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Dust Storms Properties Related to Microwave Signal Propagation

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Abstract: The study of electromagnetic signals propagation through dusty media (dust storms, air with suspended dust particles), requires knowledge of some of the electrical and mechanical properties of that media. The aim of this paper is to describe the dusty media properties related to microwave signal propagation, and to give numerical values and statistics of these parameters for dust storms that frequently occur in Sudan. Most of these values and statistics were measured and investigated by the author over the last thirty years. The parameters which are considered in this paper include (1) the dust particles geometry which is approximated by an ellipsoid, and its orientation when suspended in air (2) the dust particles 'particle size distribution'; which is found to follow power law; (3) visibility statistics during dust storms as observed in some towns in Sudan, and its variation with high; (4) Permittivity and depolarization factor of the dusty medium, which is derived based on Maxwell Garnett formula and (5) dusty media Propagation Constant and Phase Shift, which are needed to estimate signal attenuation and cross depolarization.

Keyword: Microwave; Dielectric constant; Propagation; Depolarization.

1. INTRODUCTION

Tropospheric propagation of microwave signal may suffer attenuation and cross polarization by the suspended particles such as dust, rain, snow, etc. The propagation of microwave signals in dust/sand storms found considerable interest recently, due the increasing number of terrestrial and satellite links established in the regions that frequently encounter dust and/or sand storms as well as many radar applications at high frequencies [1-12]. The attenuation of the microwave signals in dusty media may arise from two physical mechanisms, (i) absorption and (ii) scattering of energy by the suspended dust particles. Different models are available in the literature to predict the total cross-section efficiency (extinction), for the suspended (dust) particles. All these models require knowledge of the electrical properties of the scattering particles, i.e. dust dielectric constant, dust particles geometry, dust particles size distribution and visibility during the dust storms. The complicated interaction features of these factors increase the complexity of the prediction of the effect of dust/sand storm on microwave signal propagation. There is large degree of uncertainty about these parameters in the literature. The aim of this paper is to release these parameters as measured for dust storms in Sudan. Many of the numeric values and statistics released used in this paper measured and investigated by the present author over the last thirty years. Although some of these results were published before, this paper releases some new results concerning the dusty media polarization, dust particle axial ratio distribution, etc.

Dust particle size distribution investigated by different researchers [13-22]. Many of these works focused on small particles size with radius less than 10μm. Generally, these particles have small effect on microwave (millimeter wave) propagation, and they are important for pollution or optical extinction studies. In order to predict the attenuation due to dust storms, Ghu [1] assumed a model with equalized particle distribution, which is an unrealistic model. Ghobrial [3] reported an exponential distribution for only on sample. Abobakr *et al*. [18] showed that for dust collected at Riyadh, Saudi Arabia, the particle size distribution follow normal or lognormal distribution and vary with dust storms. Generally, the distribution reported in the literature varied considerably and no clear pattern can be predicted.

Different values are reported in the literature for the dust dielectric constant. These values are measured by different techniques at different frequency bands and experimental conditions [23-27]. These values will be reviewed in this paper. In addition values for dust dielectric constant measured the x-band by the present author will be released, and the effect of air relative humidity on the dust dielectric constant will be investigated. Since the propagation of microwave signal in dust/sand storms depend on the visibility, the visibility statistics investigated in some cities in Sudan.

2. Dusty Particles Geometry and Alignment

Dust particles have random irregular shapes without any particular symmetry. The dust particle shape may vary from needle-like to almost perfect sphere or disc. Different complicated particle geometries are reported in the literature [18, 19]. All scattering models depend on regular particles shape. The shape of dust particles is investigated by the present author. Dust particles as seen under microscope have random geometry and cannot be described by one simple geometry. As mentioned above, the prediction of dust storm effect on microwave propagation requires assuming simple geometry for the scattering particles.

Although dust particles are far from being ellipsoid; this geometry has three degrees of freedom, and it gives good approximation to the shape of realistic dust particles, Fig. 1.

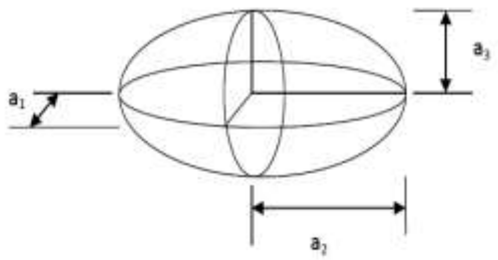

Fig. 1 Dust Particle Geometry Approximation

The present author investigated the aspect ratios of the three axes, a_1, a_2 and a_3, see Fig. 1. The probability distributions functions of these ratios are shown in Fig. 2 and 3. The axial ratio is best fit with normal distribution of variance equal to 2, and defined by:

$$f(r) = \frac{1}{2\sqrt{2\pi}} e^{-\frac{(r-\mu)^2}{8}} \qquad (1)$$

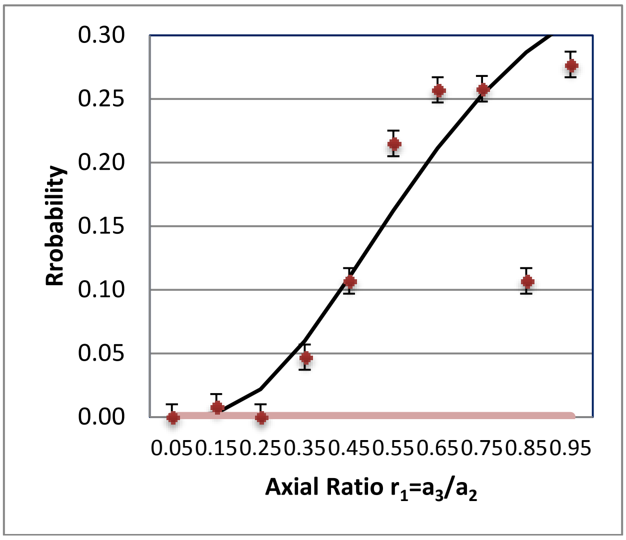

Fig. 2. Axial Ratio $r_1=a_3/a_2$

where μ is the average axial ratio and σ is the standard deviation. For the ratio a_3/a_2 the average is 0.75 and the standard deviation is 0.7, and the average axial ratio a_2/a_1 is 0.71, with standard deviation 0.64. The average ratio of the axes is given by $1:r_2:r_3$ = 1:0.71:0.53; where

