

Investigation of Millimeter Wave's Cross Polarisation Differentiation in Dust and Sand Storms

Abdulwaheed Musa^{1,2}

¹Department of Electrical and Computer Engineering, Kwara State University, Nigeria

²Institute for Intelligent Systems, University of Johannesburg, South Africa

twhid2001@yahoo.com

<https://orcid.org/0000-0001-8371-2465>

Abstract

The performance of electromagnetic wave links in dust and sand (DUSA) storms has become a topic of interest to researchers, especially with emphasis on the attenuation of signal. But the phase rotation and the cross-polarization components are not yet sufficiently treated. This work investigates the cross-polarization differentiation (also known as discrimination) as a result of DUSA storms at high frequency such as the millimeter wave band. The paper proposes mathematical models of propagation of waves in DUSA storms using the forward scattering amplitude of DUSA particles and the Rayleigh technique. The suitability of the Rayleigh approximation for the models are validated by setting three different conditions. The results show fidelity of the technique for evaluating scattering of ellipsoidal DUSA particles for the range of sizes and frequencies considered. The coefficients of the scattering are thus determined and models for attenuation and phase rotation are introduced in terms of visibility. The results obtained from the models show close agreement with some earlier published results when compared. We then computed both the attenuation and the phase rotation differentials and the cross-polarization discriminations are then predicted using the parameters from the models as inputs. The attenuation during dry DUSA storms becomes significant only when the visibility is low and severe. At such visibility, the cross-polarization discriminations also become low (i.e. significant) and the same trend and pattern is observed when the frequency is increased.

Keywords: millimeter wave, cross-polarization discrimination, DUSA storms, signal propagation, differential phase rotation, differential attenuation, complex scattering.

1. Introduction

Optimum application of frequency spectrum is possible through two orthogonal polarizations. This concept, i.e. transmission of two different polarizations using the same frequency to raise the capacity of the channel without raising the bandwidth is a very interesting method both at low and high frequency bands. Furthermore, the lower bands congestion of the radio spectrum has necessitated the attention being paid to the millimeter wave bands very necessary. It is interesting to note, however, that these past works did not tackle the problem associated with cross-polarization beyond the wavelength of 3 cm, i.e. X-band, even as frequencies higher than the X-band are now finding many new applications and enhance telecommunication expansion. Unfortunately, propagation at high frequency bands comes with difficulties and peculiar challenges to microwave signal engineers that are concerned about signal attenuation, fading, outages, cross-polarization and scattering induced interference (Musa & Paul, 2020). This serves as one of the motivations behind this research work.

The poor performance of wireless communication systems during DUSA has somewhat become obvious. An electromagnetic wave being propagated in DUSA particles suffers attenuation and possibly phase rotation capable of causing communication system outages (Musa & Paul, 2020; Musa, et. al., 2018; etc.). Differential attenuation and differential phase rotation take place when orthogonal communication channel passes through

DUSA storms, because the DUSA particles shape are not spherical, but somewhat eccentric (Bashir, et. al. 2008, Musa & Paul, 2020).

In spite of the specific contribution towards establishing the particle shape, which has now made the evaluation of cross-polarization possible, it has been well observed that phase rotation and the cross-polarization are not yet sufficiently treated. This work investigates the cross-polarization differentiation, i.e. cross-polarization discrimination as a result of DUSA storms at high frequency such as the millimeter wave band.

Furthermore, most of the existing models have been expressed in terms of concentration of number of DUSA particles, relative volume or mass of dust/unit volume of air. But these parameters DUSA particles are very difficult to measure or obtain. This has made more attention to be paid on the shape of DUSA particles and their applications, by way of further investigation conducted in this work. Instead, DUSA storms' parameters such as visibility, which is usually a factor for determining severity of a storm and can easily be measured, have been considered in this work, an additional justification of the work.

Aside the introduction section, the remaining sections of this paper have been arranged such that Section 2 presents a review of previous related works. In Section 3, the methodology, involving complex scattering and Rayleigh scatterer approximation methods, attenuation, phase rotation and cross-polarization discrimination, have been presented. Results and their discussions are contained in the fourth section. The paper ends in Section 5 with conclusion.

2. Review of Related Literature

Under this second section, some of the related works on millimeter wave attenuation, phase rotation, cross polarization and cross-polarization discrimination have been considered. Some past researchers proposed mathematical models for determining signal attenuation in DUSA storms (Bashir, et. al. 2008; Ruike, et. al., 2013; Yi, 2014; Dong & Chen, 2011; etc.). The conclusion drawn by some of these researchers is that attenuation is not significant unless during very serious storms. It has also been demonstrated by Yi (2014), Dong & Chen (2011), Elsheikh, et. al. (2010) among others that visibility, complex permittivity and wave frequency have significant impacts on electromagnetic wave propagation in DUSA storms.

