Dust Particles' Permittivity in Microwave Signal Propagation: A Review

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Abstract—Microwave propagation in dust storms has become an active research field. Dust particles' permittivity property is an important component with its applications in microwave signal propagation. Permittivity values, determined using different techniques and methods, usually serve as input variables to computation of electromagnetic scattering. They are also used to determine propagation impairments such as microwave attenuation, phase rotation, cross polarization, antenna's accretion and beam shift effects thereby making accurate knowledge of dust permittivity in the microwave frequency range very important. This paper has investigated and presented a review of some related works on the permittivity of dust particles. The current state of knowledge of dust particles permittivity is presented by examining the variety of techniques and methods, their strengths and limitations. The permittivity properties of dust samples are a function of frequency, moisture content and chemical composition. Identical chemical composition of dust sample gives identical permittivity, while different chemical compositions give a different permittivity property. Furthermore, gaps in knowledge that need to be covered are identified and the projected path and outlook of dust particle's permittivity property is also presented.

Index Terms—Complex permittivity, dielectric constant, attenuation, phase rotation, dust particle, microwave

I. Introduction

Microwave communication engineering is playing very important roles in civilian and military spheres. Microwave wave signal propagation in sand and dust storms has become an active research field. Thus, considerable interest has been shown to the problem of microwave propagation during sand and dust storms [1]-[4]. Microwave signal propagation requires accurate knowledge of electromagnetic properties of materials at different microwave frequencies [1]. A few dust parameters such as permittivity of dust particles, particle shape and sizes etc. are used as inputs to evaluate effects of dust storms on microwave signal propagation. Complex permittivity of sand and dust samples allows for evaluation of its scattering properties in electromagnetic computation. A comprehensive review of some of these parameters have been carried out [3]. Measurements of sand and dust dielectric constants have been carried out by several workers using different approaches and techniques.

Sand and dust storms have been discussed by some researchers such as [3]. It has been explained that particles driven by winds and that rarely rise higher than 2m may be called sandstorms. The diameters of sandstorm particles are usually greater than 0.08mm and may be between 0.15mm and 0.3mm. The diameters of dust particles, on the other hand, are usually within the range of 10μm and 80μm. The fall speeds of such particles can conceal the sun and its rays for extended periods. When the visibility is less than 1km, it may be termed as dust storm, or referred to as severe dust storm if the visibility is below 500m.

In Table I, further classifications and different types of storms have been summarized. According to [3], the classification was based on both the duration of the storm and the wind speed during storms. The Table also presents other important characteristics and features of sand and dust storms such as visibility and height during storms.

TABLE I: SAND AND DUST STORMS CLASSIFICATION [3]

Types	Wind speed (m/s)	Height (km)	Visibility (km)	Duration (hrs)
Haboob	11 – 21.5	0.5 – 12	0.2 – 0.4	0.5 – 6
Dust devils	5 – 10	0.5 – 2	< 1	0.1 – 0.5
Diurnal wind cycle	8 – 12	< 1	0 – 1	< 1
Frontal	9 – 17	1 – 5	0 – 1	1 – 8

Different studies such as [2] emphasized that the dielectric parameters of soil at microwave frequency bands are the functions of various properties of soil such as moisture, texture, salinity, bulk density, and temperature. Models of dust and permittivity exist reflecting certain physical and structural properties. The physical properties of the soil like texture and structure are responsible for the amount of pore space and the distribution of pore space within soil matrix. Thus, pore space and bulk density affect the dielectric properties of the moist soil in a significant manner [2].

Dust particles' permittivity property is an important component with its applications in microwave signal propagation. Permittivity is an input variable in

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electromagnetic scattering and propagation impairments such as microwave attenuation, phase rotation, antenna's accretion and beam shift effects. This development has led to the introduction of different microwave techniques to characterize the electrical properties of materials such as permittivity. However, these techniques have their peculiar merits and constraints. Although this paper does not describe a new work completely, rather it critically reviews and discusses relevant techniques and related methods of determining complex permittivity while highlighting their strengths and constraints. The paper also establishes the current state of knowledge of dust particles permittivity and suggests fresh perspective to the topic.

The paper has been written such that the theoretical concept is given in Section II. While Section III gives a detailed review of related literatures on dielectric permittivity, Section IV presents the methods and techniques for characterizing dielectric permittivity. Discussion of gaps in knowledge and the outlook in future are presented in Section V and conclusion is drawn in Section VI.