$$r_2 = \frac{a_2}{a_1} \; and \; r_3 = \frac{a_3}{a_1} = \frac{a_3}{a_2}\frac{a_2}{a_1} \qquad (2)$$

In stationary air condition, particles, which assumed ellipsoid shape, fell with the shortest axis vertical and the two other axis are randomly oriented in the horizontal plane, However, it is well known that turbulent air flow is present During dust and sand storms, this situation results in random orientation of the dust particles. Fig. 4, shows the dusty medium model used in this study. In this model the electromagnetic wave is propagated in the positive z direction.

It is worth mentioning that, in this work the term "*dusty medium*" is used to classify air with suspended soil particles and at least 80%, by weigth, of these particles have equivalent radius less than 30 µm. If more than 20% of the air borne particles has diameters greater than 60 micron the storm is called sand storm. [6].

3. Particle Size Distribution

Measurement to determine particle size distribution (psd) is carried out on ten dust samples. These samples collected were from different cities at central and northern Sudan. The hydrometer and pipette methods [28] were used to determine the samples psd. Generally, the results obtained by hydrometer and pipette techniques are expected to have an error in the range from 5% to 10%. This error arise from many reasons include the fact that calculations are based on Stock's law of sedimentation, which assume spherical particles. In fact, dust particles have irregular random shape as shown in section II above. On the other hand these methods are the most suitable techniques to determine the dust psd, since the particles size in dust varies over wide range. Sieving was used to determine the fraction of samples mass composed by particles with radii greater than 32 µm.

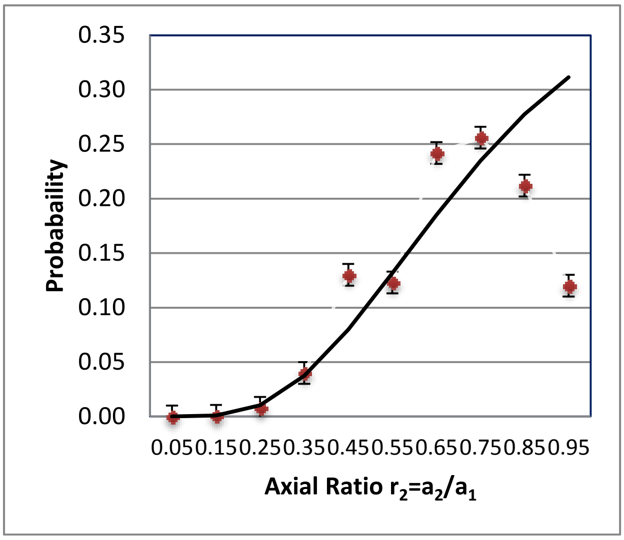

Fig. 3. Axial Ratio $r_2=a_2/a_1$

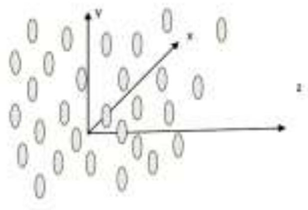

Fig. 4. Dusty Medium Model

Fig. 5 shows the psd cumulative curves for two samples collected at Khartoum in 1982, as determined by the above techniques, (for more psd cumulative curves see [19]).

It is clear that the psd cumulative curses follow straight line equation (model), given by:

$$n(r) = a_o + a_1 r \quad (3)$$

where $n(r)$ is the fraction by weight composed by dust particles having equivalent radius less than r µm , a_o and a_1 are constants which depend on the factor characterizing the dust psd.

The least square method is used to estimate the values of the constants a_o and a_1. The obtained values are shown in [19]. From these results it is noticed that, the constant a_1 is always in the range from 0.0055 to 0.0098, and has an average value of 0.0072. The constant a_o always lies in the range from -0.3551 to 0.0460, and has an average value of 0.0144.

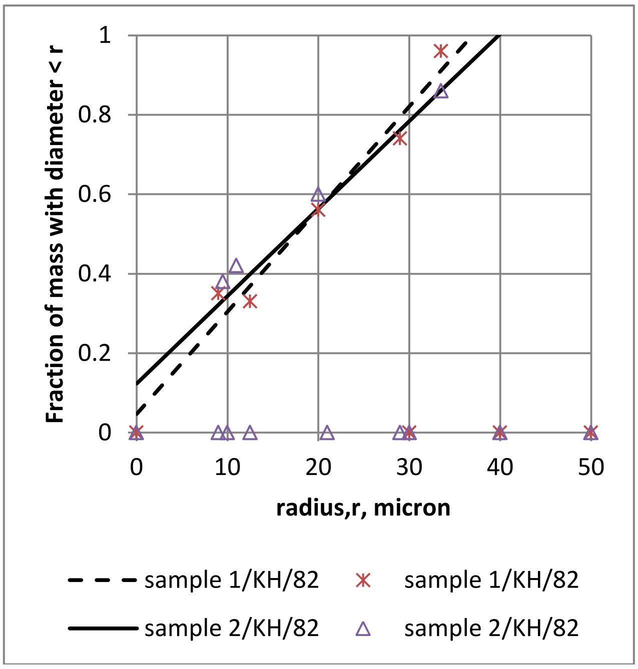

Fig. 5. Dust psd cumulative curves

It is noticed from the results in [19], that the constant a_o has negative value for some dust samples. These values are not logical since the mean sample contain some particles with negative radius. However, the negative values for the a_o rise from the fact that the presence of particles with radii less than 0.2 µm makes the behavior of the curve in this region uncertain, due to the fact that Stokes' theorem cannot be applied for particles in this range.

