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Review and Assessment of Electromagnetic Wave Propagation in Sand and Dust Storms at Microwave and Millimeter Wave Bands — Part II

Abdulwaheed Musa*, Saad O. Bashir, and Aisha H. Abdalla

Abstract—Suspended particles in the atmosphere during sand and dust storms have numerous consequences on electromagnetic wave propagation in arid regions. The electromagnetic wave signal may suffer attenuation and cross polarization upon encounter with the suspended particles. However, meager information has hitherto been reported about effect of storms on the telecommunication systems operating in such regions. This paper presents a survey of current understanding of the electromagnetic wave propagation in sand and dust storms. A review of the literature covering electromagnetic scattering theory and applications is given. The review describes the principle of approach and technology adopted for the investigation highlighting both strengths and drawbacks. Detailed parametric assessment of the effects of storms on wave propagation as it concerns signal attenuation and cross polarization is also carried out. The results demonstrate that most authors have calculated the attenuation effect, revealing that it is not very significant unless very high suspended dust densities are assumed (i.e., during severe sand and dust storms). A few papers indicate the possibility of more significant cross polarisation. The obvious gap in knowledge of this field is finally also clearly established.

1. INTRODUCTION

As already noted in Part I, electromagnetic wave propagation (EMW) in sand and dust storms (SDS) at microwave (MW) and millimeter wave (MMW) bands is an evolving field of research. This is largely attributed to the continuous growth of satellite and terrestrial microwave systems especially in the affected regions and use of higher frequencies. However, high frequency bands come with additional propagation problems. Radar operations can be hampered by attenuation of the MW and MMW due to SDS particles. The particles scatter MW and MMW and cause signal fading or outage and cross polarization (XP) in dual polarised systems. This represents what most authors have concentrated on even though other impairments include mechanical misalignment of antenna, refraction, effects of dust accretion on reflector antennas etc..

Against this premise, Part II represents an up to date review of existing related literature and an assessment of the theory of electromagnetic scattering, attenuation prediction models and XP evaluation. Some of the already established related knowledge is presented and the obvious gap in knowledge is also highlighted.

2. THEORY OF ELECTROMAGNETIC SCATTERING

Electromagnetic scattering by particles is an active research field in engineering sciences with specific applications in areas such as antenna theory, meteorology, particle sizing technology and scattering by

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* Corresponding author: Abdulwaheed Musa (twhid2001@yahoo.com).
The authors are with Department of Electrical and Computer Engineering, Faculty of Engineering, International Islamic University Malaysia, Malaysia.

dust particles. All theories and techniques for scattering computation are generally based on solving Maxwell's equations either numerically or analytically. Some exact numerical solutions, in turn, often reduce to an analytical solution by means of expanding the incident and scattered fields. Thus, analytical and numerical solutions for non-spherical particles are often interwoven. In many applications, it is assumed that the surrounding medium is homogeneous and isotropic.

2.1. Numerical Methods

The numerical techniques can be classified into differential and integral equation techniques. The differential equation techniques compute the scattered field by solving the vector wave equation in the frequency or the time domain. The integral equation techniques on the other hand are based on the volume or surface integral counterparts of the Maxwell's equations. The differential equation techniques numerically solve Equation (1) and Equation (2) subject to boundary conditions on the particle surface and at infinity.

$$\left[\nabla^2 + k^2(\mathbf{r})\right]\mathbf{E}(\mathbf{r}) = 0 \tag{1}$$

$$k^2(\mathbf{r}) = \omega^2\,\varepsilon(\mathbf{r})\mu(\mathbf{r})/c_0^2 \tag{2}$$

2.1.1. Separation of Variables Method (SVM)

The SVM for single homogeneous involves isotropic spheroids. The method is based on expanding the incident, internal, and scattered fields in vector spheroidal wave functions [18]. The expansion coefficients of the incident field are computed analytically, whereas the unknown expansion coefficients of the internal and scattered fields are determined through the boundary condition requirement. The SVM gives very accurate results but it is limited by its application to only spheroidal particles.

