Prediction of Dust Particle-Induced Cross Polarization at Microwave and Millimeter Wave Bands

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Abstract - The use of dual orthogonal polarizations to optimally conserve frequency spectrum in microwave link, otherwise known as cross polarization, has received considerable interest in the recent time in the field of electromagnetic wave propagation in sand and dust storms. Cross polarization in dust storms occurs due to the non-sphericity of the falling dust particles and the tendency of the particles to align in a direction at a time i.e. canting angle. The realization of a dual-polarized system is however limited by degree of cross polarization discrimination (XPD) that can be achieved between the two orthogonal channels. Therefore, theoretical investigation has been carried out in this work to estimate the cross polarization at microwave and millimeter wave bands by non-spherical dust particles in dust storms. The XPD being the parameter for characterization of cross polarization, is predicted using propagation constants' differentials and canting angles, as inputs. Apart from both differential phase rotation and attenuation, it has been found that the cross polarization produced by ellipsoidal dust particles strongly depend on the particle canting. XPD decreases with an increase in canting angle. It has also been observed that the values of differential attenuation increase with increasing frequency for visibility and thus depends directly on frequency. Lastly, the obtained results show that cross polarization is significant during severe visibility and for dry dust storm; the XPD is good and acceptable for dual polarization systems.

Keywords: Cross polarization, canting angle, dust particle, dust storms, microwave, millimeter wave, differential phase rotation, differential attenuation

1. Introduction

Microwave and millimeter wave signal propagation in dust storms has received appreciable interest in recent past [1] - [5]. This can be attributed to the deployment of microwave links in tropical, semi desert as well as desert regions. The congestion of the frequency spectrum has prompted frequency expansion and efficient utilization [3]. Frequency re-use is a technique attracting considerable attention as it enables frequency spectrum to be doubled. The technique involves transmitting two cross-polarized microwave beams independently modulated. The application of the frequency reuse method in orthogonal polarizations is, however, limited by cross polarization [2]. Isolation between the orthogonal polarizations is always degraded by atmospheric phenomena such as dust particles along the propagation paths. It means that cross talk or interference effect between the two polarizations must be well below the allowable threshold limit for the communication systems.

In regions without measured data, knowledge of some physical mechanisms responsible for microwave cross polarization is usually applied to estimate the microwave cross polarization generated by dust particles from storms. The theoretical prediction that particles have some preferred canting and alignment or orientation is an important consideration in the study of cross polarization. The transmitted tilt angle influences the depolarization characteristics of a linearly polarized wave [6]. Therefore, in communication system design involving cross polarization, the total cross polarization in a propagation link is estimated using the canting angle, the phase rotation and the magnitude of the signal attenuation.

One of the most important influences of dust storms on microwave and millimeter wave propagation is signal attenuation by the dust particles. Emphasis is placed on differential attenuation and differential phase rotation, in links using orthogonal linear polarizations, because of the ellipsoidal nature of the particles shape. Furthermore, linearly polarized links are well understood by the fact that falling dust particles not only have a non-spherical preferred shape and alignment, but also a canting angle whose value is not zero. The attenuation and the phase rotation coefficients have been well tackled in some past works such as [7]. Similarly, the canting angle has been investigated and evaluation of its model as input to XPD prediction has also been reported [8]. However, application of these parameters as inputs to cross polarization is yet to receive much attention. Therefore, the objective of this work is to predict cross polarization induced by dust particles using differential attenuation, differential phase rotation and canting angle from dust particle alignment at microwave and millimeter wave bands.

The report of this paper is presented such that in Section 2, some theoretical consideration of dust particles is reviewed. The microwave and millimeter wave cross polarization are discussed in Section 3, the results obtained, and their discussions are presented in Section 4, while conclusions are drawn in Section 5.