Considering the mass element δm composed by particles with radii in the range from r to r+δr, in a dust sample of M kg, thus by using (3) we have:

$$\delta m = M a_1 \delta r \quad (4)$$

Thus, the volume, δv, occupied by dust particles with radii in the range from r to r+δr, in terms of dust density, ρ_s is given by

$$\delta v = \frac{M a_1}{\rho_s}\,\delta r \quad (5)$$

Now let N' be the number of dust particles with radii in the range from r to r+δr. By using the volume of the sphere the volume occupied by these particles is

$$\delta v = \frac{4\pi}{3} r^3 N' \quad (6)$$

From (3) and (4) we get:

$$N' = \frac{3}{4\pi}\frac{M a_1}{\rho_s}\frac{1}{r^3}\delta r \quad (7)$$

For unit mass dust sample, M $=\rho_s$, and if small interval (r, r+ δr) is considered, N' = N(r)dr; where N(r) is the total number of dust particles having radii less than r. Thus (6) is written as:

$$N(r)dr = N' = \frac{3}{4\pi}\frac{1}{r^3}\delta r \quad (8)$$

From (8), the total number of dust particles is given by

$$N_T = \frac{3}{4\pi}\int_{r_o}^{r_h}\frac{1}{r^3}\,dr = \frac{3}{8\pi}\left[\frac{1}{{r_o}^2} - \frac{1}{{r_h}^2}\right] \quad (9)$$

Here r_o and r_h are the minimum and maximum radius of dust particle respectively.
The probability that the radius of the dust particle in the interval (r,r+ δr) , can be obtained from (7) and (8) as:

$$\frac{N(r)dr}{N_T} = 2\frac{{r_o}^2{r_h}^2}{{r_h}^2 - {r_o}^2}\cdot\frac{1}{r^3} \equiv \frac{a_2}{r^3} \quad (10)$$

Thus, the probability of density function of the dust psd is given by:

$$n(r) = \frac{a_2}{r^3} \quad (11)$$

Generally, dust psd can be fairly approximated by the straight line model discussed above, with the assumption that when the constant a_o is negative, the smallest theoretical value of the radius (i.e. 0.2 µm) is taken as the minimum radius in the sample. From these models, the minimum radius of the dust particle is always in the range from 0.1 µm to 9 µm, and has an average value of 3.125 µm, while the maximum radius of the dust particles is within the range 34 µm to 42 µm, and has an average value of 38 µm. Using this average values the constant a_2 is given by 1.97×10^{-2}.

4. Visibility Statistics

Table 1 gives the visibility statistics for four towns in Sudan, namely Khartoum, AbuHamad, Elobied and Atbara. The table shows the total annum time visibility is within range indicated. These statistics are obtained from the Sudanese Meteorological Department. The observation was carried out during the period from 1975 and 1980. These visibility observations were made over a period of five years.

The average total annum time visibility V is less than X m, $F(V < X)$, in the four mentioned towns and based on the results shown in Table 1, can be approximated by the following exponential function, Fig. 6

$$F(V) = 1000e^{-\frac{13}{V}} \tag{12}$$

It is noted that from these data, the visibility is less than 1 km for about 0.8% of the time per annum.

V. The Effect of Height on Visibility

The study of the effect of dust storms on the performance of earth satellite links requires knowledge of the variation of the visibility with height. The number of particles suspended per unit volume of air, (relative volume), represents one of the important factors required to compute the dusty medium parameters. In practice, visibility during dust and sand storm is used as a measure for storm severity rather than the dust relative volume. Thus, for convincing and practical reasons, in this work the visibility ie used to estimate the climatic conditions, meteorological factors and the dust particle size distribution.

Table 1. Visibility statistics in Sudan

Visibility (m)	Hrs/Annum			
	Khartoum	AbuHamad	Elobied	Atbara
0 - 100	3.80	0.61	2.37	0.79
100-200	5.40	4.82	4.03	1.59
200-300	6.13	4.03	6.22	1.60
300-400	7.27	7.53	3.77	6.18
400-500	6.75	2.45	4.20	3.85
500-600	8.41	15.16	4.56	6.75
600-700	3.77	19.62	2.63	8.76
700-800	2.63	6.83	0.35	10.16
800-900	21.64	17.34	13.67	17.43
900-1000	0.79	9.11	1.40	4.38