2.1.2. Finite Element Method (FEM)

The FEM computes the scattered time-harmonic electric field by numerically solving the vector Helmholtz equation subject to boundary conditions at the particle surface [26]. An advantage of FEM is modelling of arbitrarily shaped and inhomogeneous particles. Its concept and execution are also simple. However, FEM is time consuming as computations are spread over the entire computational domain rather than confined to the scatterer itself. It is also poorly suitable for achieving numerical accuracy.

2.1.3. Finite Difference Time Domain Method (FDTD)

The FDTD is another differential equation method which calculates the electromagnetic scattering in the time domain by directly solving Maxwell's time dependent curl equations. Ease of implementation and conceptual simplicity has recently made this method become popular [28]. However, it is time consuming as one needs to repeat all computations with changing orientation of the particles. Kahnert et al. [20] showed that assuming $\mu = 1$, the x-component of induction law becomes:

$$H_x^{n+1/2}\left(i+\frac{1}{2},j,k\right) = H_x^{n-1/2}\left(i+\frac{1}{2},j,k\right) + c_0\Delta t\left\{-\frac{1}{\Delta y}\left[E_z^n\left(i+\frac{1}{2},j+\frac{1}{2},k\right) - E_z^n\left(i+\frac{1}{2},j-\frac{1}{2},k\right)\right.\right.$$
$$\left.\left.+\frac{1}{\Delta z}\left[E_y^n\left(i+\frac{1}{2},j,k+\frac{1}{2}\right) - E_y^n\left(i+\frac{1}{2},j,k-\frac{1}{2}\right)\right]\right]\right\} \tag{3}$$

in which c_0 is the propagation velocity of the electromagnetic field. Similar equations are obtained for the y and z components and also for the x, y and z components of Faraday's law. Equation (3) shows that the solution algorithm in this method is iterative.

2.1.4. Point-matching Technique (PMT)

The PMT is exactly satisfied in the boundaries, exterior to the dust particle and the incident plane wave is expanded in a complex Fourier series. This is simply because of symmetry of the semi-axis of the ellipsoid at the origin. This made it easier to solve the unknown coefficients, as opposed to expanding the incident wave in spherical harmonics [6]. The forward scattered amplitudes ($\theta = 0$) for the dual polarizations (vertical as well as horizontal) are given by the following expressions:

$$S_v(0) = \frac{1}{E_v}\sum\nolimits_{m=-\infty}^{\infty}\sum\nolimits_{n\geq|m|}^{\infty}(-j)^{n-1}\,x\left[a_{mn}^{v}\frac{m}{\sin\tau}P_n^{|m|}(\cos\tau) + b_{mn}^{v}\frac{dP_n^{|m|}(\cos\tau)}{d\tau}\right] \tag{4}$$

$$S_h(0) = \frac{1}{E_h}\sum\nolimits_{m=-\infty}^{\infty}\sum\nolimits_{n\geq|m|}^{\infty}(-j)^{n+2}\,x\left[a_{mn}^{h}\frac{dP_n^{|m|}(\cos\tau)}{d\tau} + b_{mn}^{h}\frac{m}{\sin\tau}P_n^{|m|}(\cos\tau)\right] \tag{5}$$

in which $P_n^{|m|}$ are Legendre functions of the first kind, and τ is the angle of incidence between the direction of propagation and the axis of symmetry.

The integral equation methods consist of the volume-integral equation method (e.g., method of moments — MoM and the discrete dipole approximation — DDA) and the surface-integral equation method (e.g., Null-field method-NFM).

2.2. Analytical Methods

As illustrated, 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. Therefore, certain approximations like Rayleigh, Born, Wentzel-Kramers-Brillouin etc. are usually required to overcome the difficulty and avoid laborious computation.