2. THEORETICAL CONSIDERATION OF DUST PARTICLES

Cross polarization is hinged on the theory of falling particles having some preferred orientation and canting angle. The falling particles may induce a degradation in XPD value both in linear and circular polarizations due to their different properties in different directions [9]. Some forces influencing dust particle alignment in cross polarization during dust storms have been investigated [10], [11] and [12]. Similarly, dust particles canting as input to cross polarization was also investigated [8]. A model whose output can enhance the calculation of cross polarization in terrestrial and satellite links was developed.

Turbulent and inertial torques are respectively responsible for disruption and creation of alignments. Systematic alignment of dust particles is an important requirement for canting which is in turn an important XPD input [8]. It was also shown that dust particles could exhibit non-random orientation at some sizes [12]. The work showed that the canting angle can be evaluated by setting the alignment forces to equilibrium state. Applying the canting angle model showed results that were of the same order of magnitude as those obtained using existing theories on cross polarization at a microwave band.

Cross polarization may be said to be induced when phase and attenuation constants for vertical and horizontal polarizations in dust storms are not the same. The complex forward direction scattering has different values for horizontal and vertical polarizations, and this can be explained by the particle drop distortion. This gives rise to a differential phase rotation and a differential attenuation between the polarizations, producing cross polarization. Since the two axes of the ellipsoidal dust particle are randomly oriented on the horizontal plane, the attenuation and the phase rotation constants for the horizontal polarization wave may be expressed as (1) and (2):

$$A_h = \frac{A_1 + A_2}{2} \quad (1)$$

$$\beta_h = \frac{\beta_1 + \beta_2}{2} \quad (2)$$

For a vertical polarization wave, the attenuation and phase rotation are unchanged and can be expressed, respectively, as:

$$A_v = A_3 \quad (3)$$

$$\beta_v = \beta_3 \quad (4)$$

The differential attenuation and the differential phase rotation between the vertical and the horizontal polarizations can, consequently, be written as:

$$\Delta A = A_h - A_v \quad (5)$$

$$\Delta\beta = \beta_h - \beta_v \quad (6)$$

3. CROSS POLARIZATION

Dust particle experiences small tilts of its principal planes during dust storm, such that horizontally and vertically polarized waves do suffer measurable cross polarization. This effect, often referred to as the canting angle, has been discussed [8]. The relationship between the canting angle and the cross polarization is given in this work.

Each symmetry axis of the particle gives a different amplitude attenuation and a different phase change when the polarized wave is incident at an angle. The differential attenuation and the differential phase rotation change the wave's polarization state [13]. As shown in Figure 1, the canting angle of an oblate particle can be represented as θ, and the two linearly polarized waves E_H and E_V can be aligned in the horizontal and the vertical axis.

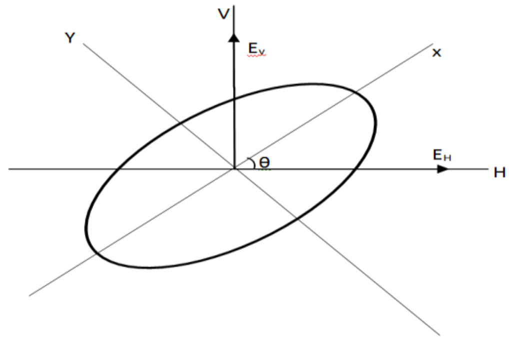

Figure 1. Illustration of an oblate dust particle.

Provided $\theta \neq 0^0$, the polarization states of the waves are altered after going through the dusty medium. Using coordinate transformation, the waves E'_H and E'_V can be gotten from E_H and E_V.

$$\begin{bmatrix} E'_H \\ E'_V \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} T_X & 0 \\ 0 & T_Y \end{bmatrix} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} E_H \\ E_V \end{bmatrix} \tag{7}$$