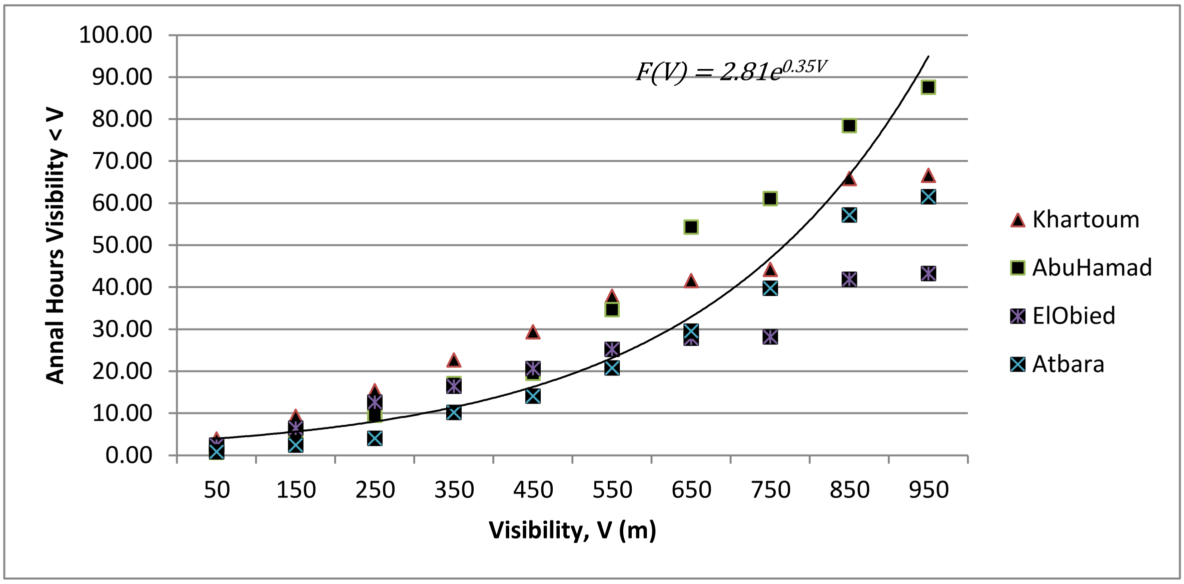

Fig. 6. Visibility Statistics in Sudan

It is well known that visibility during dust storms decreases as the height increases. Chepil and Woodruff [29] gave the following empirical relationship between the dust mass concentration (M, kg/m^3) and the height (h, m):

$$M = \frac{a}{h^b} \qquad (13)$$

where a and b are constants. These constant depend on the climatic conditions, meteorological factors and the dust particle size distribution.

Patterson and Gillete [30] relate the dust mass concentration and visibility, at the height h during the dust storms by:

$$MV^{\gamma} = C \qquad (14)$$

where C is a dimensional constant (kg/m^3) and γ is a dimensionless constant. In Central and northern Sudan dust storms are not generally locally generated and the tropical climatic conditions dominate. Thus, under these conditions, the values C= 2.3x10-5 kg/m3 and γ =1.07 are applicable [30]. By substituting for M from (11), (12) can be written in terms of visibility as:

$$V^{1.07} = C\frac{h^b}{a} \qquad (15)$$

let V_o be the visibility at some reference height h_o. Thus (13) can be written in the form:

$$V = V_o\left[\frac{h}{h_o}\right]^{\frac{b}{1.07}} \qquad (16)$$

Chepil and Woodruff [30] gave an average value of 0.28 for the constant b. This value will be used in this work. The Sudanese Meteorology Department measures visibility at a height of 15 m. Using this reference height in (16); i.e. h_o=15 m, and substituting for the constant b, the variation of visibility with high is given by:

$$V = 3V_o h^{0.26} \quad \text{(km)} \qquad (17)$$

In this expression h is km.

Fig. 7 shows the variation of the visibility with height for different reference visibilities. From these plots, it is noticed that for reference visibility is greater than 300 m, the storm visibility becomes greater than 1 km at a height of about 300 m.

VI. Dust Dielectric Constant

As mentioned before, different values are reported in the literature for the dielectric constant of dust. These values are measured by different techniques at different frequency bands and experimental conditions [23-27]. Reviewing the reported dielectric constant values and the techniques used to obtain them, one concluded that many of the reported measurement techniques may be considered as inaccurate either due to the technique used or the way adopted to prepare and collect the samples. The dust dielectric constant values shown in Table 2 are seen to be the most accurate and reasonable values reported in the literature.

