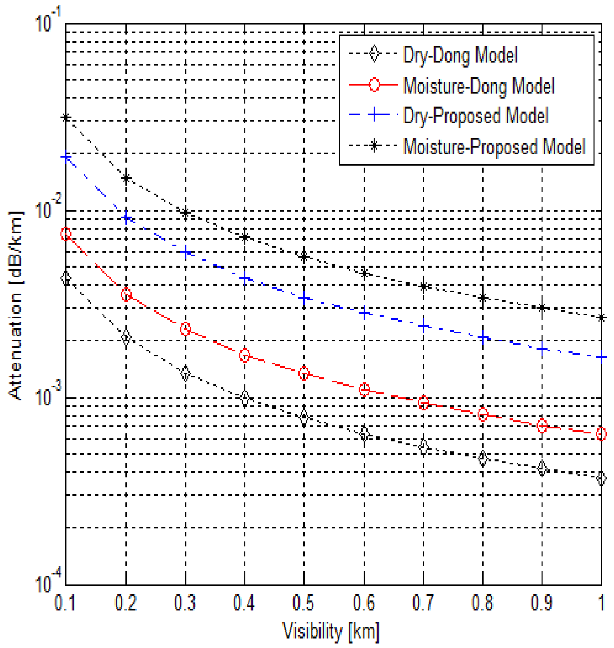

Figure-2. Validation of the proposed model (attenuation against visibility -polydisperse medium).

4.2 Models Implementation

Figure-3 is the illustration of the attenuation and the phase rotation values (for different visibility and frequency) when dust particle shape is considered as ellipse. This is when the proposed model as expressed in(20) is solved using the particle shape factors $l_1 = 0.22$, $l_2 = 0.34$ and$l_3 = 0.44$. There is linearly dependent relation of both attenuation and phase rotation with visibility and frequency. It can also be observed that the attenuation decreases as the visibility gets clearer (i.e. improves). Figure-3b is the phase rotation component when (21) is implemented.

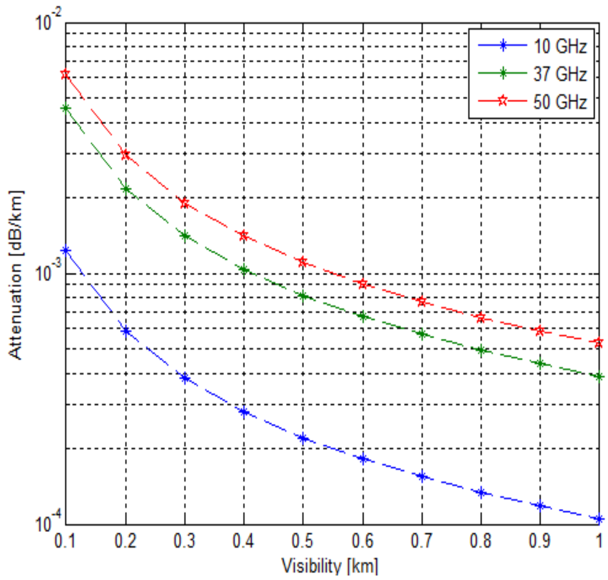

Figure-3(a). Attenuation against visibility using horizontal component (monodisperse medium).

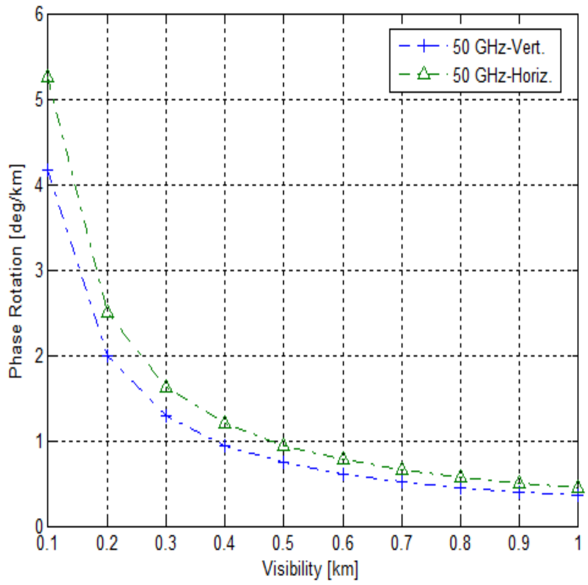

Figure-3(b). Phase rotation against visibility (monodisperse medium).

In Figure-4, the vertical and the horizontal components of attenuations are shown for 10GHz, 37GHz and 50GHz using (20). One important observation in the results is the difference in values between the horizontal polarization and the vertical polarization. The horizontal polarization waves component of the attenuation is higher than the vertical polarization waves component.