In other words,

$$E'_H = (T_X \cos^2\theta + T_Y \sin^2\theta) E_H + [(T_X - T_Y)\sin\theta\cos\theta]\, E_H \tag{8}$$

$$E'_V = [(T_X - T_Y) sin\,\theta\; cos\,\theta] E_H + (T_X sin^2\,\theta + T_Y\, cos^2\,\theta) E_V \tag{9}$$

where θ is the canting angle, $E_{V,H}$ is the orthogonal wave (linearly polarized) aligned respectively in the vertical and the horizontal axes and $E'_{V,H}$ is the attenuated wave after passing through particles. Transmission coefficients in the major and the minor axes can be expressed as:

$$T_X = exp[-(A_X - j\Psi_X)L] \tag{10}$$

$$T_Y = exp[-(A_Y - j\Psi_Y)L] \tag{11}$$

where L is the effective path length (km), Ψ_X and Ψ_Y are, respectively, the phase coefficients in the major and the minor axes of drop particle in rad/km, while A_X and A_Y are, respectively, the attenuation coefficients in the major and the minor axes of the drop particle in Np/km.

It can be recalled that the XPD may also be defined as the ratio of energy received in the principal polarization from the same signal to the energy received in the orthogonal polarization. Therefore, the horizontal and the vertical XPD can be expressed thus in dB:

$$XPD_H = 10log\frac{|(T_X\cos^2\theta + T_Y\sin^2\theta)E_H|^2}{|[(T_X - T_Y)\sin\theta\cos\theta]E_H|^2}$$

$$XPD_H = 20log \frac{[(T_X/\ T_Y)+\tan^2\theta]}{[(T_X/\ T_Y-1)\tan\theta]} \quad (12)$$

$$XPD_V = 10log \frac{|(T_X \sin^2\theta + T_Y cos^2\theta)E_V|^2}{|[(T_X - T_Y)\sin\theta\cos\theta]E_V|^2}$$

$$XPD_V = 20log \frac{[(T_X/\ T_Y)+\tan^2\theta+1]}{[(T_X/\ T_Y-1)\tan\theta]} \quad (13)$$

Equation (12) and (13) can be simplified and rewritten as

$$XPD_H = 20log \frac{[\gamma+\tan^2\theta]}{[(\gamma-1)\tan\theta]} \quad (14)$$

$$XPD_V = 20log \frac{[\gamma\tan^2\theta+1]}{[(\gamma-1)\tan\theta]} \quad (15)$$

where the differential phase rotation and the differential attenuation between the channels is denoted as γ. For a wave propagating in a dust storm, γ can be obtained using the expression:

$$\gamma = e^{-(\Delta A - j\Delta\beta)L} \quad (16)$$

where L is the propagation path length in the dust storm in km, $\Delta\beta$ is the differential phase rotation in $radian/km$ and ΔA is the differential attenuation in Np/km.

There are two linearly polarized waves, superimposed and 90° out-of-phase in a circularly polarized wave. Therefore, if E_R and E_L denote the right-hand and the left-hand circularly polarized waves respectively, (17) and (18) are obtained.

$$E_R = E_H - jE_V \quad (17)$$

$$E_L = E_H + jE_V \quad (18)$$

Equation (17) and (18) can be substituted into (7) to give (19) and (20) which are like E_R and E_L gotten after propagation through the dust particles:

$$E_R' = (T_X + T_Y)E_R + [(T_X - T_Y)]exp(-j2\theta)E_L \quad (19)$$

$$E_L' = [(T_X - T_Y)]exp(j2\theta)E_R + (T_X + T_Y)E_L \quad (20)$$

Note that the left-hand and the right-hand XPD are all the same and can be expressed as:

$$XPD_c = 20log \left|\frac{T_X + T_Y}{T_X - T_Y}\right|$$

$$XPD_c = 20log \left|\frac{(T_X/T_Y)+1}{(T_X/T_Y)-1}\right| \quad (21)$$

For a circular polarized wave, i.e. a linear polarization of 45^0, in suspended dust particles medium, the XPD is simplified further as written in (22):