II. Theoretical Framework and Concept

Consider a material with dielectric constant which may be defined as the ratio of the permittivity of the material to the permittivity of the vacuum. The dielectric constant (k) of the material can be mathematically expressed as

$$k = \varepsilon/\varepsilon_0 \quad (1)$$

where ε is the material permittivity and ε_0 is the vacuum permittivity.

The expression, also known as relative permittivity of the material, is dimensionless because it is a ratio of similar quanta. Furthermore, the relative to free-space dielectric property of a material is a complex parameter represented as

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \quad (2)$$

where ε_r is the relative permittivity, ε_r' is the real part and ε_r'' is the imaginary part.

Relative to free space, the interaction of the applied electromagnetic field with moist grain depends on the complex dielectric permittivity.

The dielectric permittivity of a given sample is said to be its property which explains the behaviour of electromagnetic wave with the sample [2]. The complex parameter in (2) consists of its real part (permittivity) and its imaginary part (i.e. loss factor). The permittivity symbolizes the ability of the material to store microwave energy, while the loss factor is the ability of the material to absorb microwave energy.

The dielectric properties of a material depend on the concentration and activity of permanent electric dipole molecules, ionic conduction and on the degree of dipole alignment with the time-varying electric field applied.

The number of induced dipoles per unit volume defines the dielectric constant real part when a dielectric media is placed in an electric field. The dipoles seem to align with the field direction in the presence of oscillating electric field [2]. The dielectric constant and the dielectric loss of samples increase as density of the samples increase. This suggests a direct relationship between density of samples and their dielectric properties. The relation between the dielectric loss and bulk density could be attributed to increase in rotational inertia and viscosity. Thus, noticeable delay is observed between the forcing field and orientation of the dipoles. This gives more absorption power to the sample and subsequent increase in the imaginary part of the complex dielectric.

Also, suffices to mention that microwave signals can penetrate dielectric slabs or dielectric half spaces which are thick and with layers. The signals are sensitive to the properties of the layers [3]. Other related functions which the dielectric parameters of samples at microwave frequency bands depend upon include water content, temperature and salinity.

III. Dielectric Permittivity of Dust Particles

Some semi empirical models to determine the permittivity of dielectric samples have been proposed [5] –[7]. These efforts have not been completely successful. Even though the models may be useful for some mixtures, they do not hold generally. The complexity of the applications has become an issue of concern because it is nearly impossible to analytically calculate some parameters. Thus, for each type of sand or dust, the parameters need to be obtained experimentally. Often, the models employ trial and error assumptions and are rated by their ability to determine experimental data. Thus, while the first part of this section highlights some of the efforts aimed at proposing semi empirical models for determining the dielectric permittivity of sand and dust, the last part of this section focuses on the actual experimental attempts.

Some of the earlier models failed to incorporate dielectric properties of bound water which sometimes leads to notable variance between theoretical and experimental dielectric constants of moistened samples. This problem was tackled by [6] in one of their works. Based on refraction index which is a function of soil text and moisture content, a semi empirical mixing model was presented by [7] while evaluating the microwave dielectric behaviour of soil-water mixtures at 18GHz. Using a semi empirical model, [8] extended [7] model for wider validity range of frequency. It is an important model with very wide frequency bands and incorporates key variables such as bulk density, sand texture and temperature. Except for the expression of the complex dielectric constant's real part, [7] and [8] models are quite similar.

Models proposed to illustrate some physical and structural properties (e.g. [6], [7]), like some other practical or experimental approach, only considered bulk permittivity [2]. Using different techniques and mixing formula, [9] presented mean permittivity of compressed dust samples. The constraint with this technique is having to infer solid dust particle permittivity from air-mineral mixture, by applying mixing formula to bulk measurements, since the samples were not completely solid. The work carried out by [10], however, addressed the issue of bulk permittivity by considering scaled permittivity.

Lastly on the semi empirical models, some of the models were limited to isotropic mixtures often given for one shape scatterers only (spherical shape in most cases). [11] tried to address this problem. However, this attempt only gave a low frequency solution. Besides, the scattering losses were not included in the effective permittivity. Nonetheless, the dielectric constant or permittivity of a given system [12] expressed in (3) addresses some of these challenges.

$$\epsilon_{e,i} = \epsilon_a \left\{1 + v \frac{\epsilon - \epsilon_a}{\epsilon_a + A_i(\epsilon - \epsilon_a)}\right\} \qquad (3)$$

where $\epsilon_{e,i}$ is the effective permittivity of a mixture in i direction (particles of ellipse shape), ϵ is the dust's permittivity suspended in a background medium of turbulence having permittivity, ϵ_a , v is the relative volume of suspended particles and A_i is the depolarization factor also in i direction.

