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# Investigation of Forces Affecting Dust Particle Alignment in Cross Polarization

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***Abstract*— This paper implicitly discusses method of using dual orthogonal polarizations to optimally conserve frequency spectrum. This has, in the recent time, received considerable interest in the field of electromagnetic wave propagation in sand and dust storms. The realization of a dual-polarized system is thus 1imited by degree of cross polar discrimination (XPD) that can be achieved between the two orthogna1 channels. Cross polarization discrimination is a parameter widely used to quantify the effects of polarization interference. Aside from non-sphericity of falling dust particles, dust induced microwave cross polarization has been attributed to tendency of the particles to align in a particular direction. This paper investigates and identifies important forces acting on the alignment which are inputs to the cross polarization discrimination evaluation. The method adopted involves the use of reliable measure of turbulence shear, inertial torque and Brownian motion effects. The result obtained shows the influence of the relevant forces on the alignment of the dust particles. Inertial torque becomes a domineering force for systematic alignment at some particle size range.**

***Keywords—cross polarization; microwave propagation; particle alignment; dust storms; inertial torque; turbulent torque; Brownian force.***

## I. Introduction

Research in the field of electromagnetic wave propagation in sand and dust storms is an expansive area. Efforts made by various authors [1– 6] to estimate cross polarization (XP) due to dust storms revealed that heavy XP can be induced by dust particles. Dust induced XP occurs due to the non-sphericity of the falling dust particles and the tendency of the particles to align in a particular direction at a time [1 – 4]. Lack of information on the shape and especially the alignment of dust particles noted and demonstrated by the past investigators of XP [4, 7] have made adequate knowledge of dust particle shapes and alignment along propagation path become important.

Electromagnetic wave propagated through a non-spherical particle usually changes its polarization as it travels [8]. If the XP is high enough, different information channels can be transmitted with the same frequency; thus increasing channel capacity and minimizing frequency separation. The isolation between the channels could be excellent in free space. However, in a transmission medium filled with precipitation particles (rain, snow, dust storms etc.), the isolation usually degrades. The realization of a dual-polarized system is thus 1imited by degree of cross polar discrimination (XPD) that can be achieved between the two orthogna1 channels. XPD is a parameter widely used to quantify the effects of polarization interference. This method of conserving the frequency spectrum has received attention in the literature [1-2, 8-9].

McEwan and Bashir [4] attempted a theoretical treatment of the alignment predicting that certain particles will align with long axes horizontal. However, there exists a problem of overestimation of the forces responsible. The present work investigates the forces causing the alignment. The method adopted in tackling this problem involves the use of more reliable measure of turbulence shear found in the literature, inertial torque and Brownian motion effects. Thus, the tendency to overestimate the inertial torque is corrected and the behaviour of the azimuths of horizontal axes is predicted. Lastly, the numerical results obtained show that there exists some form of systematic alignment of particles in the most relevant size range that was considered.

## II. Theoretical Development

### A. Reynolds Number

In fluid flow, Reynolds number is an important dimensionless number. It expresses the ratio of inertial forces to the viscous forces and is used to characterize different flow regimes within a similar fluid. Its value serves as a criterion for the stability of laminar flow. Laminar flow occurs at low Reynolds numbers where viscous forces are dominant. Low Reynolds values are characterized by high stability and constant fluid motion. Turbulent flow occurs at high Reynolds numbers and is dominated by inertial forces which tend to produce flow instabilities [10]. The Reynolds number is expressed thus:

$$Re = \frac{\rho U d}{\mu} \tag{1}$$

where $\rho$ is the density of the fluid $\left(kg/m^3\right)$, $U$ is the fluid velocity $\left(m/s\right)$, $d$ is a characteristic length of the system (m) and $\mu$ is the dynamic viscosity $\left(Nsm^{-2}\right)$.

The Reynolds number is also important in determining the fall velocity of a particle. This is the velocity at which the applied force matches the drag force. It is also referred to as terminal settling velocity. When the particle Reynolds number indicates laminar flow, Stokes' law can be used to calculate its fall velocity. However, if Reynolds number indicates turbulent flow, a turbulent drag law must be constructed to model the appropriate settling velocity. This is also demonstrated in this work.

### B. *Forces Affecting Particle Alignment*

As mentioned, particle alignment (as well as shape) is a critical factor governing the performance of XP (in dual polarized systems); and a number of forces are capable of influencing the alignment. These forces such as the aerodynamic, Brownian and electrostatic forces tend to create or destroy the falling particles alignment. Reviews have shown that particles in dust storms carry charges on them, and they have impact on the movement of the dust storm [11 – 13]. Electric forces acting on stationary or slow-moving (without acceleration) charges, and the way these forces are modified in the presence of object are known as electrostatics [14]. It also involves the build-up of charge on the surface of objects due to contact with other surfaces. The force that electric charges exert is capable of influencing alignment especially at high microwave frequency.