$$XPD_C = 20\log_{10}\left|\frac{1+\gamma}{1-\gamma}\right| \quad (22)$$

4. RESULTS AND DISCUSSIONS

The formulated theories presented and explained in earlier section are applied in this section. Results are obtained and discussed. The first category of XPD inputs in form of differential attenuation and the differential phase rotation are computed using (5) and (6) as well as the products of attenuation and phase rotation expressions in a mono-dispersive medium of ellipsoidal dust particle shape reported in [7]. At 10 GHz, 37 GHz and 50 GHz and a range of visibility, Figures 2 and 3 show the differential attenuation and the differential phase rotation respectively.

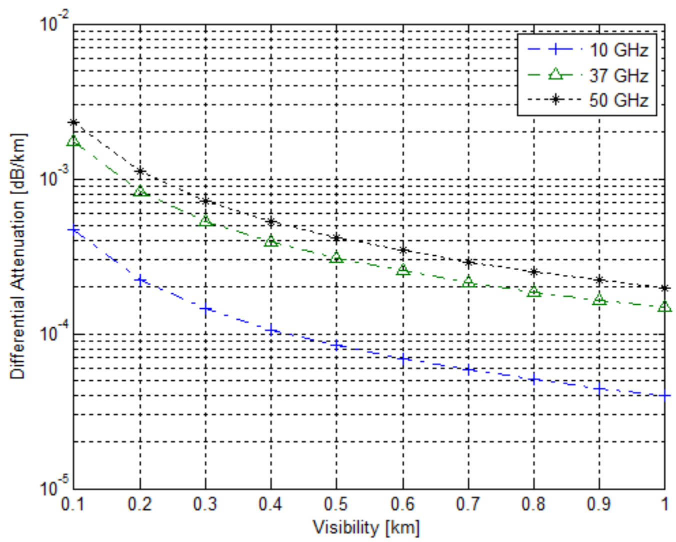

Figure 2. Differential attenuation.

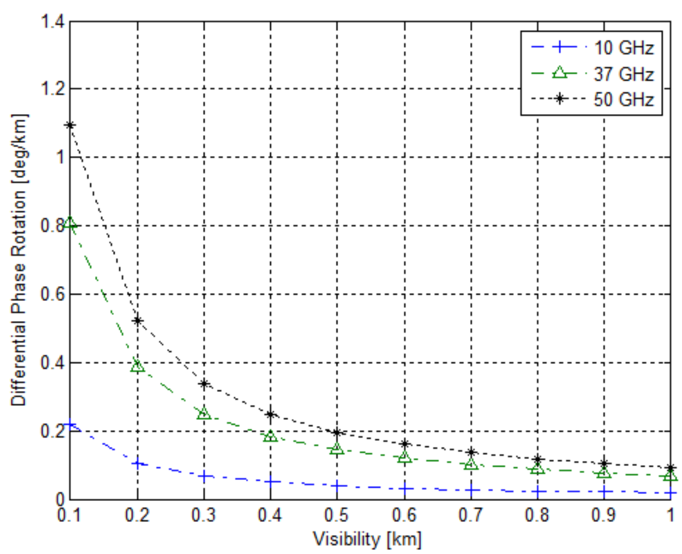

Figure 3. Differential Phase Rotation.

Figures 2 and 3 proves that the differential attenuation and the differential phase rotation increase with an increase in frequency and a decrease in visibility. Suffice to point out that the increment in differential attenuation as frequency increases as shown in Figure 2 is like that made by [14] for rain induced depolarization. [15] also predicted increase in differential attenuation when frequency increases. This relation of increase in both differential attenuation and phase rotation as visibility decreases is so because as dust storms' visibility decreases, the dust particle concentration expectedly increases.

XPD induced by dust storms is computed using (14), (15), (16) as well as (22). While the differential attenuation and the differential phase rotation are as obtained in Figures 2 and 3, the XPD is evaluated for a range of visibility during dust storms and propagation path length as shown in Figures 4, 5, 6 and 7.