For the experimental works, we start with the repeated measurements of complex permittivity of scaled and bulk sand conducted by [9]. At 10GHz, the measurements were performed by observing the effect on Q-factor of a large open resonator and the resonant frequency. It is to be noted that the macroscopic refractive index of scattered dust particles, equivalent of the specific attenuation and phase rotation that the dust particle density would cause on a microwave path, was produced by this measurement. Chu [13] predicted the dielectric constant for spherical dust particle from an assumed dielectric constant premised on Rayleigh approximation method. Relatively close agreement was noted when compared with results such as those reported in [9] that used the open resonator approach. Like the work of [9] however, discrepancy was noted in the loss tangent.

Using the technique of resonant cavity, collected samples from Khartoum in Sudan were measured by [14]. Loss tangent of 0.039, a value greater than the Chu assumption, was recorded. In this work, it was observed that the collected samples did not have the same dielectric constants. This is easily attributed to the chemical compositions of the samples. Dielectric permittivity is a function of chemical composition; even as it is also found to depend on frequency and hygroscopic water content or moisture.

[15] and [16] further investigated the dependence of permittivity on chemical composition, frequency and water content (moisture). Except where metallic or magnetic minerals are present, the chemical composition of dry dust was found to have little effect on dielectric constant. The moisture or water content of the dust samples were found to depend largely on the prevailing climatic conditions of the samples' source; and a function of air humidity could affect complex permittivity too [17]. Goldhirsh [18] earlier established the dependence of real and imaginary parts of complex permittivity on moisture content in his review works of attenuation associated with dust storms. Few other studies such as [19] also submitted that water content effect is quite dominant on the imaginary part and could as well influence the values on the real part of dielectric permittivity.

Stuchly [4] also measured the complex dielectric permittivity of wet dust at X-band (9.4GHz) using a modified very-long-sample method. Measurements of the complex dielectric permittivity for four granular solids with different water bonding forces such as sand, silica gel, polyamide and mashed potato powder were carried out. In the work, two ranges of water bonding were confirmed. It was found, in the first range, that water had low permittivity because of dominant adsorption forces existing below the critical moisture content point. However, free water with high permittivity was found to be dominant in the second range.

Although frequency range is another important factor which dielectric constant depends on, however, [14] and [20] noted that the dielectric constant is not sensitive to frequency range greater than 4GHz.

Using wave-guide method, [21] measured the dielectric constant of (saline) dust sample. A significant contribution of this work was the band of frequency that was considered. In a study which appeared to be the first of its kind on millimetre wave propagation in saline sandstorms, the author carried out measurement of the permittivity properties of saline particles at W-band (94GHz). To prevent problems associated with looseness and obscurity, the dust sample was measured vertically. Even though the fundamental objective of the study was to investigate attenuation and phase shift coefficients of saline dust, the average result of the measurement given as 2.229 + j0.066 was not benchmarked against any known published theoretical or practical works.

[22] measured the dielectric constant of sand using a two-port filled wave guide method. This novel technique was a combination of near-field microwave and embedded modulated scattering. The approach recorded an average value of 2.76 – j0.03 for S-band frequency (precisely between 2.6 and 3.95GHz). The low-loss nature of the sample, however, made the computation of the actual loss factor very difficult to carry out. In other words, the technique does not work well for low loss materials. Similar difficulty in calculating the very small loss factor (i.e. the imaginary part) of complex dielectric was also reported by [10] and [23]. As such, while the real part of the complex dielectric was easily determined, the small loss factor was taken as zero. However, little variation or difference in small figures or values give a high percentage error in determining loss factor. Suffice

to mention, nonetheless, that the volume scaling formulas were still possible to be directly checked in this novel work despite the obvious limitation.

Because of the way some samples were collected and prepared, the measurement techniques adopted as well as the problem associated with bulk permittivity, both [2] and [24] contested the accuracy of many of the reported dielectric constant values. [24] tried to compile what was believed to be accurate values from the literature. This work also emphasised that that water content of dust increases the dielectric constant.