2.2.1. Rayleigh Approximation Method

The Rayleigh scatterer is about the simplest approximation method. The Rayleigh scattering is a function of electric polarizability of particles and occurs when the particle is electrically small. However, once the particle is of the order of the size of the wavelength, Mie scattering occurs. The assumption for Rayleigh approximation is that:

$$\frac{2\pi a}{\lambda} \ll 1 \tag{6}$$

in which a is the radius of the dust particle and λ is the transmitting wavelength. Scattering and absorption cross sections yield the following expressions:

$$\sigma_{sca} = \frac{8}{3}\pi^5\left(\frac{2}{\lambda}\right)^4 a^6\left|\frac{\varepsilon-1}{\varepsilon+2}\right|^2 \tag{7}$$

$$\sigma_{abs} = \frac{8\pi^2 a^3}{\lambda}I_m\left(\frac{\varepsilon-1}{\varepsilon+2}\right) \tag{8}$$

From Equation (6), it follows that for most particles in Rayleigh approximation the following yields:

$$\sigma_{abs} \gg \sigma_{sca} \tag{9}$$

Provided $I_m\varepsilon$ is not very small for a given frequency. The extinction or total cross-section in this approximation is given by:

$$\sigma_{ext} = \sigma_{sca} + \sigma_{abs} \tag{10}$$

2.2.2. Mie Theory

Mie theory gives a complete analytical solution of the Maxwell's equations. The solution accommodates possible ratios of particle diameter and wavelength. The extinction or total cross-section efficiency factors by Mie solutions can be expressed as [12]:

$$\sigma_t = \frac{\lambda^2}{2\pi}(ka)^3\left[c_1 + c_2(ka)^2 c_3(ka)^3\right] \tag{11}$$

in which k is the wavenumber 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. The Mie theory application is limited to spherical particles only.

While other methods include the geometric optics approximation (GOA) or ray optics approximation and perturbation theory, the conclusion to be drawn from all the methods reviewed is that no single technique exists that can be applied equally well to all problems. Each method has different applicability range in terms of shape, size and refractive indices. So, user decides which method is most suitable in each individual case. Other important factors to consider are the permittivity, the scatterer homogeneity or inhomogeneity, symmetries or asymmetry, and single particle in a fixed orientation or in ensembles of particles with different (or even random) orientations.

3. EFFECTS OF SAND AND DUST STORMS ON ELECTROMAGNETIC WAVE PROPAGATION

In determining effects of SDS on EMW propagation, the important particle parameters, i.e., visibility statistics, dust particles geometry or shape, particles sizes and distribution, and permittivity which are usually being employed as empirical inputs already attracted emphasis and consideration. The common effects of SDS on EMW propagation which include signal attenuation and XPare further discussed in details in this section.

3.1. Signal Attenuation

The most reliable way of assessing the magnitudes of propagation impairments on radio links is by direct observation. However, direct measurements are quite scarce. Other methods are indirect approaches which make use of mathematical models. The models detailed in the previous section are always a function of empirical inputs such as particle shapes, permittivity, PSD and recently, visibility. Studies have been conducted on the effects of SDS on EMW propagation. Al-Hafid et al. [1] measured the direct effect of SDS on MW links at 11 GHz in Iraq. The SDS attenuated the received signal to fade depths of 10 to 15 dB for tens of minutes at a time. Attenuations of 10 dB and 26 dB with 150 min and 40 min duration were respectively observed. The measured attenuation was much greater than the predicted values. Chen [7] in measurement results also showed that the received signals decayed for 10–15 dB per tens of minutes.

Haddad et al. [15] also measured and calculated the SDS microwave attenuation. Attenuation of 0.034 dB/m measured was 30 times larger than the calculated value. This is a pointer to the importance of theoretical study of the EMW scattering in SDS. Amidst other reasons, Ansari & Evans [2] attributed the difference between measured and calculated attenuation to moisture and permittivity. It was found that the attenuation increased with increasing moisture content. Other substantial reasons and factors were later identified as will be shown.

The work of Ryde [25] believed to be the beginning of empirical study of the effect of SDS on EMW found MW scattering properties to be negligible except for frequencies greater than 30 GHz and very dense storms. However, Ryde only succeeded in calculating radar reflectivity of waves passing through the SDS with particle diameters in the range of 1 to 25 µm. [14, 32] also examined the attenuation effects of SDS. Goldhirsh [14] considered the average measured density of samples collected in Sudan to predict attenuation model.

