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

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Abstract—Electromagnetic wave propagation in arid and semi-arid regions is influenced by sand and dust storms. Meagre information has hitherto been reported as to the effect of storms on telecommunication systems operating in such regions. This paper presents a survey of current understanding of the wave propagation during storms. In this first part of the review—Part I, detailed parametric assessment of some electrical and mechanical properties affecting wave propagation in sand and dust storms is given. The second part of the review—Part II describes the principle of approach and technology adopted for the investigation highlighting both strengths and drawbacks. The results demonstrate that most authors have calculated signal attenuation effect, revealing that it is not very significant unless during severe storms. A few papers indicate the possibility of more significant cross polarisation. Part I explicitly gives an account of the sand and dust storms' phenomenon, reviews the storms' parameters affecting electromagnetic wave propagations and discusses the microwave and millimeter wave bands.

1. INTRODUCTION

Increase in frequency of occurrence of sand and dust storms (SDS) has made the study of wind-blown sand and dust (SD) particles as well as their effects on human activities an important topic of research [41, 46]. Appreciable interest has been expressed in the problem associated with influence of SDS on microwave (MW) link performance [16, 17, 19, 27, 35]. This has been largely attributed to the continuous growth of satellite and terrestrial MW systems and use of higher frequencies. There is now spectral congestion of the conventional frequency bands owing to evolvement of new and demanding telecommunication applications over the past decade. This has given rise to a steady move toward higher carrier frequencies for increased information transfer rates and to further miniaturize equipment for portability. However, a range of meteorological phenomena such as SDS make MW propagation a serious problem as operations can be hampered by attenuation due to SDS particles.

This paper does not seek to describe new work as such; nor will it be possible within the limited scope of the review to provide a comprehensive list of the very extensive bibliography which encompasses the subject matter. Also, the paper takes cognizance of related existing reviews. Such reviews (e.g., [10]) though limited to lower frequency may however be easily extrapolated to higher wavelengths in MW and millimetre wave (MMW) bands. Thus, this part of our paper represents an up to date review of existing related literature and assessment of the important storms' parameters affecting electromagnetic wave propagations during SDS.

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2. SAND AND DUST STORMS PHENOMENON

A sand or dust storm is a very strong windstorm that blows loose sand or dust from a dry surface [25]. The wind is usually caused by convection currents, strong enough to carry clouds of SD, moves entire sand dunes and greatly reduces visibility. Different SD sizes have been reported [7, 8, 22], but finding afterwards [27] revealed that dust relates to small solid particles, conventionally taken as those below 80 μm in diameter. Diameters of dust storms particle are generally within the range of 10 μm and 80 μm, while particles with diameters lager than 80 μm are referred to as sand. Besides, when the horizontal visibility during a storm is less than 1 km and when the dust is being circulated into the atmosphere within sight of the observer [44], it can be classified as a dust storm. It becomes a severe dust storm when the visibility is shorter than 500 m or approaching zero. Sand being driven by winds where the sand particles rarely rise higher than 2 m is on the other hand generally referred to as sand storms.

In this work, both storms (i.e., SD) are treated and commonly referred to as SDS. SDS can therefore be defined as a severe weather condition characterized by strong winds and dust-filled air over an extensive area. It is turbulent but having a definite direction and differs from one location to the other in its particle size, humidity and intensity. It is common in arid and semi-arid regions, especially in the Middle East and arid parts of Asia. SDS occurs in northern Nigeria, other parts of Africa and the Sahara, regions of the northwest and east coast of Australia and North America. That which comes off the Sahara desert is locally known as a simoom while haboob is a form of SDS prevalent in Sudan. The SDS characteristics pose dangers to system reliability in the affected regions [36].

2.1. Sources and Causes of Sand and Dust Storms

The Sahara desert and drylands are the main terrestrial sources of SDS [36]. It has been argued that poor management of the Earth's dry lands are increasing SDS frequency from desert margins. The cultivation of the semiarid land removes wild grasses whose roots stabilize the soil. Thus, the dry soil is exposed to the wind and as the force of wind repeatedly strikes the ground, they loosen and break off smaller particles of dust which then begin to travel in suspension. While these are all regarded as man-made sources, the natural sources include volcanoes, forest fires and meteorites.