As earlier hinted, to address the problem associated with most measurements which used bulk or compressed dust samples in resonant cavity, waveguide or near-field microwave and embedded modulated scattering techniques, a novel approach was used by [10] and [23] to determine permittivity of dust sample. The measurement was at X-band frequency using Looyenga's formula. The values of permittivity representing only dust particles were estimated in [10] and further strengthened by determining the bulk and the scaled permittivity values. The results of the measurements were extensively reported in [23]. The limitations and constraints of these two works (i.e., small loss factor) have been mentioned earlier.

IV. Methods and Techniques for Characterizing Dielectric Permittivity

Measurement of complex dielectric permittivity of dust particles especially at microwave frequency bandwidth can be carried out using various methods and techniques. While Section III has presented more detailed review of the topic, some methods and techniques to determine permittivity of sand and dust are presented in this section. In other words, the section investigates and presents a review of some of the measurement methods.

Generally, the resonant methods are used in characterizing low loss materials. However, further study has shown that the resonant methods are equally applicable in characterizing high-loss materials given that very small samples are used. Unlike the non-resonant methods, the resonant methods come with better accuracy and sensitivity [1]. Although the tuneable resonant method has its application in a wider frequency band, it is nonetheless expensive. Besides, its accuracy may also fail as the frequency band increases.

[4] confirmed three main types of measuring methods used for complex dielectric permittivity especially at microwave frequencies to include the reflection, the transmission as well as the perturbation methods.

Short-open circuit is a very popular (perhaps the most popular) reflection method premised on the measurement of input impedance of a given sample in a short-open circuit waveguide. Very-long sample method is another type of reflection method. This method uses the input impedance of a long dielectric sample.

A modified very-long sample method was proposed by [4]. Unlike the very-long sample method which had hitherto been used only for measuring very high loss dielectric samples, the modified very-long sample method as proposed measured low loss dielectric samples in powdered and granular forms even for relatively short samples. The modified method claims suitability for a wide frequency range, different waveguides and transmission lines, and over a wide dielectric permittivity range.

The transmission methods are based on measuring the coefficient of complex transmission of a dielectric sample in the waveguide. The transmission-only measurement method is utilized to address the errors associated with some reflection methods. The measuring arrangement of this method is however complicated, and its accuracy is low when compared with other highlighted methods [4]. These explain why the method is less popular compared to the reflection method. The reflection method is perhaps the most widely used measurement techniques because of its relative simplicity [1].

Finally, the measurement technique based on the variation in the Q-factor and resonance frequency of a resonant cavity having a small dielectric sample is often referred to as the perturbation technique. Although the required instrumentation for this technique is complicated, the method is however useful for very small sample of a given material.

V. Discussions and Outlook for the Future

In this section, the fundamental findings are discussed while observing the existing gaps in knowledge which are expected to be bridged. Besides, outlook for future and useful recommendations are also given.

In Table II, a summary of some of the selected works on dust particle permittivity highlighting the technique, frequency range and permittivity values is given. The merits and limitations of the method and/or approach are also emphasised.

TABLE II: DUST PARTICLE PERMITTIVITY

Reference	**Method/Technique**	**Frequency**	**Permittivity**	**Remarks**
[2]	Wave guide	9.78 GHz	-	+Different bulk density
[4]	Modified very-long-sample	9.4 GHz	1.82 + j0.13 7.16 + j6.5	+Simple procedure +Wider application (frequency/permittivity) *Low accuracy.
[5]	Transmission method	5–19 GHz	_	+Extended frequency range
[6]	Modified relaxation model	0.3–37 GHz	_	+Applicable to various soils at different wetness and temperature. *Bulk measurements.
[8]	Semi-empirical model	0.3-1.3 GHz	_	*Lower frequency range.

				+Accounts for bulk density soil texture and temperature.
[10]	Looyenga's formula	X band	_	+Novel approach +Scaled permittivity
[11]	Mixing formula Quasi-static analysis model	1-3 GHz	_	+Applicable to isotropic and multiphase mixtures. *Low frequency range
[15]	Cavity and transmission line.	8.6 GHz	5.23 + j0.26	*Lower frequency range.
[18]	Open resonator measurements	10 GHz	3.35 + j0.042 7.42 + j1.119	*Bulk measurements.
[19]	Two-arm microwave bridge	37 GHz	2.515 + j0.074 2.88 + j0.0353	+Extended frequency range. *Bulk measurements.
[21]	Wave guide	94 GHz	2.229 + j0.066	+Higher frequency range
[25]	Extrapolation	14 GHz 24 GHz 37 GHz 100 GHz	5.5 + j1.3 5.1 + j1.4 4.0 + j1.33 3.5 + j1.6	+Wide frequency range. *Extrapolation of past results.
[26]	Looyenga mixture model	8-12 GHz	5.73 + j0.42	+Agrees with measured and computed values