A characteristic of the works to this level was the lack of sufficient information on dielectric constant and refractive index at higher microwave frequencies. This limited the attenuation calculation to around 10 GHz and rendered the models unsuitable for higher frequency. Ansari & Evans [2] extended the attenuation calculations to 37 GHz. Published bulk permittivity was used and this further undermined the validity of this attempt. In a review of microwave propagation in SDS, [33] also observed that attenuation was negligible for frequencies up to 30 GHz except in very rare instances. [34] dealt with particle sizes effect. Louza and Audeh [20] extended the technique for calculating attenuation due to rainfall to calculate attenuation due to dust at 10 GHz. A linear relationship between the number of particles/cm^3 and attenuation was observed in the formulation. But the number of particles of dust does not come readily. In addition, the rigorous Bessel function process in the model and difficulty in applying it to other dust particle's permittivity make its implementation tedious and in some cases impossible.

To this point, many earlier investigators (except few), considered the dust particle shape as spherical and phase rotation problem was not tackled thereby making the model unsuitable for XPD prediction. It is to be noted, however, that the general conclusion by these workers was that except for very dense storms and charged particles, attenuation by dust storms is not serious.

Lastly, many measurements and theories [24, 30] show that sand particles in SDS carry charges on them, and they have an effect on the wind-sand movement. Thus, in addition to the factors already considered in the MW attenuation, Zhou and Zheng [31] incorporated the factor of charges on dust particles. The paper assumed a given surface charge density and charges partially and uniformly distributed, and presented a theoretical analysis to simulate the attenuation of electromagnetic waves propagating in charged particles in SDS. The results obtained were consistent with the experimental result of scattering attenuation given by Haddad et al. [15]. This accounts better for the discrepancies between the measured and the calculated attenuation earlier observed. Dong et al. [9, 10] also demonstrated the notable influence of the charged particles on the propagation of electromagnetic waves. It was concluded that the influence of the charged particles on microwave signal attenuation is obviously greater than that of the uncharged; and the higher the charges concentration, the higher the attenuation.

3.1.1. Attenuation Prediction Model

Theoretical models to calculate the attenuation caused by SDS have been developed. The models are generally based on the theories and techniques for scattering computation as detailed in Section 2. A different attenuation model is the effective material property as employed by Dong et al. [9].

[32], Ghobrial & Sharif [13], Haddad et al. [15], Ansari & Evans [2], Goldhirsh [14] and recently Musa & Bashir [22] developed their models based on the Rayleigh scattering approximation. The limitation of Rayleigh approximation necessitated the use of Mie scattering theory as demonstrated by Islam et al. [16] and Elabdin [12]. However, at V band upward, the Mie criterion fails by orders of magnitude. Thus its application at some MMW bands also becomes questionable. More details of some selected attenuation prediction models for SDS are presented below.

i. [14]: This model considered the relative volume and mass of dust particles per cubic meter of air; and used an average measured density of samples collected in Khartoum to predict attenuation. The results were expressed in terms of a specifically measured severe dust storm but they may be generalized to other dust storms. Like the other earlier investigators, phase shift problem was not tackled and the dust particle shape was considered as sphere making the model unsuitable for XPD prediction. The attenuation coefficient (k) was expressed in terms of the visibility.

$$k = \frac{2.317 \cdot 10^{-3} \cdot \epsilon''}{\left[(\epsilon' + 2)^2 + \epsilon''^2\right] \cdot \lambda} \cdot \frac{1}{V^\gamma} \,[\text{dB/km}] \tag{12}$$

in which ϵ' and ϵ'' are the real and imaginary contributions of the relative dielectric constant of the dust particles respectively, λ is the wavelength in meters and V is the visibility.

ii. [12]: Another attenuation formula for microwave propagation in SDS was derived using Mie scattering theory. The formula is as expressed in Equation (13)

$$A_d = \frac{a_e f}{V} \left(X + Y a_e^2 f^2 + Z a_e^3 f^3\right) \,[\text{dB/km}] \tag{13}$$

in which a_e is the equivalent particle radius (m), V is the visibility (km), f is the frequency (GHz); and X, Y and Z are constants whose values depend on real (ϵ') and imaginary parts (ϵ'') of the dielectric constant of the dust particles.