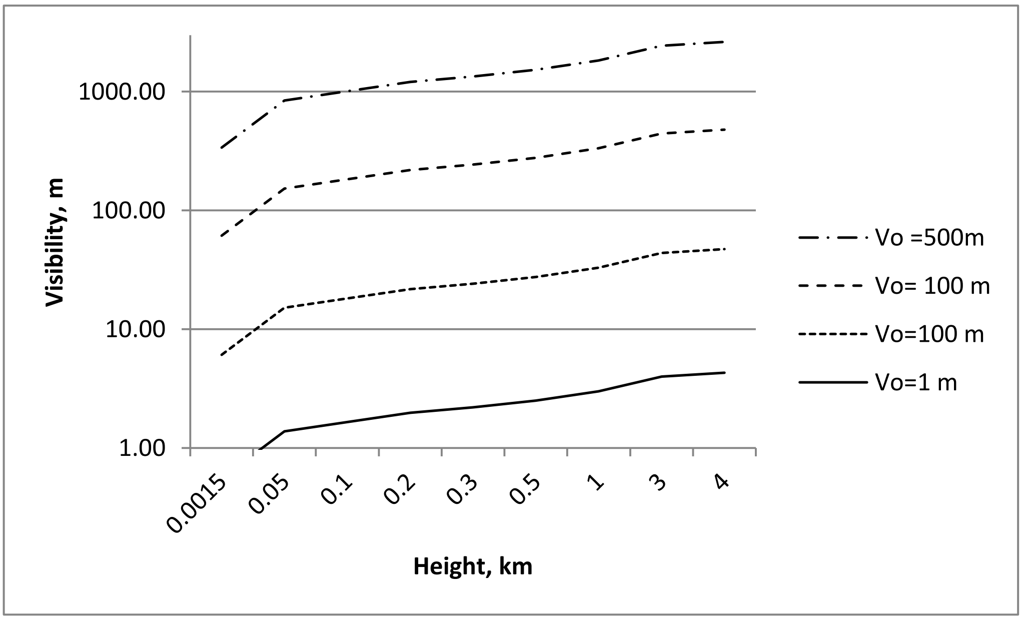

Fig. 7. Variation of Visibility with Height

Measurements on dust samples collected in Khartoum, Sudan, showed that in air with 82% relative humidity, dust absorbs 5.1% by weight moisture [3,23,24]. The moisture content of dust seriously increases the dust dielectric constant. The dust dielectric constant in air with H% relative humidity ($\epsilon_H' + j\epsilon_H''$) can be measured by [25]:

$$\epsilon_H' = \epsilon' + 0.04H - 7.78x10^{-4}H^2 + 5.56x10^{-6}H^3 \quad (18a)$$

$$\epsilon_H'' = \epsilon'' + 0.02H - 3.71x10^{-4}H^2 + 2.76x10^{-6}H^3 \quad (18b)$$

where ($\epsilon' + j\epsilon''$) is the dry dust dielectric constant

Table 2. Dust Dielectric Constant

Band	Frequency Range GHz	Dielectric Constant	Reported by
S	2-4	4.56 +j0.251	Gobrial [3]
X	8-12	5.73+j0.415	Sharif [25]
Ku	12-18	5.50+j1.300	Ruike etal [11]
K	18-26.5	5.10+j1.400	Ruike etal [11]
Ka	26.5-40	4.00+j1.325	Ruike etal [11]
W	56-100	3.50+j1.640	Ruike etal [11]

VI. Dusty Medium Permittivity

As mentioned above, the dusty medium composed of dust particles with radii less than 35 μm suspended in air. If $\epsilon_{e,i}$ is effective permittivity of a mixture in i direction, composed of ellipsoid particles with permttivity ϵ suspended in medium having permittivity ϵ_a . Maxwell Garnett formula estimated this effective permittivity as [31]:

$$\epsilon_{e,i} = \epsilon_a \left\{1 + \nu \frac{\epsilon - \epsilon_a}{\epsilon_a + A_i(\epsilon - \epsilon_a)}\right\} \quad (19)$$

Where ν is the suspended particles relative volume and A_i is the depolarization factor in the i direction. Since the dust particles assumed ellipsoid particles, the dipole moment induced on the dust particles depends on the direction of the electric field that excite the particles. Thus the dusty medium classified as an isotropic medium, in which the permittivity depend on the direction.

For air medium, $\epsilon_a = 1$, thus (19) reduced to

$$\epsilon_{e,i} = 1 + \nu \frac{\epsilon - 1}{1 + A_i(\epsilon - 1)} \quad (20a)$$

$$\epsilon_{e,i} = 1 + \nu\xi_i \quad (20b)$$

Where ξ_i is the normalized polarizability, (divided by volume and permittivity of free space), of the dust particles in the i direction. Polarizability measures the ability of the particles to acquire a dipole moment in an electric field E.

Generally, the relative volume, ν, of dust disperses in air during dust storms, much less than unity even for very low visibilities. This volume depends on the number of suspended dust particles. It represents one of the important factors required to compute the dusty medium propagation constants. In practice, visibility during dust and sand storm is used as a measure for storm severity rather than the dust relative volume. Dust relative volume, ν , is related to visibility , (V, km), during the storm by [8]:

$$\nu = \frac{9.43x10^{-9}}{V^{1.07}} \quad m^3/m^3 \quad (21)$$

Substitute for the relative volume in (20), the dust medium effective permittivity in the i direction is given in terms of visibility and depolarization factor as

$$\epsilon_{e,i} = 1 + \frac{9.43x10^{-9}}{V^{1.07}}\xi_i \quad (22)$$

VII. Dusty Media Depolarization Factor

Consider the ellipsoid geometry shown in Fig. 1, with the semiaxes fall in the order $a_1 > a_2 > a_3$, (a_1, a_2 *and* a_3 are orthogonal directions). The depolarization factor in the i direction is given by:

$$A_i = \frac{a_1a_2a_3}{2}\int_0^\infty \frac{1}{(s+a_i^2)\sqrt{(s+a_1)(s+a_2)(s+a_3)}}ds \quad (23)$$

Integrating (23) we get

$$A_i = \frac{r_2r_3[F(x,m) - \prod(n,x,m)]}{\sqrt{1-r_2^2(1-r_i^2)}} \quad (24)$$

where $F(\phi,k)$ *and* $\prod(n,x,m)$ are incomplete elliptic integral of the first kind and third kind respectively [32-36], with

$$x = \sqrt{1-r_2^2}; 0 < x < 1 \quad (25a)$$

$$m = \frac{1-r_2^2}{1-r_3^2} < 1 \quad (25b)$$

The depolarization factor in the 1, 2 and 3 directions are obtained as follows.

$$A_1 = \frac{r_2r_3}{\sqrt{1-r_3^2(1-r_2^2)}}[F(x,m) - E(x,m)] \quad (26a)$$

$$A_3 = \frac{r_2^2}{r_2^2 - r_3^2} - \frac{r_2r_3}{(r_2^2 - r_3^2)\sqrt{1-r_3^2}}E(x,m)$$

$$= \frac{r_2}{r_2^2 - r_3^2}\left[r_2 - \frac{r_3}{\sqrt{1-r_3^2}}E(x,m)\right] \quad (26b)$$

Generally, it is not easy to solve the elliptic integral since their solution involves some numerical methods. Fig, 8a and 8b, show plots of the Elliptic integral of the first kind and of the second kind showing the different ellipsoid axial ratio r_1 and r_2.