In desert areas, SDS is most commonly caused by either thunderstorm outflows, or by strong pressure gradients which cause an increase in wind velocity over a wide area. The vertical extent of the dust or sand that is raised is largely determined by the stability of the atmosphere above the ground as well as by the weight of the particulates.

2.2. Parameters and Characteristics of Sand and Dust Storms Particles

The study of EMW propagation through SDS media requires knowledge of some of the electrical and mechanical characteristics of that media. Investigations have showed that the EMW scattering in SDS is influenced by parameters which include visibility, particle shape, size, moisture, permittivity etc..

2.2.1. Visibility

Knowledge of visibility has guided the formulation of propagation models in SDS. It is a more realistic parameter that meteorological observations of SDS are usually based upon. Optical visibility is directly related to the severity of SDS and thus a measure of the severity of the storm. Visibility is often used to describe the distance at which a mark disappears against the background for terrestrial SDS. The term visibility is also normally applied to denote the degree of SDS density instead of the total number of dust particles [18]. Needless to mention that visibility decreases with increasing intensity of dust in a storm. Low visibility implies high number concentration of particles while low number concentration of particles represents high visibility.

2.2.1.1. Relation between Visibility and Volume Fraction

The mass of suspending dust per unit volume of air is related to visibility by [24]:

$$M = \frac{C}{V^{\gamma}} \tag{1}$$

in which, M is the dust mass in kg/m^3 of air; V is the visibility (km); C and γ are constants that depend on the type of land from which the storm originated as well as the climatic conditions. It may also depend on factors such as the presence or absence of local erosion, or the distance from the source of the aerosol. There is no single value of C that is generally applicable to relate the mass concentration of soil-derived aerosols and visibility. Different values have been reported in the literature. [13] recorded 5.6×10^{-5} and 1.25 as the values of C and γ respectively while [23] stated that 2.3×10^{-5} and 1.07 are applicable to Sudan situation.

Equation (2) is obtained from Eq. (1) when it is divided through by ρ_0, and the expression is given in terms of volume fraction (or relative volume).

$$v_f = \frac{C}{V^{\gamma}\rho_0} \tag{2}$$

in which, ρ_0 is the solid density of dust. It is noted that,

$$v_f = \frac{\rho}{\rho_0} \tag{3}$$

ρ is the dispersed density in the medium (or dust concentrations). A relation between visibility and dust concentration was given by Chepil as expressed in Eq. (4).

$$\rho = \frac{5.6 \times 10^{-5}}{V^{1.25}} \,[\mathrm{kg/m^3}] \tag{4}$$

The equation provides ease of application to a range of dust storms characteristics. It also provides means of estimating dust concentrations (ρ) from information on the visibility associated with a given SDS. Substituting Eq. (4) and the value of solid density of dust ($\rho_0 = 2.65\,\mathrm{g/cm^3}$) into Eq. (3) gives:

$$v_f = \frac{2.1132 \times 10^{-8}}{V^{\gamma}} \tag{5}$$

in which, the constant, γ is here given as 1.25. Ghobrial and Sharief used the Sudan's situation to predict that:

$$\rho = \frac{2.3 \times 10^{-5}}{V^{1.07}} \,[\mathrm{kg/m^3}] \tag{6}$$

$C = 2.3 \times 10^{-5}$ and $\rho_0 = 2.44 \times 10^3\,\mathrm{kg/m^3}$ were also used for Sudan dust to obtain:

$$v_f = \frac{9.43 \times 10^{-9}}{V^{\gamma}} \tag{7}$$

in which γ is 1.07. The difference observed in Eq. (4) and Eq. (6) on one hand and Eq. (5) and Eq. (7) on the other hand can obviously be attributed to difference in the values of C and the solid density assumed.

Relation between visibility and density of SDS particles was also established by [14]. Finally, some authors [18, 27, 34] have demonstrated the possibility of empirically expressing attenuation coefficient in terms of visibility. The characterization of SDS using visibility is more realistic than using concentration number of particles per unit volume (N) or volume fraction (v_f) which is difficult to measure.

2.2.2. Shape and Alignment

The shape of SDS particles is important in the investigation of their depolarizing effect. Also, shape is an important factor in determining a variety of aerodynamic and other forces which tend to create or destroy systematic orientation of the falling particles. Dust particles have random irregular shapes without any particular symmetry and cannot be described by any simple geometry [23]. Study has shown that only non-spherical particles with some degree of systematic alignment cause depolarization [33]. Authors have therefore assumed different shapes of the scattering particle to carry out scattering and XP computations. Although dust particle shape is very complicated, the nearest geometry that approximates dust particle is the ellipsoid with axis ratio varying over wide range (from 0 to 1). The attenuation and the phase constants of a medium with suspending ellipsoids can be computed if the ratios of the ellipsoid axes are known.