iii. [11]: Model for attenuation due to charged sand particles was based on the forward scattering amplitude function for charged sand particles using Rayleigh approximation and the effective permittivity method. The results showed that the attenuation with charged sand was more significant than when there was no charge. The influences on the MW attenuation were also higher with higher concentration of the surface charges on sand particles. In a medium with equal sized particles, the attenuation was given as Equation (14):

$$\alpha = 8.686 k_0 \left[-\frac{3.46a}{V_b} I_m \left(\frac{\varepsilon_m^* - 1}{\varepsilon_m^* + 2}\right) + \frac{15a^2 \rho q \sin^2\theta_0}{26 V_b \varepsilon_0 E_0 \left(1 - \cos\theta_0\right)} I_m \left(\varepsilon_m^* - 1\right)\right] \tag{14}$$

At charge-to-mass ratio, $q = 0$, the attenuation reduced to Equation (15):

$$\alpha = 8.686 k_0 \left[-\frac{3.46a}{V_b} I_m \left(\frac{\varepsilon_m^* - 1}{\varepsilon_m^* + 2} \right) \right] \tag{15}$$

in which k_0 is the free space propagation constant, a is the particle radius, V_b is the visibility, ε_m^* is the complex dielectric constant of the particle; $\varepsilon_m^* = \varepsilon' - i\varepsilon''$, ε' is the real part ε'' is the imaginary part, ρ is the mass density of the particle, q is the charge-to-mass ratio, θ_0 is the charge distribution angle, ε_0 is the permittivity of vacuum and E_0 is the intensity of incident electric field.

iv. [11]: This is a unique method of calculating attenuation in SDS using the effective material property technique and general formulation of the complex propagation factor. The attenuation was obtained from the general formulation of wave propagation constant based on an equivalent complex permittivity of the SDS medium. The attenuation was given as:

$$\alpha = 8686 \cdot \frac{2\pi}{\lambda} \left[\frac{\varepsilon_{eq}'}{2} \left(\sqrt{1 + \tan^2 \delta} - 1 \right) \right]^{\frac{1}{2}} \text{ [dB/km]} \tag{16}$$

in which ε_{eq} is the complex relative permittivity of the SDS and λ is the wavelength.

v. [8]: The FDTD and the turning bands methods were used to compute the microwave attenuation in SDS. The formula which considered PSD function and the extinction cross section of a spherical particle was given as:

$$\alpha = 8.686 \times 10^3 \sum_{k=1}^{k} \sigma_{ext} (k\Delta r) N (k\Delta r) \Delta r \text{ [dB/km]} \tag{17}$$

in which K is an integer number of $r_{\max}/\Delta r$, $r_{\max}$ is the maximum radius of storm particle and Δr is the incremental radius.

3.2. Signal Depolarization

Signal depolarization is another important transmission parameter in modern day communication systems. Impact of depolarization becomes significant for systems reusing frequency by transmitting two orthogonally polarized signals for optimum frequency spectrum utilization. This occurs as a wave is propagated through a non-spherical particle along a path; the wave changes its polarization as it travels [21, 27] resulting in cross-polar interference, i.e., part of the transmitted power or energy emitted in one polarization interferes with the orthogonally polarized signal.

Study [3, 4, 21, 23] has shown that differential phase delay and differential attenuation from non-spherical scatterers (e.g., raindrops and SDS particles) cause depolarization also known as XP. In a first attempt to calculate XP in SDS [5], particles were treated as oblate spheroids with an axial ratio of approximately 0.95 and the particle symmetry axes were assumed to be all aligned in the same direction. However, later measurements have suggested much higher eccentricity. Point matching technique was used at 9.4 GHz over a 1 km path length. The prediction showed small attenuation; but 1.5 deg/km phase shift giving XPD of 51 dB. In other words, this paper draws attention to the possibility of significant XP due to differential phase shift, even though absorption was small.

The second known investigation [2] on XP considered 37 GHz. It was found that the effects were quite small in modest dry SDS with visibilities around 100 m for linear polarization. However, significant results could be obtained in humid areas for circular polarization and for bad storms with visibilities around 20 m and less. Thus the authors' conclusions emphasized a satisfactory performance of dual polar systems for linear cross polarization but that circular polarization would prove to be unsuitable. However, lack of information on the shape and alignment of dust particles was noted. Assumptions were therefore made to take care of this.