Neglecting the electrostatic force, both aerodynamic and Brownian forces are investigated and discussed in this paper. Aerodynamics is concerned with study of forces and the resulting motion of solid objects through the air. Understanding flow field (motion of air) around an object enables the calculation of forces and moments acting on the object.

As dust particle falls at its terminal velocity through the air, the air flow around it generates an inertial torque on it. It will rotate the ellipsoid so that its longest axis is horizontal and its shortest axis is vertical ( $a > b > c$ ) as shown in figure 1. This is an alignment creation force.

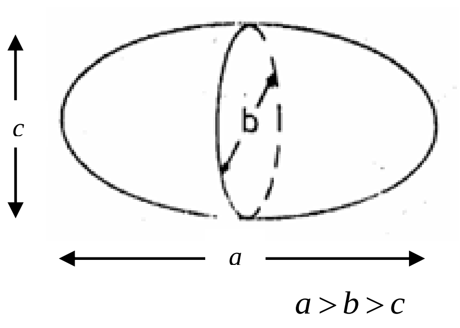

Fig. 1. Illustration of an ellipse.

Turbulent fluid flow is a flow in which small irregular fluctuations as a function of time are superimposed on a mean flow. An irregular fluctuating motion is a characteristic of fluid motion when laminar flow tends to disappear. In dust storms, turbulence produces random velocity shears which tend to destroy systematic alignment necessary for calculating dust-induced XP.

The motion of a particle suspended in viscous fluid results from fluctuating forces which are the consequence of collisions with molecules of the fluid [15]. Brownian motion exerts two influences, a direct contribution to the bulk stress tensor from the Brownian torque or force acting on the particle and an indirect effect on the viscous stress through the orientation or spatial distribution function. Very small particles undergo random and jerky displacements because the bombardment by fluid molecules is no longer balanced on all sides. This motion is referred to as Brownian forces. This force can be quantified in terms of mean-square displacement, $(\bar{X})^2$. Einstein derived a relationship for the mean-square displacement and was later verified by many other investigators like Nelson [16].

$$\left(\bar{X}\right)^2 = 2\frac{MR}{A}T\frac{C_c}{3\pi\mu d}t \; [m^2] \qquad (2)$$

where $M$ is gas molecular weight, $R$ is gas constant, A is the Avogadro’s constant, $T$ is absolute temperature, $C_c$ is a correction factor and $t$ is displacement time.

## III. Dust and Cross Polarization

Dust relates to small solid particles, conventionally taken as those below 75 μm in diameter, which settle out under their own weight but may remain suspended for some time [17]. It may be termed as sand when the diameters of the particles are greater than 80 μm. An obvious source of dust and sand is the sand and dust storms (SDS).

SDS is a very strong windstorm that blows loose sand and dirt from a dry surface, and carries clouds of sand or dust. It greatly reduces visibility and often used interchangeably as dust storm or sand storm. The wind is usually caused by convection currents, and is usually strong enough to move entire sand dunes. SDS is said to occur when the horizontal visibility is less than 1000m, and when the dust is being circulated into the atmosphere within sight of the observer [18].

The rapid expansion in communication systems has given rise to techniques for optimal frequency spectrum utilization. This has led to the adoption of frequency re-use technique employing dual-polarizations as exemplified in some satellite systems e.g Arabsat. Dust particles have the potentiality of causing microwave degradation for substantial percentage of time especially at frequencies above 10 GHz. This can lead to drop in the availability and quality of services rendered by communication systems. Attenuation and XP of microwave signals due to scattering and absorption of electromagnetic energy by dust particles are a source of impairments to terrestrial and satellite communication systems. Thus, terrestrial link and satellite communication systems owe viability to solutions associated with dust particles. It is against this premise that investigation into the forces affecting particle alignment necessary for XP is carried out.

The dust particles have random irregular shapes and cannot be described by any simple geometry. However, authors e.g. [3] have assumed different shapes because one needs geometry of the scattering particle in order to carry out scattering and XP computations. So far, the nearest geometry that approximates dust particle is the ellipsoid with axis ration varying over wide range (from 0 to 1). See Fig 1 for illustration of the ellipse. Only non-spherical particles with some degree of systematic alignment could cause depolarization [4].

Dust particle induces XP interference. If a wave is propagated through a non-spherical particle along a path, it will usually change its polarization as it travels [4, 8]. The generation of such a cross polarized component may however be a problem for communication system because as the wave propagates through the atmosphere, a part of the energy emitted with a given polarization becomes orthogonally polarized, thereby causing interferences between the two communication channels.