[39] observed that the ellipsoid geometry has three degrees of freedom which gives good approximation to the shape of realistic dust particles. The aspect ratios of the three axes a_1, a_2 and a_3 were investigated and a ratio of the axis was found to be $1 : r_2 : r_3 = 1 : 0.71 : 0.53$. r_2 and r_3 are defined in Eq (8).

$$r_2 = \frac{a_2}{a_1} \quad \text{and} \quad r_3 = \frac{a_3}{a_2}\frac{a_2}{a_1} = \frac{a_3}{a_1} \tag{8}$$

The average axial ratio a_2/a_1 was 0.71 while a_3/a_2 was 0.75. This result is quite similar to what earlier investigators also recorded.

In treating the concern over particle shape and alignment, [33] used two methods to quantify shapes of particles taken from a SDS in Khartoum. Ellipses were fitted by eye to the outlines of photomicrographic images of particles in the first 2-D method. The mean axis ratio was 0.55. The second method which was 3-D allowed particles to be modelled as ellipsoids rather than spheroids. With the aid of a microscope, the extreme widths and lengths of the particle outlines were measured by a rotatable graticule. The height which is third dimension was obtained producing $a_2/a_1 = 0.76$ and $a_3/a_1 = 0.53$ as the mean axis ratios.

[23] also gave an account of particle shapes and axes ratio determination adopting method almost similar to that of [33]. Thus, the obtained ratios were observed to be in good agreement with those obtained by [33]. To determine a_2/a_1 ratio, a small amount of dust is blown in air and allowed to settle under gravity effect. A camera fitted to a microscope provided information on a_1 and a_2 to determine a_2/a_1. For a_3/a_2 ratio determination, an electrostatic field was applied to an adhesively covered slide held parallel to and a few cm above the bench where a small amount of dust was placed by charging the slide. Particles were attracted to the slide with the longest axis in the direction of the field; i.e., normal to the slide. The a_1 dimension did not appear when photographed and thus a_3/a_2 ratio was determined.

[39] submitted that under stationary air condition, ellipsoidal particles fall with the shortest axis vertical and the two other axes are randomly oriented in the horizontal plane. However, during SDS which is usually characterized by the presence of turbulent air flow, there exists a random orientation of the particles. It suffices to mention, however, that SDS particles (especially of some certain microns) can exhibit non-random orientation. This will be demonstrated in our future works. Turbulent torques and less importantly, Brownian motion have been identified as forces capable of disrupting alignment. While electrostatic fields of thunderstorm strength could also have a large influence on alignment, a systematic alignment would tend to be generated by electrostatic forces and inertial torques.

2.2.3. Sizes and Distribution

Particle sizes and distribution is an important parameter both for investigating the characteristic properties of SDS and calculating signal transmission parameters. The particle size distribution (PSD) function affects the wave attenuation in SDS [12]. Attenuation and phase shift of a microwave signal have been estimated utilizing measured PSD [1] or numerical distribution methods. Unlike rain, there is paucity of data on dust particle sizes. Generally, the PSD reported in the literature varied considerably and no clear pattern of prediction seems to be available. [8] determined sand PSD by sifting and found sand particles radii not to be less than 0.04 mm. They are usually between the range of 0.08 and 0.15 mm depending on the location. The work also found 0.1 mm to be the radius of particle sizes that would be set into motion by a wind of 5 m/s velocity during SDS.

Another early attempt was reported by [21] where PSD for four SDS events in Khartoum was measured. The result indicated that dust particles may have a mean diameter that is less than 50 μm. Few other works [7] also corroborated this finding but with expanded scope. It was reported that all particles had a radius of less than 0.15 mm and the distribution was exponential. Dust particle sizes thus vary considerably over a wide range of values. Particles may have average mean diameter of 114 μm [38]. The radius distribution of dust and sand may vary from 0.05 to 150 μm [4, 22]. Lastly, finding afterwards [27] revealed that dust relates to small solid particles, conventionally taken as those below 80 µm in diameter.