Musa & Paul (2020) reported that cross-polarization in DUSA storms is a function of DUSA particles' shape. Cross-polarization in DUSA storms was also studied by McEwan & Bashir (1983), YingXia & JiYing (2013), Srivastava & Vishwakarma (2013), Musa & Paul (2020) and several others. McEwan & Bashir (1983) assumed that all DUSA particles are ellipsoids and that the ratios of the axes were equal to the average value of the ratios of the axes of some of the particles, about 100 of them, that were investigated and measured using microscopes. The obtained results were presented as a function of the relative volume occupied by the particle. But this relative volume as a quantity cannot be easily and directly measure in practice. At 10 GHz, an expression was given for evaluating the cross-polarization discrimination of waves with circular polarization in DUSA storms. It was found that the cross-polarization in DUSA storms could be of a serious consequence. It is interesting to note, however, that these past works did not tackle the problem associated with cross-polarization beyond the wavelength of 3 cm (i.e. X-band), even as frequencies higher than the X-band are now finding many new applications and enhance telecommunication expansion.

Against this premise, the cross-polarization discrimination in dust storm is addressed at millimeter wave bands in this work. Method of Rayleigh approximation is checked for calculating the wave scattering at the millimeter wave bands. The coefficients of the scattering are determined and then the models for attenuation and phase rotation in DUSA storm are presented in terms of visibility and relative permittivity instead of relative volume (i.e. mass of dust/unit volume of air). This is because the visibility in DUSA storms can easily be measured and it is usually a factor for determining severity of a storm. Lastly, the Rayleigh approximation's results are applied as inputs to cross-polarization discrimination.

Attenuation of electromagnetic waves could occur as a result of scattering and absorption by DUSA particles (Bashir, 2008). The solutions of the actual integral formula of scattering amplitude function are complex since the function is a dependent of the local field in the DUSA particle and the permittivity. Besides, the local field

is usually not known. As such, approximation techniques such as Rayleigh, Wentzel-Kramers-Brillouin, Born, etc. are generally applied to solve the complexity.

The approximation technique of Rayleigh allows for an analytical solution of the Maxwell's equations of the electromagnetic waves scattering by dielectric particles. The Rayleigh scattering happens when the considered particle is small electrically, and when the scattering is a function of the particles' electric polarizability. This method is verified in this work for calculating scattering of electromagnetic wave at millimeter wave bands.

The first is that the Rayleigh approximation is justifiable when the external field is continuous and homogeneous. This happens if the radius of the particle, a , satisfies the condition $a \leq 0.05\lambda$ (or $ka \ll 1$); where λ is wavelength and k is propagation constant. The second condition validated is that the incident field penetrates very fast inside the particle such that the static polarization is confirmed in a short period of time when compared with the period of the wave. In other words, $k|\bar{m}|a \ll 1$, where m is the refractive index of the particle (Ahmed, 1987). The third validation condition is added from Bashir (2008) and that is Rayleigh approximation is justifiable when there is also phase homogeneity. Thus, for the phase to be homogenous both inside the particle and outside the particle, it means that $\frac{2\pi a}{\lambda}|\epsilon - 1| \ll 1$. ϵ is permittivity.

We set a limit of 0.5 as values much less than 1 (Bashir, 2008) and $\epsilon = 3.8 - j0.038$ (McEwan & Bashir, 1983) and then tested and implemented all the three conditions in this work. As an example, ka and $k|\bar{m}|a \ll 1$ are 0.2 and 0.4 respectively even at frequency up to 100 GHz. The last condition, however, holds only for the millimeter wave of less than 85 GHz frequency. Having validated the conditions, the next section details the steps taken to arrive at the proposed propagation models.

3. Methodology

This section deals with the research methodology and implementation. Specifically, the attenuation and the phase rotation in DUSA storms are derived and then expressed in terms of visibility. Their differentials are obtained and used as inputs to cross-polarization discrimination.

3.1 The Attenuation and the Phase Rotation

To derive the attenuation and the phase rotation of wave propagation in DUSA storms, the complex refractive index, \bar{m} , of a scattering medium with its definition expressed as:

$$\bar{m} = 1 - j2\pi k^{-3}NS(0) \tag{1}$$

where k is free space phase constant, $S(0)$ is the complex forward scattering amplitude function, while N equals number of DUSA particles/cubic meter, is referred. The Rayleigh-scatterer defines the complex forward direction as:

$$S(0) = jk^3p_i \tag{2}$$

where p_i is the polarizability and can be expressed as:

$$p_i = \frac{v}{4\pi[l_i + (\frac{1}{\epsilon - 1})]} \tag{3}$$

where is v the volume (ellipsoid is assumed) and l_i are three orientation factors such that $l_1 + l_2 + l_3 = 1$ when the propagation field is applied along one of the ellipsoidal axes.