+ strength/merit
* limitation/demerit

Numerical or semi empirical technique remains a challenge for researchers on dust particle permittivity and its application in microwave signal propagation. Besides, the empirical techniques for determining permittivity also pose unresolved questions. Development of new models or modification of existing ones to further improve the numerical and other forms of efficiencies, especially about ease of applications to analytically determine some parameters or data, will require more research efforts in the future.

Estimates of severity of cross polarization and prediction of attenuation and phase rotation can be improved by a careful study of particle permittivity. Although attenuation calculation has been extended to higher frequency, the use of bulk permittivity undermined the validity of this attempt. As such, research outlook points towards more attention on scaled permittivity with lesser focus on bulk permittivity. Also, better models of the water uptake of particles and its effect on permittivity may be useful. This has some impact on cross polarization and may be essential if attenuation of higher frequency, such as the microwave and millimetre waves, is to be considered.

Moisture content of a material is one of the most dominant factors in measuring the dielectric properties of such material in the microwave region. Moistened dust particles induce significant changes of the dielectric constant of the particles and cause higher attenuation. Optimizing microwave instrumentation for measuring the moisture content of dielectric samples requires an accurate knowledge of the relationship between the dielectric permittivity and the moisture content.

Suffice to point out that the dielectric constant and the dielectric loss of dry sand and dust are frequency dependent. Temperature is another important factor for materials with different chemical characteristics. However, except in the case of magnetic or metallic minerals, chemical composition of dry sand and dust has an insignificant effect on permittivity. Furthermore, the loss tangent decreases with particle size. This is not unexpected going by loss from adsorbed water on the outer surface sand and dust particles because of increase in volume to surface area ratio. Also, the real part of complex dielectric is a function of particle size at some given frequency range (8 – 11GHz).

In the characterization of the microwave related materials and despite the extra care and precautions required in carrying out measurement of the imaginary part of low loss materials arising from high percentage of error associated with the computations of loss factor, it is imperative to state that the iterative technique of computing the dielectric constant of dust such as the one used by [22] gives very accurate results. Other techniques such as resonant cavity method suggested to overcome the challenge of high percentage error from slight variations is also very credible.

Although it may appear to be a very difficult venture, consideration of dust particle/water system as a non-homogenous structure can be suggested. This is expected to further enhance this topic. Lastly, methods adopted for practical measuring or computing permittivity regardless, it can be suggested that the method should be applicable to a wide range complex permittivity, frequency and temperature; the method should have simple instrumentation, measurement and calculations procedures; and the method should have protection against change in sample's moisture and density during measurement to further validate and ensure credibility of obtained results.

VI. Conclusion

Complex permittivity values of dust particles are important components in predicting microwave attenuation and in turn, cross polarization. Small attenuation values are to be expected from low permittivity values and vice versa. Different sand and dust samples have different values of permittivity whose property is largely dependent on moisture content, chemical composition of the sample and frequency. Sample's permittivity is the same if the chemical composition is also similar. Difference in particle sizes does not result in change in the permittivity except because of different chemical compositions. The water content effect is important in dielectric loss such that it increases within given frequency bands.

A review of permittivity of dust particles in microwave signal propagation has been presented in this article. While it is impossible, within the scope of this review work, to provide an all-encompassing list of the very extensive reference regarding the topic, this work has demonstrated an in-depth review of the topic. The state of current knowledge of the topic has been established and existing gaps have been identified. A range of methods to determine dielectric permittivity of dust with their merits and constraints has been discussed. Relevance of permittivity to microwave signal propagation has also been implicitly mentioned. Some suggestions and recommendations on potential new research areas to explore have also been provided. Further modifications and refinements of these techniques can be expected to develop models of wider applicability and acceptance. It is hoped that the survey of the literatures as presented becomes a useful tool for researchers in this area.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The authors contribution to this work is such that Babu Sena Paul suggested the research while Abdulwaheed Musa conducted the research and wrote the paper. Furthermore, Babu Sena Paul provided technical guide and carefully proofread the manuscript for compliance and necessary corrections. Paul's cost center also provided the support grant to carry out the research. Both authors approved the final version.

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