The above expression used to determine the depolarization factor for dusty medium, i.e. ellipsoid dust particles uspended in air. The results shown in Fig. 9a and 9b for A_1 and A_3, respectively.

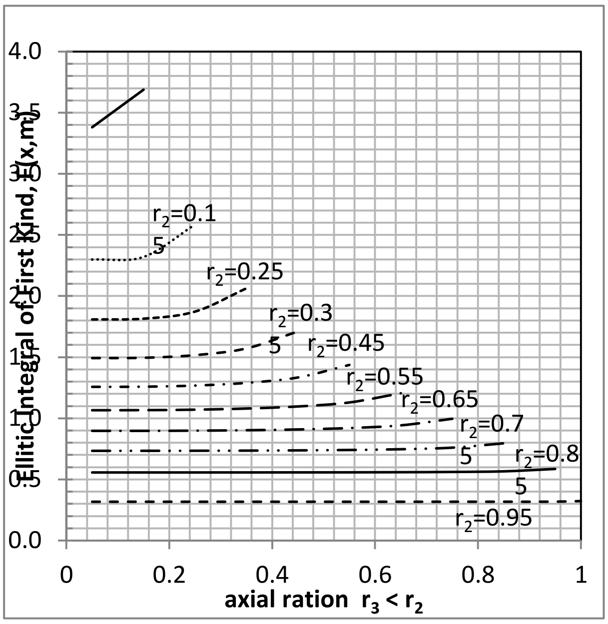

Fig. 8a: Solution of Elliptic Integral of First Kind

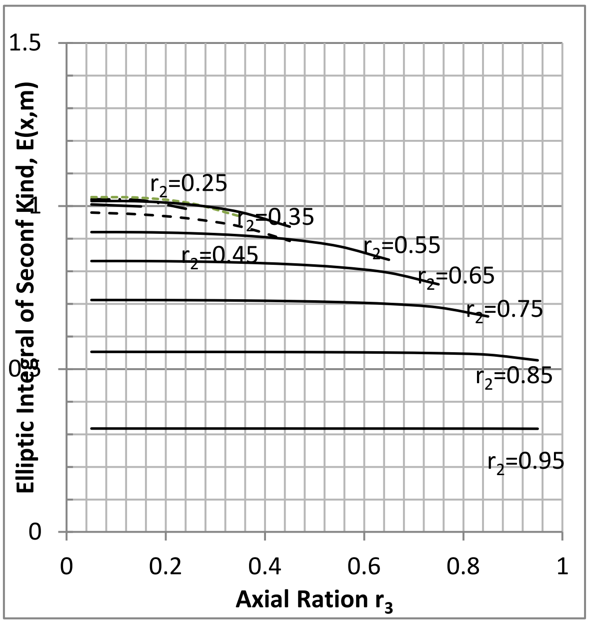

Fig. 8b: Solution of Elliptic Integral of Second Kind

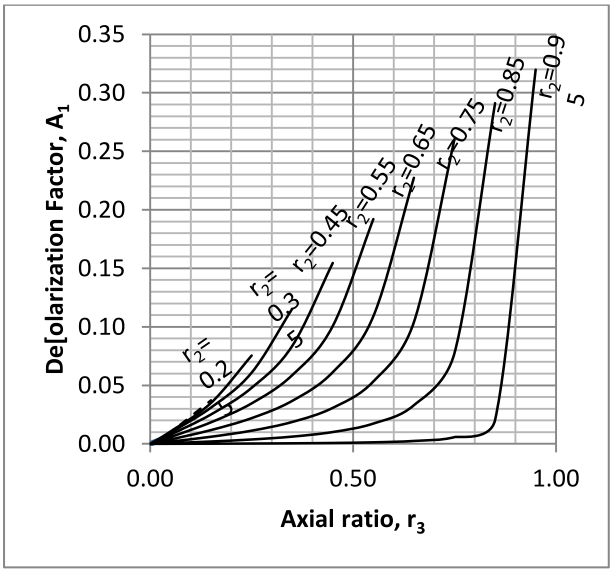

Fig. 9a. Dusty Medium Depolarization factor in the direction 1

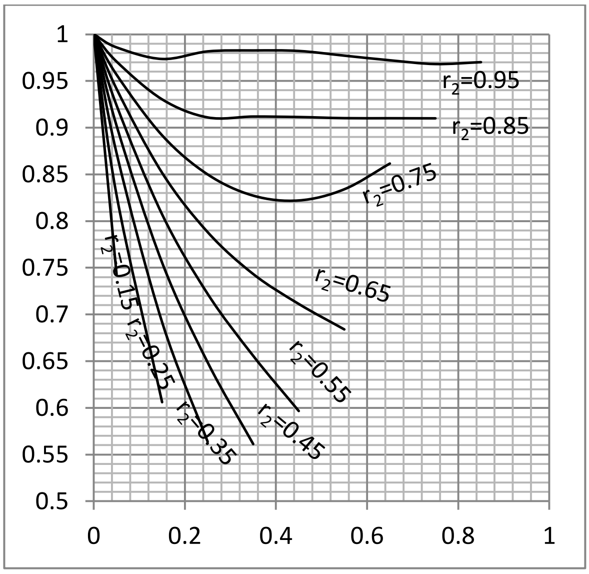

Fig.9b. Dusty Medium Depolarization factor in the direction 3

VIII. Propagation Constant and Phase Shift

The propagation constant is a measure of the change undergone by the amplitude of the wave as it propagates in a given direction through the medium. The propagation constant depends on the frequency and the medium effective permittivity. In the i direction constant is given by:

$$\alpha_i + j\beta_i = j\frac{\omega}{c}\sqrt{\epsilon_i} \quad (27)$$
$$= j\frac{2\pi}{\lambda}\sqrt{\epsilon_{e,i}}$$
$$= j\frac{2\pi}{\lambda}\sqrt{1+\nu\xi_i}$$

where α_i is the attenuation constant in the i direction,
β_i is the phase constant in the i direction,
λ is the wavelength.