At some point, the general conclusion was that the size of particles was too small to contribute significantly to the microwave systems [7]. Later investigations, however suggested otherwise. [39] noted that these particles had some effects on MMW propagation. Measurement to determine samples PSD was carried out on ten dust samples collected in Sudan using the hydrometer and pipette methods.

Furthermore, PSD can be approximated by a straight line equation given in Eq. (9). Cumulative curves of PSD may follow the equation:

$$n\left(r\right) = a_0 + a_1 r \tag{9}$$

in which $n\left(r\right)$ is the fraction by weight composed by dust particles having equivalent radius less than $r(\mu m)$, and a_0 and a_1 are constants which depend on the factor characterizing the dust PSD. Using Eq. (9) and other models given by [39], the minimum radius of the dust particle was found in the range of 0.1 µm to 9 µm with 3.125 µm as the average value. Similarly, the maximum radius of the particles is within the range 34 µm to 42 µm with 38 µm as the average value.

2.2.3.1. Typical Distribution Types

Gaussian (normal distribution), log-normal and Rosin-Rammler distributions are typical distributions in particle size whose details can be found in the literature. [4] measured the probability density function (PDF) of dust samples during five different SDS in Riyadh, Saudi Arabia. Of the 16 samples and using square method of fitting, it was found that 14 samples were best described by normal and log normal functions. Only two were described by power law. [5] also dealt with particle sizes.

[19] used lognormal PSD to compare some predicted attenuation with a measured data and found close agreement. Exponential distribution was, however, employed by some other investigators as mentioned earlier. The Elsheikh's work investigated the PSD to obtain the optimum particle size for an improvement in the accuracy of attenuation prediction models. The authors attributed the variance dependence of the PSD to different geographical location and storm conditions. Thus, the fact that no single size distribution is globally applicable is thus made obvious.

2.2.3.2. Techniques for Characterization of Particle Size and Size Distribution

[1] used the techniques of pipette, sedimentation balance, hydrometer, optical microscope and Coulter counter to determine the PSD of some dust samples from severe SDS collected in Iraq. The cumulative weight techniques yielded nearly identical results for all the tested samples. Numerous commercial instruments and software packages are available for particle size and distribution analysis. The major techniques for characterization of particle size and size distribution are discussed below.

(i) *Sieving Techniques:* This is one of the oldest techniques widely used to determine PSD over a broad size range (from 100 mm to 20 µm). The method is based only on the size of the particles and is independent of other particle properties, e.g., density and surface roughness [30]. Its wide application is attributed to high reliability, cost efficiency and relative simplicity. However, PSDs are susceptible to large uncertainties due to measurement of smallest diameter by this method. The method also requires long analysis times especially as sieves with finer aperture openings are used.

(ii) *Gravitational Sedimentation Techniques:* Another widely used technique for PSD determination is the gravitational sedimentation technique. Its principle is based on measuring the terminal settling velocity, i.e., the velocity with which particles in a fluid settle due to the gravitational forces acting downward on the particle. This is balanced by the buoyancy of the fluid and other drag forces acting upward (against the settling of particles). Expressing the relationship using Stokes' law of sedimentation, the terminal velocity is given in Eq. (10). The equation, however, applies only to laminar (non-turbulent) flow.

$$u = d^2 g\left(\rho_s - \rho_a\right)/18\mu \tag{10}$$

in which, u is settling velocity of the particles; d is the particle diameter; ρ_a and ρ_s are the density of the fluid and solid particle respectively; g is the gravitational acceleration; μ is the viscosity of the fluid. The technique is robust and relatively inexpensive with typical size range of about 0.1 µm to 300 µm. Accuracy of analysis can be significantly affected by some physical factors such as particle-to-particle interaction and Brownian forces (in certain size ranges).

(iii) *Microscopy Techniques:* This technique is often referred to as an absolute method for determination of size and size distribution of small particles because it allows direct visualization and measurements of individual particles. Typically, the calculated sizes are expressed as equivalent geometric diameter. In addition to making a direct measurement of sizes, this method also has the ability to determine the particle shape. Analysis is relatively easy and can be achieved in a short period of time. The technique, however, has magnification and resolution limitations [30].