The existence of XP hinges on the theoretical prediction that particles have some preferred orientation. Under stationary air conditions and in the absence of turbulence or wind shears, the aerodynamic forces tend to direct particles in such a direction that their principal axis will be contained within the vertical plane [19]. This anisotropy (i.e. different properties in different directions) may induce a degradation of the XPD factor both in linear and in circular polarizations [20]. Despite its significance on the prediction of the XPD, this issue has not received adequate attention in the existing related works.

## IV. Result and Analysis

### A. Inertial Torque creating alignment

Potential flow solutions for a translating ellipsoid were given [10]. For an ellipsoid falling in air with a terminal velocity, $v$ and with it oriented so that the air flow is directed along the $a,b,c$ ellipsoid axes in turn, the kinetic energies $U'$ are as follows:

$$U'_{a,b,c} = \frac{L_i}{1-L_i} V\rho v^2 \quad \text{(i=1, 2, 3)} \tag{3}$$

where $V$ is the ellipsoid volume, $\rho$ is the air density, $v$ is the particle terminal velocity and $L_i$ is shape dependent factor. The $L_i$ are shape dependent dimensionless numbers that satisfy $L_1 + L_2 + L_3 = 1$. They could be obtained with fair accuracy using the following approximation [21].

$$\frac{L_1}{L_2} = \frac{b}{a};\ \frac{L_1}{L_3} = \frac{c}{a} \tag{4}$$

### B. Turbulent Torque disrupting alignment

The required expression for the torque exerted on the sphere reads:

$$M = 4\pi\mu a^3 \frac{du}{dh} \tag{5}$$

where $\mu$ is the fluid (air) viscosity $\left(1.8\times10^{-5}\,Nsm^{-2}\right)$, $u$ is fluid (air) velocity, $a$ is the radius (the radius is replaced by equivolumic radius, $a_e = \sqrt[3]{abc}$ in a non-spherical dust particle). $\frac{du}{dh}$ is an expression for the torque on the particle as a function of the local wind shear. It is the rate of change of air velocity near the particle with respect to a position coordinate, $h$, measured in a direction perpendicular to the mean flow.

Both the forces creating or disrupting the alignment are illustrated in figure 2. It is interesting to observe form the graph the existence of some form of systematic alignment of particles in the most relevant size range that was considered; especially from around 20 to 100 $\mu m$ and even more.

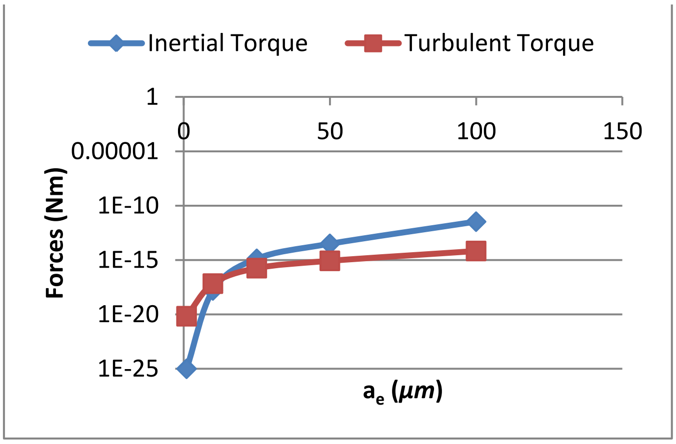

Fig. 2. Inertial and turbulent forces affecting particles alignment.

### C. Brownian Forces

The details of the Brownian forces cannot be predicted exactly. However, it may be assumed that the events (of collisions, displacements, etc.) are random. Therefore, even though the details of the phenomenon are not known, the average behaviour can be determined. At $20°C$ (i.e. T=293 k) and viscosity of $\left(1.8\times10^{-5}\,Nsm^{-2}\right)$, equation (2) can be expressed as

$$\bar{X} = 6.925\times10^{-9}\sqrt{C_c\, t/d} \qquad \text{[m]} \tag{6}$$

Note that the ratio in equation (2) is known as the Boltzmann's constant. Setting $t = 1\sec$ and applying the values of $C_c = 1.076$ and $C_c = 1$ for $d > 10\,\mu m$, the Brownian forces are evaluated using equation (6); the result is as shown in the curve. The curve is the Brownian displacement of dust particles falling through air of viscosity $1.8 \times 10^{-5}\ Nsm^{-2}$.