Solving (27) one get:

$$\alpha_i = \frac{\pi}{\lambda}Im[\nu\xi_i] \quad (28a)$$
$$\beta_i = \frac{2\pi}{\lambda}\left\{1+\frac{1}{2}Re[\nu\xi_i]\right\} \quad (28b)$$

The phase shift per unit length of the path for the wave travelling in dusty medium in the i direction can be obtained directly from (28) as:

$$\varphi_i = \frac{\pi}{\lambda}Re[\nu\xi_i] \quad (29a)$$

$$\xi_i = \frac{\epsilon-1}{1+A_i(\epsilon-1)} \quad (29b)$$

As shown above the dust particles axial ratio is not constant. Thus (29) shall be modified to handle the variation in the axial ratio.

Since the dust particles will align with the longest axis vertical, thus only the ratio r_2 is needed. Let $A_i(r)$ be the depolarization factor in the direction i due to particles with axial ratio in the range $r_i \leq r \leq r_i + \delta r$. The depolarization due to these particles is given by

$$\delta\xi_i = \frac{\epsilon-1}{1+A_i(r)(\epsilon-1)} \qquad (30)$$

Thus the total polarization is given by

$$\xi_i = \int_{r_i=0}^{1} f(r)\ \frac{\epsilon-1}{1+A_i(r)(\epsilon-1)} \qquad (31a)$$

$$\xi_i = \int_{r_i=0}^{1} \frac{1}{2\sqrt{2\pi}} e^{-\frac{(r-\mu_i)^2}{8}} \frac{1}{a+bri+cri+\frac{1}{(\epsilon-1)}} \qquad (31b)$$

It is clear from this results that, the computation of the dusty media depolarization and permittivity is not simple and need some effort.

IX. CONCLUSIONS

This paper revealed and investigated the electrical and mechanical properties of dusty media needed to study the propagation of microwave signals in such media. Here dusty media is defined as air with suspended soil particles and at least 80%, by weigh, of these particles have equivalent radius less than 30 µm. The parameters which are considered in this paper include:

1. Dust particles geometry, which is best approximated by an ellipsoid, the ellipsoid axis ratio distribution are best fitted with normal distribution with variance 2. The average ratio of the axes is given by $1:r_2:r_3$ = 1:0.71:0.53. The dust particles orientation when suspended in study air, is assumed with the longest vertical, and the other two axes randomly are oriented in the horizontal plane.
2. Dust particles 'particle size distribution'; which is found to follow power law, (power 3).
3. Visibility statistics during dust storms as observed at some towns in Sudan, show that: the visibility is less than 1 km for about 0.8% of the time per annum in Sudan. A model was derived for the variation of visibility with height;
4. Expressions are derived for the dusty media permittivity, and depolarization factor. The expression derived based on Maxwell Garnett formula. Using these parameters the media propagation constant (propagation constant and phase shift) can be computed. The depolarization factor computation involves solution of the first and the second kind Elliptic integral. Approximation for these integrals are given in the paper. However, the computation of the dusty media depolarization and permittivity is not simple and it need some efforts.

REFERENCES

[1] Chu T. S. Effects of Sandstorms on Microwave propagation, *The Bell System Technical Journal, Vol. 58, No. 2, 1979*.

[2] Neves, J. and Watson, P. A, "Cross-polarization, differential attenuation and differential phase shift measured on a 36.5 GHz terrestrial link", *URSI Commission F Symp., Canada, preprints, pp 5.1.1-5.1.6, 1980.*

[3] S. I. Ghobrial, "The effect of sand storms on microwave propagation," in *Proc. Nat. Telecommunication Conf.*, vol. 2, Houston, Texas, 1980, pp. 43.5–43.5.4.

[4] Goldhirsh, "A parameter review and assessmof dusty medient of attenuation and backscatter properties associated with dust storms over desert regions in the frequency range of 1 to 10 GHz, ", *IEEE Trans. Antenna Propagat. Vol. AP-30 No. 6, pp 1121 - 1127, 1982.*

[5] Ansari, A. J. and Evans, B. G., "Microwave propagation in sand and dust storms", *Inst. Elect. Eng. Proc., VI, vol. 129, pt. F, No. 5, 1982.*

[6] S. I. Ghobrial and S. M. Sharif, "Microwave Propagation in Air with Suspending Dust Particles"; *International Symp. On Antenna and EM Theory, ISAE'85, China, 1985.*

[7] Bashir, S. O. and McEwan, N. J., "Crosspolarization and gain reduction due to sand or dust on microwave reflector antennas", *Electron. Lett., Vol. 21, No. 9, pp. 379-380, 1985.*

[8] Ghobrial, S. I and Sharif S. M., "Microwave attenuation and cross polarization in duststorms", *IEEE Trans. Antenna Propagat. Vol. AP-35, pp 418-425, 1987.*