(iv) *Laser Light Diffraction Techniques:* The principle of Light diffraction instruments are based on the basic assumptions of scattering from spherical particle shape, single scattering (i.e., little or no interaction between the light scattered from different particles), and that the scattering pattern at the detectors is the sum of the individual scattering patterns generated by each particle interacting with the incident beam in the sample volume. Size range is typically between 0.04 µm and 8000 µm. The method has ease of application and rapid analysis capability. However, if particle shapes deviate from spherical configurations, significant error may be introduced in the PSD results thereby making it unsuitable for non-spherical particles. While the laser light scattering instruments are often referred to as Fraunhofer diffraction instruments, other method also includes Laser Doppler Phase Shift.

2.2.4. Permittivity

Accurate knowledge of the dielectric permittivity of materials in the microwave frequency range is very important for microwave applications because it enables evaluation of scattering properties in electromagnetic computation. The dielectric constant (k) of a material is the ratio of its permittivity ε to the permittivity of vacuum ε_0, i.e., $k = \varepsilon/\varepsilon_0$. It is therefore also known as the relative permittivity of the material and is dimensionless since it is a ratio of two similar quantities.

Some measurements of the complex permittivity of SDS samples have been carried out in recent years [2, 29, 45]. Attempts to suggest a physical model of dielectric properties of SD has been met with application complexity since analytical calculation of some parameters is impossible and they have to be retrieved experimentally for each type of SD. At present, models of SD permittivity exist reflecting certain physical and structural properties (e.g., [11, 15]). Most of these models only took bulk permittivity into consideration [28]. However, recent studies by [9] introduced scaled permittivity.

[6] conducted a series of 10 GHz measurements of the complex permittivity of both bulk and dispersed sand and clay by observing the effect on the resonant frequency and Q-factor of a large open resonator. The measurement directly produced the macroscopic refractive index of the dispersed particles. This was equal to the specific phase shift and attenuation that the particle density would cause on a MW path. Secondly, mean permittivities of compressed samples of the same materials were measured by different techniques using mixing formula. A major drawback associated with this method is that the mixing formula must be applied to the bulk measurements to infer the solid particle permittivity from that of the air-mineral mixture (as the samples are far from being solid).

Using Rayleigh approximation, an assumed dielectric constant was used by [14] to predict dielectric constant for spherical sand particle. Fair agreement was noted when compared with past results which made use of open resonator. Similar to the case of Ahmed, discrepancy was however noted in the loss tangent of clay. Measurements on samples collected in Khartoum were carried out by [20] using the conventional resonant cavity technique. The results showed a loss tangent of 0.039 which was larger than the Chu assumption. It was also found that different samples have different dielectric constants, and this was attributed to the different chemical compositions of the samples. Permittivity is observed to be very much dependent on hygroscopic water content, frequency and chemical composition.

Further investigation on the effects of chemical constituents, frequency, and humidity on the permittivity was carried out by [23, 40]. Effect of chemical composition of dry soils has little effect on dielectric constant except where metallic or magnetic minerals are present. The hygroscopic water content of the samples was found to have much dependence on the prevailing climatic conditions during SDS. Water content (moisture) which is a function of the air relative humidity can also affect the dust complex permittivity [31]. In a parametric review of dust particle permittivity, [26] also established the critical dependence of both the real and imaginary permittivity on the moisture content. Particle permittivities over a wide range of frequency and water contents were also deduced from the available literature and given by [7]. Important submissions from this effort were that moisture content dominates the imaginary part and could also increase the real part value.

At this stage of development, it is obvious that sufficient interest was shown to knowledge of dielectric constants, and it was noted that the dielectric constant, though dependent on frequency, is not sensitive to frequency above 4 GHz [20, 32]. At frequencies up to 18 GHz, [15] evaluated the MW dielectric behaviour of soil-water mixtures and presented a semi empirical mixing model based upon the index of refraction as a function of water content and soil textural composition. [37] extended Dobson's model for wider validity range of frequency. A novel method of combined embedded modulated scattering and near-field MW was developed by [29]. This technique however does not work well for low loss materials. [28, 39] considered many of the reported dielectric constant values as inaccurate apparently due to the measurement techniques and the way the samples were collected and prepared. The work attempted to compile (from the literature) values believed to be the most accurate and reasonable. An important conclusion from this work is that moisture content of dust increases the dust dielectric constant.