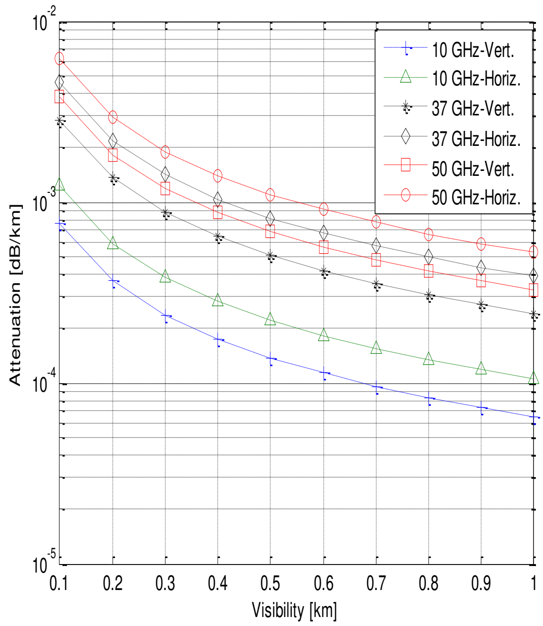

Figure-4. Attenuation against visibility - vertical and horizontal (monodisperse medium).

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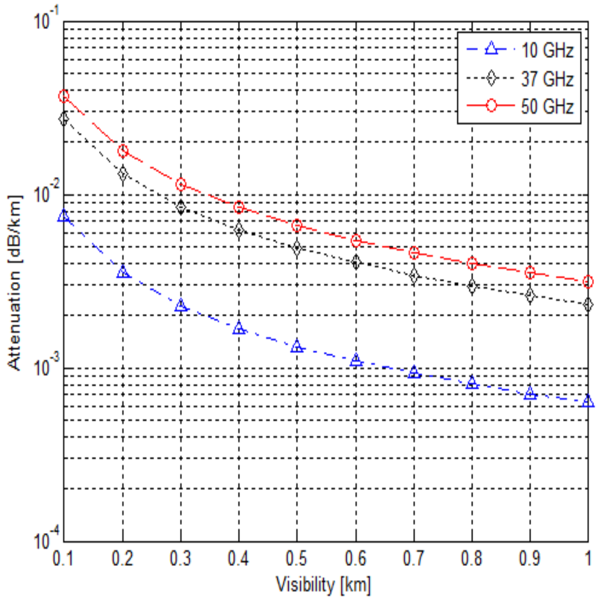

Figure-5(a). Attenuation against visibility - horizontal component (polydisperse medium).

Finally, models for microwave attenuation and phase rotation in ellipsoidal particles and size distributions are implemented. The results, using (25) and (26) are as shown in Figure-5. The results generally show characteristics like others implemented earlier, except that the attenuation and the phase rotation have higher values.

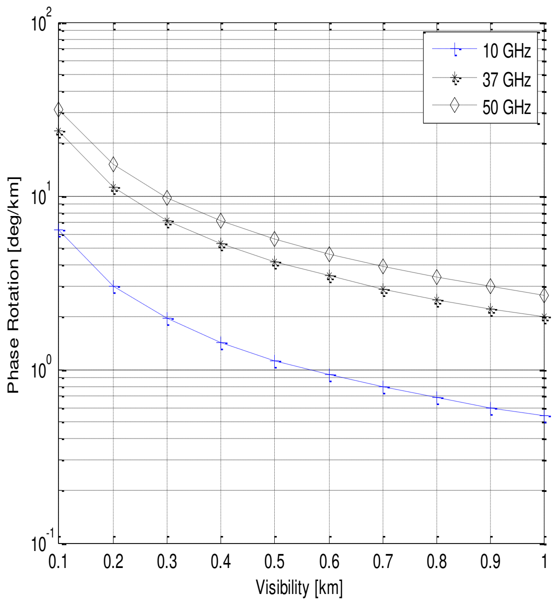

Figure-5(b). Phase rotation against visibility - horizontal component (polydisperse medium).

5. CONCLUSIONS

Microwave attenuation and phase rotation in SDS have been investigated, and models for their prediction have been developed and proposed under different conditions. The models are as contained in (20) and (21) representing monodisperse medium and (25) and (26) representing polydisperse medium. The models, as proposed, were derived by considering dust particle shape as an ellipse and by carefully considering the dust particle concentration as it relates with visibility. Comparison was made between existing models and the proposed models, and excellent conformity was observed in all the results obtained.

A definite conclusion to be drawn is that increase in frequency leads to increase in both attenuation and phase rotation. But increase in visibility leads to a decrease in the microwave attenuation and phase rotation.

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