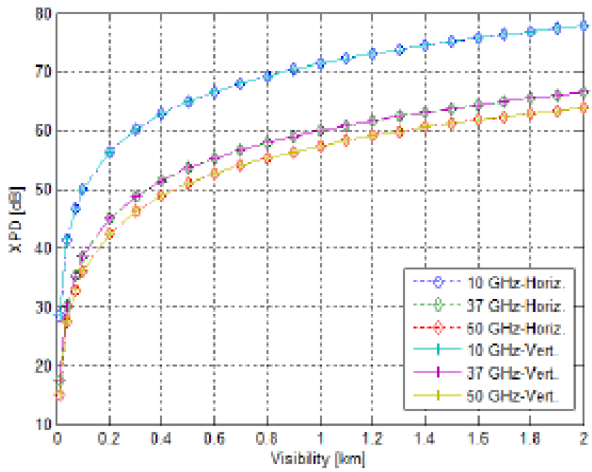

Figure 4. XPD at $L = 1\ km$ and $\theta = 8^{\circ}$.

The vertical component of the linear polarizations appears a little higher than the horizontal component. It is instructive to say that this was also established by [13], [16] as well as [17].

The canting angle variation on cross polarization is shown in Figure 5 at frequency of 37 GHz and path length of 1 km. It is observed that the XPD becomes relatively smaller as the canting angle is increased. For instance, the XPD between 1^{0} and 3^{0} is very significant when compared with those between 22.5^{0} and 45^{0}.

Furthermore, an interesting observation in Figure 5 was that the XPD obtained at 45^{0} is the same as the XPD for circular polarization obtained in Figure 6. The outcome is not unexpected because (14) and (15) becomes (22) at 45^{0}. This further confirms that the XPD depends on the visibility as well as the dust particle shape and orientation. The XPD lowest numerical value is when the polarization is either linear (with polarization bisecting the principal planes of the medium which is at 45^{0}) or circular.

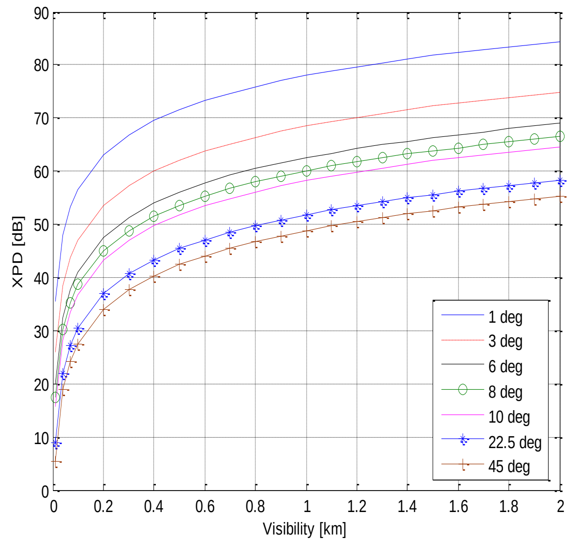

Figure 5. XPD - horizontal component.

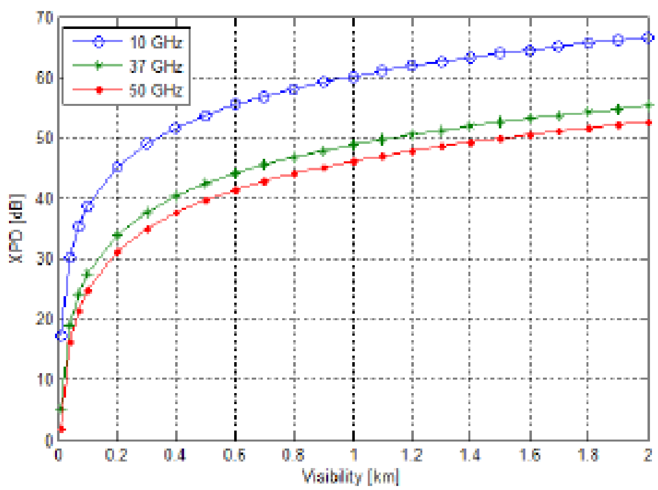

Figure 6. XPD - different frequency.