Available literature thus far showed that most of these measurements have used compressed, bulk samples of soil in a waveguide or resonant cavity or using a combined embedded modulated scattering and near-field MW techniques. Appreciable amount of air were still found in such samples. To address this problem, another novel measurement method at X-band frequency was presented by [9]. In the recent study, Looyenga's formula was used to obtain the permittivity of the dry SDS component from the mixture.

Finally, Maxwell Garnett formula [42] for effective permittivity of a mixture in i direction, having ellipsoidal particles with permittivity ϵ suspended in a medium with permittivity ϵ_a is given as:

$$\epsilon_{e,i} = \epsilon_a \left\{ 1 + v \frac{\epsilon - \epsilon_a}{\epsilon_a + A_i(\epsilon - \epsilon_a)} \right\} \tag{11}$$

in which, v is the suspended particles relative volume and A_i the depolarization factor in the i direction. Since visibility remains the parameter used to measure SDS severity in practice, the relation between visibility and relative volume is thus recalled i.e., Eq. (7); and the dusty medium effective permittivity in the i direction is finally expressed in terms of visibility and depolarization factor.

$$\epsilon_{e,i} = 1 + \frac{9.43 \times 10^{-9}}{V^{\gamma}} p_i \tag{12}$$

In summary, different values of dust dielectric constant have been reported using different techniques at different frequency bands and experimental conditions. The dielectric properties of a material are a function of moisture content, chemical composition and frequency. Permittivities of SDS are the same if their chemical compositions are identical. Low permittivity consequently produces low predicted attenuations.

3. MICROWAVE AND MILLIMETER WAVE BANDS

In wave propagation, it is apparent that wavelength is the metric that determines the complexity of the interaction of the wave with its environment. The complexity increases as the wavelength shortens (or with increase in frequency). While MW applications fall in the frequency range of 3–30 GHz, the MMW are electromagnetic radiation with shorter wavelengths. The term MMW refers to the radio spectrum between 30 GHz (1 cm or 10 mm) to 300 GHz (1 mm). But in the context of wireless communication, MMW corresponds to bands of spectrum near 38, 60 and 94 GHz, and more recently to a band between 70 and 90 GHz. These spectrums have been allocated for the purpose of wireless communication in the public domain [3]. The common MMW bands are Ka-band: 26.5 to 40 GHz, Q-band: 33 to 50 GHz, V-band: 50 to 75 GHz and W-band: 75 to 110 GHz.

Demand for frequencies is getting higher and this has made acquisition of quality spectrum and other signal measurements very tough. This challenge increases in the MMW bands. The major limiting factor and main disadvantage of operating at the MMW bands is the hydrometeor scattering [43]. In any case, the MMW wireless technology presents the potential to offer bandwidth delivery comparable to that of fiber optics, but without the financial and logistic challenges of deploying the fiber technology.

4. CONCLUSION

The study of EMW propagation in SDS is an active research field. To this end, Part I of this survey has focused on the SDS phenomenon, dust particles characterization and parameterization. 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 review of the literature, the existing state of knowledge on microwave effects of dust storms can be summarised as follows:

Firstly, the lower frequency bands already show repletion, and this has necessitated a turn towards MW and MMW bands for the communication systems to exploit the large bandwidths available. However, this operational turn is accompanied by impairments that substantially degrade the communication links as the frequency increases. Secondly, a number of SDS parameters ranging from permittivity values of the particles, particle sizes and shapes are usually employed as empirical inputs to determine the effects of storms on EMW propagation. Finally, having reviewed the SDS phenomenon and its electrical properties and parameters, it is necessary to come up with the possible effects on the EMW propagation and the different methods or techniques used in carrying out evaluation of such effects. This is to be demonstrated in Part II of this topic.