The concern about particle shape and alignment uncertainties was also noted by McEwan and Bashir [21] as mentioned in Part I, Section 2, where the treatment given to the particle shape was reported. Particle alignment was theoretically investigated. The conclusion was that particles of equivolumic radii greater than about 50 μm would normally be systematically aligned by the inertial torque, with the shortest length vertical. Expressions were given in terms of the relative volume occupied by dust — a quantity difficult to directly measure in practice; and problem of overestimation of the inertial forces was also observed. The prediction on slant paths where circular polarization or a non-vertical linear polarization might be used was severe. Over a distance of 1 km, XPD of 16 dB was recorded in SDS with 10^{-5} gm/cm^3 of air.

Another early attempt [13] noted the problem of dust particles shape and dimensions as particularly significant in XP computations. A significance of this work is the expression of results as a function of visibility and not mass of dust per unit volume of air. It was found that for linear polarisation, the effect of dust storm was negligible except ones with high moisture. The model is however limited by the constraint of the phase difference between the two linearly polarized waves producing circular polarization, i.e., $\phi < 20^\circ$. Besides, the permittivity of dust particles used in arriving at the expression is not always applicable. The expression of a circular polarized wave is:

$$\mathrm{XPD} = 10\log_{10}\left|\frac{1+2m\cos\phi+m^2}{1-2m\cos\phi+m^2}\right| \text{ [dB]} \tag{18}$$

in which m is the ratio of the amplitudes of the two linearly polarized waves producing circular polarization and $\phi = 90^\circ$ — phase difference between them. From Equation (18), Equation (19) was derived.

$$\mathrm{XPD} = 91.6 - 20\log_{10}(f \cdot d) + 21.4\log_{10} V \text{[dB]} \tag{19}$$

in which f is the frequency (GHz), d is the path length (km) and V is the visibility (km).

Jervase and Sharif [17] also addressed the effect of random depolarizing factors on XPD. An expression for the XPD introduced by dust storms and reflector tolerance in earth-satellite links was derived. It was observed that larger elevation angles offer a better isolation. Bashir [4] noted that for random azimuth, the attenuation and phase shift for horizontal polarization is the mean of the values applicable where long axis is normal and parallel to the direction of propagation. Circular polarization and linear polarization of 45° were observed to experience worst case XPD. The XPD expression was given in terms of a constant, γ.

$$\mathrm{XPD} = 20\log_{10}\left|\frac{1+\gamma}{1-\gamma}\right| \text{ [dB]} \tag{20}$$

in which γ is the differential attenuation and phase shift between dual channels. It is mathematically defined in Equation (21).

$$\gamma = e^{-(\Delta A - j\Delta\varphi)L} \tag{21}$$

in which ΔA is the differential attenuation (Np/km), $\Delta\varphi$ is the differential phase shift (radians/km) and L is the path length (km).

Musa and Bashir [23] and Yin and Xiao [29] also investigated XP induced by SDS and calculated the XPD by considering the amplitudes of polarized waves and the phase difference at a given path length. Yin and Xiao calculated the XP of microwave propagation in storms around 10 GHz. It was found that the XP can significantly affect the wave propagation in SDS. Musa and Bashir made use of the XPD formula for a circular polarized wave given in Equation (20) and Equation (21) for MW XP. Clearly, the canting angle factors were left out in the calculations of the XPD.

3.3. Other Impairments

Other impairments on EMW propagation but seldom attract much attention include tropospheric scintillations and intersystem interference. Scintillations occur due to variations in the magnitude and the profile of the refractive index of the troposphere leading to amplitude fluctuations. The fluctuations increase with frequency. They also depend on the length of the slant path decreasing with the antenna beam width. Expectedly, the fluctuations in the amplitude are also accompanied by a phase fluctuation. The intersystem interference may occur between an earth-space system (satellite) and earth-to-earth systems (terrestrial), or between two satellite systems whenever adjacent orbital positions are used or a frequency band is shared. Intersystem interference is escalated by potential differential attenuation whenever the desired signal undergoes a significant attenuation, while at the same time the undesired signal from an adjacent satellite experiences low attenuation [19].