[9] J. A. Jervas and S. M. Sharif, "Influence of Dust Storms and Reflector Tolerance on Cross Polarization of Earth Satellite Links", *Proc. Arabsat Symp., Riyadh, Saudi, pp. 166-169, 1988*

[10] S. M. Sharif, "Clutter and Backscattering of Dust Storms at the X-band", *Sudan Engineering Society Journal, Vol.41, No.34, pp 31-36, 1997.*

[11] Yang Ruike, Wu Zhensen and You Jinguang, "The Study of MMW and MW Attenuation Considering Multiple Scattering Effect in Sand and Dust Storms at Slant Paths", International Journal of Infrared and Millimeter Waves Volume 24, Number 8, 2003, pp:1383-1392,

[12] Ansari, A.J. Evans, B.G. , Microwave propagation in sand and dust storms, Communications, Radar and Signal Processing, *IEE Proceedings F, Vol: 129 No: 5, pp. 315 – 322, 2008.*

[13] Dominik, C., Gail, H.-P., and Sedlmayr, E. "The size distribution of dust particles in a dust-driven wind", Journal of Astronomy and Astrophysics, vol. 223, no. 1-2, 1989, p. 227-236.

[14] Prospero, J. M., "Atmospheric dust studies on Barbados", Bulletin Am. Meteor. Soc. 49, 1968, pp.645.

[15] Delany A. C., Parkin D. W., Griffin J. J., Goldberg E. D. and Reimann, B. E. F., "Airborne dust collected at Barbados, Geochim. Cosmochim. Acta 31, 1967, pp. 885

[16] Prospero J. M. and Bonatti E., "Continental dust in the atmosphere of the eastern Equatorial Pacific", J. Geophys. Res. 74. 2969, pp. 3362

[17] Zhuang Guoshun, Guo Jinghua, Yuan Hui and Zhao Chengyi, "The compositions, sources, and size distributi'on of the dust storm from China in spring of 2000 and its impact on the global environment, *Chinese Science Bulletin* Vol. 46 No. 11 June 2001

[18] Abobakr S. Ahmed, Adel A. Ali and Mohammed A. Alhaider, "Measurement of atmospheric particle size distribution during sand/duststorm in Riyadh, Saudi Arabia", Atmospheric Environment (1967), Volume 21, No. 12, 1987, pp. 2723-2725.

[19] S. M Sharif**,** S. M., "Dust Particle-Size Distribution", International Geosciences and Remote Sensing Symp., IGARRS'87, Ann Arbon, Michigan, USA, 1987.

[20] Ghobrial, S. I., Sharif, S. M., Ateem M. E. and ElTigani, M.,"Dust Storms in Sudan: Intensity and Particles; Characteristics", Proc. Jordan IEEE'85 Conf., Jordan, 1985, pp. 326-328.

[21] Alfaro, S.C., A.Gaudichet, L.Gomes, and M. Maillé, Modeling the size distribution of a soil aerosol produced by sandblasting, *J. Geophys. Res*, *102*, 11,239-11,249, 1997.

[22] Arimoto, R., B. J. Ray, N. F. Lewis, U. Tomza, and R. A. Duce, Mass particle size distributions of atmospheric dust to the remote ocean, J. Geophys. Res., 102, 15,867– 15,874, 1997.

[23] Ghobrial, S.I.; Effect of hydroscopic water on dielectric constant of dust at X-band, Electronics Letters, Vol.: 16, No. 10, pp: 393 - 394

[24] S. M. Sharif and S. I. Ghobrial, "X-Band Measurements of Dust Dielectric Constant", Proc. IRSI Commission F, 1983, Symp., Belgium, 1983, pp. 143-147

[25] S. M. Sharif, "Chemical and Mineral Composition of Dust and Its effect on Dielectric Constant", IEEE Trans. On Geosciences and Remote Sensing, Vol. 33, No. 2, pp 353-359, 1995.

[26] F. E. Geiger and D. Williams, "Dielectric Constants of Soils at Microwave Frequencies,", NASA Tech. Docu. NASA-TM-X-65 987.

[27] Stuchly, S. S, "Dielectric properties of some granular solid containing water", J. Mircowave Power, Vol. 5, No. 2, pp. 62-68, 1970.

[28] Arpad Kezdl: "Handbook of soil mechanics, vol. I, soil physics"; Elsevier Scientific 1974.

[29] Chepil, W. S. and Woodruff, N. P., "Sedimentary Characteristics of Dust Storms-II: Visibility and Dust Concentration", Am. J. Sci., 255, pp. 104-114, 1957.

[30] Patterson, E. M. and Gillete, D. A., "Measurement of visibility vs. Mass Concentration for Air Borne Soil Particles", Atmospheric Environment, Vol. 11, pp. 193-196, 1977.

[31] J. C. Maxwell-Garnett, Philos. Trans. R. Soc. London, Ser. A 203, 385 _1904_.

[32] Werner S Weiglhofer, Electromagnetic depolarization dyadics and elliptic integrals J. Phys. A: Math. Gen. 31 7191, 1998.

[33] D. S. Jones. Scattering by inhomogeneous dielectric particles. Quart. J. Mech. Appl. Math., 38, 135_155, 1985.

[34] R. C. Jones. A generalization of the dielectric ellipsoid problem. Phys. Rev.,68(3_4), 93_96, 1945.

[35] L. D. Landau, E. M. Lifshitz, and L. P. Pitaevski_i. Electrodynamics of Continuous

[36] Media. Pergamon, Oxford, second edition, 1984.