REFERENCES

1. Abdulla, S. A. A., H. M. Al-Rizzo, and M. M. Cyril, "Particle-size distribution of Iraqi sand and dust storms and their influence on microwave communication systems," *IEEE Transactions on Antennas and Propagation*, Vol. 36, No. 1, 114–126, 1988.
2. Abuhdima, E. M. and I. M. Aleh, "Effect of sand and dust storms on microwave propagation signals in Southern Libya," *2010 15th IEEE Mediterranean Electrotechnical Conference*, 695–698, 2010.
3. Adhikari, P., "Understanding millimeter wave wireless communication," VP of Business Development for Network Solutions, Loea Corporation, San Diego, 2008.
4. Ahmed, A. S., "Role of particle-size distributions on millimeter-wave propagation in sand/duststorms," *Inst. Electr. Eng. Proceedings*, Vol. 134, 55–59, 1987.
5. Ahmed, A. S., A. Ali, and M. A. Alhaider, "Airborne dust size analysis for tropospheric propagation of millimetric waves into dust storms," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 25, No. 5, 593–599, 1987.
6. Ahmed, I. Y., "Microwave propagation through sand and dust storms," PhD Thesis, University of Newcastle Upon Tyne, UK, 1976.
7. Ansari, A. J. and B. G. Evans, "Microwave propagation in sand and dust storms," *Proc. Inst. Electr. Eng*, Vol. 129, 315–322, 1982.
8. Bagnold, R. A., *The Physics of Blown Sand and Desert Dunes*, First Publ. 1941, Chapman & Hall, London, U.K., 1984.
9. Bashir, S. and N. McEwan, "A novel measurement method of a single dust particle permittivity at a microwave frequency band as I/P to accurate scattering computations. Part I," *Radioelectronics and Communications Systems*, Vol. 55, No. 4, 178–185, 2012.
10. Bashir, S. O. and N. J. McEwan, "Microwave propagation in dust storms: A review," *IEE Proceedings*, Vol. 133, Pt. H, No. 3, 241–247, 1986.
11. Boyarskii, D. A., V. V. Tikhonov, and N. Y. Komarova, "Model of dielectric constant of bound water in soil for applications of microwave remote sensing," *Progress In Electromagnetics Research*, Vol. 35, 251–269, 2002.

12. Chen, H. Y. and C. Ku, "Microwave and millimeter wave attenuation in sand and dust storms," *International Conference on Microwave, Radar and Wireless Communication*, 527–532, Warsaw, Poland, IEEE, 2012.
13. Chepil, W. S. and N. P. Woodruff, "Sedimentary characterisation of duststorms: II-Visibility and dust concentration," *American Journal Sci.*, Vol. 255, 1957.
14. Chu, T. S., "Effect of sand storms on microwave propagation," *Bell Syst. Tech. J.*, Vol. 58, 549–555, 1979.
15. Dobson, M., F. T. Ulaby, M. T. Hallikainen, and M. A. El-Rayes, "Microwave dielectric behavior of wet soil-part II: Dielectric mixing models," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 23, No. 1, 35–46, 1985.
16. Dong, Q., J. D. Xu, Y. L. Li, H. Zhang, and M. J. Wang, "Calculation of microwave attenuation effect due to charged sand particles," *J. Infrared Milli Terahz. Waves*, Vol. 32, 55–63, 2011.
17. Dong, Q., J. Xu, Y. Li, and M. Wang, "Microwave propagation in charged sand particles," *2010 9th International Symposium on Antennas Propagation and EM Theory (ISAPE)*, 379–382, IEEE, 2010.
18. Elabdin, Z. E. O., M. R. Islam, O. O. Khalifa, and H. E. Abd-El-Raouf, "Mathematical model for the prediction of microwave signal attenuation due to duststorm," *Progress In Electromagnetics Research M*, Vol. 6, 139–153, 2009.
19. Elsheikh, E. A. A., M. R. Islam, A. Z. Alam, A. F. Ismail, K. Al-Khateeb, and Z. Elabdin, "The effect of particle size distributions on dust storm attenuation prediction for microwave propagation," *Proc. Int. Conf. Computer and Communication Engineering*, 1156–1161, Kuala Lumpur, Malaysia, 2010.
20. Ghobrial, S. I., "Effect of hygroscopic water on dielectric constant of dust at X-band," *Electron. Lett.*, Vol. 16, 393–394, 1980.
21. Ghobrial, S. I., "The effect of sand storms on microwave propagation," *Proc. Nat. Telecommunication Conf.*, Vol. 2, 43.5–43.5.4, Houston, Texas, 1980.
22. Ghobrial, S. I. and J. A. Jervase, "Microwave propagation in dust storms at 10.5 GHz — A case study in Khartoum, Sudan," *IEICE Trans. Commun.*, Vol. E80-B, No. 11, 1722–1727, 1997.
23. Ghobrial, S. I. and S. M. Sharief, "Microwave attenuation and cross polarization in dust storms," *IEEE Transactions on Antennas and Propagation*, Vol. 35, No. 4, 418–425, 1987.
24. Gillett, D. A., *Environmental Factors Affecting Dust Emission by Wind Erosion*, C. Morales, Ed., Wiley, New York, 1979.
25. Glickman, T. S., *Glossary of Meteorology*, 2nd Edition, American Meteorological Society, Washington, 2000.
26. Goldhirsh, J., "A parameter review and assessment of attenuation and backscatter properties associated with dust storms over desert regions in the frequency range of 1 to 10 GHz," *IEEE Transactions on Antennas and Propagation*, Vol. 30, No. 6, 1121–1127, 1982.
27. Goldhirsh, J., "Attenuation and backscatter from a derived two-dimensional duststorm model," *IEEE Transactions on Antennas and Propagation*, Vol. 49, No. 12, 1703–1711, 2001.
28. Gupta, V. K. and R. A. Jangid, "The effect of bulk density on emission behavior of soil at microwave frequencies," *International Journal of Microwave Science and Technology*, Vol. 2011, ArticleID 160129, 6 pages, 2001, doi:10.1155/2011/160129.
29. Hughes, D. and R. Zoughi, "A novel method for determination of dielectric properties of materials using a combined embedded modulated scattering and near-field microwave techniques — Part I: Forward model," *IEEE Trans. Instrum. Meas.*, Vol. 54, No. 6, 2005.
30. Jillavenkatesa, A., S. J. Dapkunas, and L. H. Lum, "Particle size characterization," National Institute of Standards and Technology, US, 2001.
31. Kim, K., "Measurement of grain moisture content using microwave attenuation at 10.5 GHz and moisture density," *IEEE Transactions on Instrumentation and Measurement*, Vol. 51, No. 1, 72–77, 2002.