4. GAPS IN KNOWLEDGE AND FUTURE OUTLOOK

The field of electromagnetic wave propagation is vibrant and wide with new observational technologies and sophisticated numerical models. However, there are still several major gaps in knowledge which need to be covered. In the past, emphasis has been placed on monitoring and assessing the influence of atmospheric parameters that are critical in communication systems design. While the real experimental measurements are required to obtain the actual parameters for the theoretical model, effort is now expected to be concentrated on atmospheric effects of direct relevance to systems design and operation.

Due to the rare propagation measurements above 30 GHz, validity of only a few propagation models so far presented has been tested using the measurements data. Suffice to mention that no known record of measurement of XPD at the MW or MMW band exists. In future, further propagation experiments especially at higher frequency bands are envisaged. Compilation of available geographical and morphological data on SDS to possibly obtain better estimates of the occurrence frequencies of various visibilities in the storms would also be of immense value.

Generally, it is observed that the level of understanding of XP in SDS is several orders of magnitude lower. Since study has shown that XP occurs due to the non-sphericity of the falling particles and the tendency of the particles to align in a particular direction at a time (canting angle), further study on the canting angle and forces responsible for the alignments is encouraged and expected to be reported. The authors intend to return to this particular point in their later works. A theoretical investigation is on-going on whether storm particles would exhibit any non-random orientation (necessary for XP induction and its calculation) or not. Besides, particle shape measurements could be improved upon by including some measure of the asymmetry. The theory itself can be extended to deal with the already mentioned question of the canting angle and of preferred particle long-axis azimuths.

More so, numerical techniques for solving the electromagnetic scattering problem still pose unresolved mathematical questions. Thus it can be expected that scattering theory will remain a challenging field of active research. The development of new formulations to further improve the numerical efficiency of existing methods, especially with regard to applications to ensembles of particles consisting of different shapes and in different orientations will require persistent research efforts in the future. Although a wide range of procedures to predict signal attenuation characteristics and XP have been reported. Further refinements and necessary modifications can be expected in order to develop models of universal acceptance and global applicability.

Furthermore, a characteristic of the works to this level was that lack of information on dielectric constant and hence refractive index at higher MW frequencies made the calculation of attenuation and XP to be limited to around 10 GHz. Thus, many models may not be suitable for higher frequency. Estimates of XP severity may be improved by a more careful consideration of the relations between dust particle concentration and visibility and also the way the concentration decays with height. Also, better models of the water uptake of particles and its effect on permittivity may be useful. This has some impact on XP and may be essential if attenuation of higher frequency (usually MW and MMW bands) is to be considered.

Lastly, present understanding of charges, electric field build-up and subsequent lightning discharge in terrestrial thunderstorms and their effects on EMW propagation is far from complete. In later papers, we hope to contribute some additional knowledge to some of the areas suggested.

5. CONCLUSION

The study of EMW propagation in SDS is an active research field. To this end, this part of the survey has focused on the theory of electromagnetic scattering, signal impairments occasioned by the SDS and methods of evaluating them. While a number of conclusions can be drawn, one that cannot be over emphasized is that propagation prediction is not a precise art. Currently, a main concern of the relevant research is to enhance the knowledge of the dynamics of the propagation phenomena in SDS. From this literature review, the existing state of knowledge on MW effects of SDS can be summarised as follows.

Firstly, there are clear indications that terrestrial and satellite links do experience fading associated with SDS. The lower frequency bands already show repletion and this has necessitated a turn towards MW and MMW bands for large bandwidths exploitation. However, this operational turn is accompanied by impairments that substantially degrade the links as the frequency increases. Secondly, it was also found that attenuation of EMW waves increased with increasing water content and severity of SDS.

Finally, there appears to be a strong possibility of significant XP on circularly and linearly polarised links due to differential phase shift and attenuation. Having reviewed and presented the SDS propagation effects with their prediction models, a more comprehensive review should cover available measured data for testing the existing methods and for development of more accurate empirical and semi-empirical models.

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