Brownian motion exerts two influences, a direct contribution to the bulk stress tensor from the Brownian torque or force acting on the particle and an indirect effect on the viscous stress through the orientation or spatial distribution function. Figure 3 shows that at some point, as particle diameter decreases (i.e. for very small particles), Brownian displacement is the dominant effect. At these diameters, gravitational force is negligible. This occurs within the lower microns range, dependent upon the density of the particle.

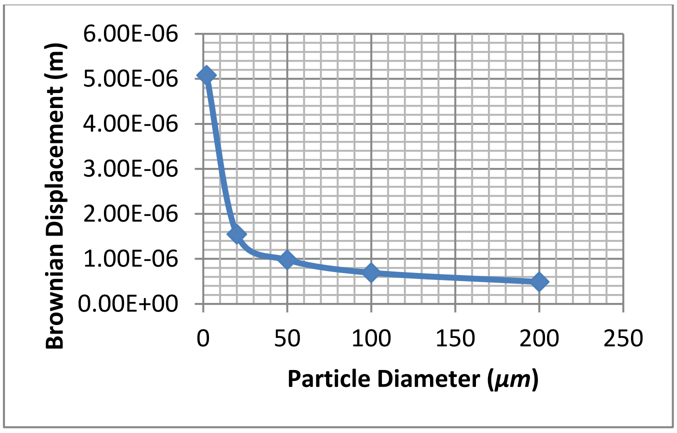

Fig. 3. Brownian displacements of dust particles falling through still air of $\mu = 1.8 \times 10^{-5}\ Nsm^{-2}$, T=293 k and $g = 10ms^{-2}$ .

For the particle diameter considered, both Stoke's and Allen's flow equations expressed in (7) and (8) are employed to obtain the terminal velocity. For the Stokes flow:

$$u = d^2 g(\rho_s - \rho_a)/18\mu \qquad (7)$$

Allen's flow:

$$u = \sqrt[1.4]{\left[\frac{0.072 \times d^{1.6} \times g(\rho_s - \rho_a)}{\rho_a^{0.4}\mu^{0.6}}\right]} \qquad (8)$$

Figure 4 gives a graphical representation of these equations for particles of varying diameter falling through air. As shown in figure 4, the terminal velocity increases as the characteristic length of the system increases. It should be noted that if the terminal velocity is sufficiently high enough to cause the onset of a turbulent wake then the transfer of kinetic energy from the particle to the fluid (inertial effects) can no longer be neglected.

At predominant inertial torque, a systematic alignment necessary to induce XP takes place. It is observed that the particle sizes have some interesting relation with the forces acting and consequently, the effects of the forces. At lower particle radius, the inertial torque is low while the disrupting force is relatively high. Conversely, at higher particle radius, the inertial torque is high, but the disrupting force is low.

From observation of the graph in figure 2 and the above assertion, a fundamental condition for a systematic alignment and formation of canting angle necessary for XP induction is for the inertial force responsible for creation of alignment to be far greater than the turbulent force disrupting the alignment.

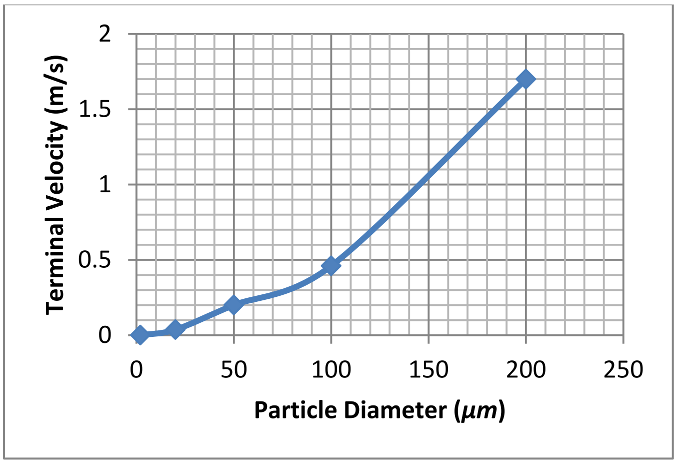

Fig. 4. Terminal velocities based on Stokes' and Allen's [22] laws with fluid density = 1.225 $kgm^{-4}$ and g=10 $ms^{-4}$ .

## V. Conclusion

Forces responsible for the tendency of particles to align in a particular direction at a time were investigated; those creating and disrupting alignment were predicted and analysed. Inertial torque of fluid flow round a particle is an alignment creating force while turbulent torque is a form of force disrupting the alignment. Another form of force identified and investigated is the Brownian motion. The numerical results obtained showed an existence of some form of systematic alignment of particles in the most relevant size range considered. To this level of this work, electrostatic forces are assumed negligible. Finally, this work is expected to significantly contribute to the technique of evaluating microwave XP by incorporating aerodynamic and Brownian effects into treatment of the particle alignment.

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