32. Lasne, Y., "Effect of salinity on the dielectric properties of geological materials: Implication for soil moisture detection by means of radar remote sensing," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 46, No. 6, 1674–1688, 2008.
33. McEwan, N. and S. Bashir, "Microwave propagation in sand and dust storms: The theoretical basis for particle alignment," *International Conference on Antennas and Propagation, ICAP 82*, No. 219, 227–231, IEE Conference Publication, 1983.
34. Musa, A. and S. O. Bashir, "Electromagnetic waves propagation in dust storms at millimeter wave Band," *Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS)*, Vol. 4, No. 2, 162–167, SCHOLAR Link Research Institute Journal, ISSN: 2141-7016, 2013.
35. Musa, A. and S. O. Bashir, "Prediction of cross polarization discrimination at millimeter wave band due to dust storms," *ARPN Journal of Engineering and Applied Sciences*, Vol. 8, No. 7, 465–472, 2013.
36. Naval Research Laboratory (NRL), "Forecasting dust storms," Retrieved, 2013.
37. Peplinski, N. R., F. T. Ulaby, and M. C. Dobson, "Dielectric properties of soils in the 0.3–1.3-GHz range," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 33, No. 3, 803–807, 1995.
38. Sharif, S., "Performance of earth-satellite links during duststorms at the X-band," *Sudanese Engineering Journal*, Vol. 40, No. 33, 1993.
39. Sharif, S. M., "Dust storms properties related to microwave signal propagation," *University of Khartoum Engineering Journal (UofKEJ)*, Vol. 1, No. 1, 1–9, 2011.
40. Sharief, S. M. and S. I. Ghobrial, "X-band measurements of the dielectric constant of dust," *Proc. URSI Commission F Symposium, Louvain-la-Neuve*, 143–147, ESA Publication SP-194, Belgium, 1983.
41. Shao, Y., *Physics and Modeling of Wind Erosion*, Kluwer Academic Publishers, Boston, 2000.
42. Stratton, J., *Electromagnetic Theory*, McGraw-Hill, New York, 1941.
43. Stutzman, W. L., "The special section on propagation effects on satellite communication links," *IEEE Proceedings*, Vol. 81, No. 6, 850–55, 1993.
44. Tan, S., "A statistical model for long-term forecasting of strong sand dust storms," MSc Thesis, University of Nevada, Las Vegas, 2011.
45. Yan, Y., "Microwave propagation in saline dust storms," *Int. J. Inf. Millim. Waves*, Vol. 25, 1237–1243, 2004.
46. Zhou, Y., Q. Hea, and X. Zheng, "Attenuation of electromagnetic wave propagation in sandstorms incorporating charged sand particles," *The European Physical Journal E*, Vol. 17, 181–187, 2005.