Also, the XPD is a function of operating frequency as its severity becomes more pronounced when the frequency is increased. At 1 km path length, XPD are 38.8 dB (at 0.1 km visibility) and 60.2 dB (at 1 km visibility) for 10 GHz frequency, but 27.5 dB (at 0.1 km visibility) and 48.9 dB (at 1 km visibility) for 37 GHz frequency as shown in Figure 6.

The propagation path length is also a variable in the prediction of XPD. The XPD decreases when the path length is extended. At 1 km path length (and 37 GHz), the XPD varies between 27.5 dB and 48.9 dB when visibility is between 0.1 km and 1 km as shown in Figure 7. However, at 5 km path length, the XPD is between 13.7 dB and 34.9 dB respectively for visibility of 0.1 km and 1 km.

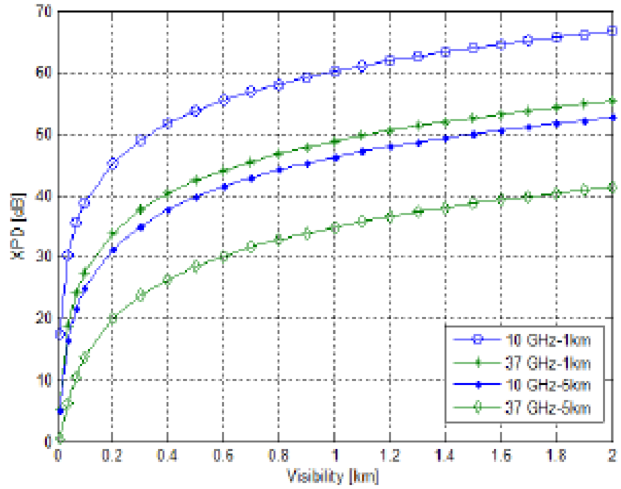

Figure 7. XPD - circular polarized showing the path length effect.

Finally, the results from this work are benchmarked against those obtained by earlier investigators. The findings of this work generally follow same trend with those obtained by [15], [17] and [18]. XPD of circular polarization is 24.8 dB at 50GHz, 1 km path length and visibility at 100 m. The reported values by some earlier investigators are between 19.4 and 77.5 dB for 10 GHz and path length of 1 km. 18.5 dB was recorded by [15] when the visibility was very low at 2 m, frequency was 10 GHz and a 2% water regain. This means that cross polarization is severe when visibility is low. At similar frequency, [18] obtained 50 dB when visibility was 100 m and path length was 1 km. The variation, however, is accounted for by the difference in the attenuation and the phase rotation data, the operating frequency considered and the moisture percentage.

5. CONCLUSION

In this paper, dust particle induced XP at microwave and millimeter wave has been treated. XPD induced by dust particles has been found to be a function of phase rotation, attenuation and canting angle orientation especially in linear polarizations. XPD is directly proportional to visibility (as increase in the storms' visibility results in an increase in XPD), but the canting angle increase reduces the XPD value. An increase in frequency reduces the values of XPD obtained.

It is also noted that when visibility is 100 m or less, cross polarization is severe even for short hops. However, it may be said to be negligible for visibilities greater than 100 m. Low visibility less than 100 m do occur during the summer in more arid areas.

Lastly, for circular and 45^0 linear cross polarizations in dry regions, it is found that 24.8 dB and 46.2 dB of XPD are respectively possible for 0.1 km and 1 km visibility when frequency is 50 GHz and path length is 1 km. A definite conclusion from the foregoing is that for a dry dust storm, the XPD is good for application in dual polarized communication systems.

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