The complex forward scattering amplitude function, $S(0)$, can be re-expressed as in (4) when (3) is substituted into (2).

$$S(0) = jk^3 \cdot \frac{v}{4\pi[l_i + (\frac{1}{\epsilon-1})]} \quad (4)$$

A scattering medium's complex refractive index could also be written thus:

$$\bar{m} = 1 + \frac{\alpha_0 a}{13} \psi_i = 1 + \frac{\alpha_0 a}{13} (\psi'_i - j\psi''_i) \quad (5)$$

where

$$Re(\bar{m} - 1) = \frac{\alpha_0 a}{13} \psi_i Re[\psi_i] \quad (6)$$

The attenuation and phase rotation are obtained when (6) is multiplied by the free space constant, k . Denoting attenuation as α_i ,

$$\alpha_i = kIm(\bar{m}) = -\frac{k \cdot \alpha_0 a}{13} Im[\psi_i] Np/m = -\frac{k \cdot \alpha_0 a}{13} Im[\psi_i] (8.68)dB/m \quad (7)$$

If the phase rotation is denoted as β_i ,

$$\beta_i = kRe(\bar{m} - 1) = \frac{k \cdot \alpha_0 a}{13} Re[\psi_i] rad/m = \frac{k \cdot \alpha_0 a}{13} Re[\psi_i] \left(\frac{180}{\pi}\right) deg/m \quad (8)$$

We can express (7) and (8) as a function of volume fraction, v_f , which is defined as:

$$v_f = \frac{4}{3} \pi a^3 N \quad (9)$$

Let the values of k and α_0 be substituted into (7) and (8) to obtain (10) and (11).

$$\alpha_i = -9.1 \times 10^4 \cdot f \cdot v_f \cdot [I_m(\psi_i)] [dB/km] \quad (10)$$

$$\beta_i = 6 \times 10^5 \cdot f \cdot v_f \cdot [R_e(\psi_i)] [deg/km] \quad (11)$$

where f is frequency in GHz, $R_e(\psi_i)$ and $I_m(\psi_i)$ are real and imaginary parts of the dielectric constant's i -th value. $i = 1, 2$ corresponding to the polarization wave in horizontal while $i = 3$ is corresponding to the polarization wave in vertical.

In meteorology, DUSA storms are observed, measured and characterized mostly by using visibility. A definition of the volume fraction, v_f , is given by Goldhirsh (2001) as:

$$v_f = \frac{1.297 \times 10^{-7}}{v\gamma} \quad (12)$$

and can be substituted to the attenuation and phase rotation evaluation models. This is a more realistic expression of the models in terms of visibility as shown in (13) and (14) than the expressions in (10) and (11).

$$\alpha_i = -1.18 \times 10^{-2} \cdot \frac{f}{v\gamma} \cdot I_m(\psi_i) [dB/km] \quad (13)$$

$$\beta_i = 7.78 \times 10^{-2} \cdot \frac{f}{v\gamma} \cdot R_e(\psi_i) [deg/km] \quad (14)$$

Equation (13) and (14) are the expressions for the attenuation and the phase rotation in DUSA storms.

3.2 Cross-Polarization Discrimination

A cross-polarization discrimination in wave of circular polarization and a linear polarization that is 45 degree propagating in DUSA medium was given in Bashir (2019) as:

$$XPD = 20 \log_{10} \left| \frac{1+\gamma}{1-\gamma} \right| \tag{15}$$

where γ which is the attenuation and phase rotation differentials between the channels is given as:

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

where $\Delta\alpha$ is the attenuation differential in Np/km , $\Delta\beta$ is the phase rotation differential in deg/km and L is the path length of propagation in DUSA storm in km .

The scattering in the complex forward direction have values that are different for the polarizations (i.e. that of horizontal and that of vertical) because of distortion in particle drop. This explains the existence of attenuation and phase rotation differentials between the linear polarizations resulting in cross polarization. Only the horizontal polarization experiences change because the two ellipsoidal particle's axes are oriented (randomly) in the plane. The attenuation and the phase rotation will not change in vertically polarized waves. For the horizontal polarization wave, the attenuation constant and the phase rotation constant can be written as:

$$\alpha_h = \frac{\alpha_1 + \alpha_2}{2} \tag{17}$$

$$\beta_h = \frac{\beta_1 + \beta_2}{2} \tag{18}$$

while that of vertical polarization wave, can be respectively written thus:

$$\alpha_v = \alpha_3 \tag{19}$$

$$\beta_v = \beta_3 \tag{20}$$

The attenuation and the phase rotation differentials between the horizontal and vertical polarizations are expressed thus:

$$\Delta\alpha = \alpha_h - \alpha_v \tag{21}$$

$$\Delta\beta = \beta_h - \beta_v \tag{22}$$

4. Results and their Discussions

Under this section 4, the results are presented and discussed. The proposed model in (13) and (14) are also validated against the models of Ahmed, Alhaider and Goldhirsh (2001) before its implementation. For the validation, permittivity, $\epsilon = 3.8 - j0.038$ (i.e. 0% moisture content) (Musa & Paul, 2020) is adopted. Equation (20) is validated against already published models using vertically polarized plane at 10 GHz as shown in Figure 1. Very good agreement of the models can be observed. Ahmed and Alhaider models give higher attenuation values, and

show conformity with the results obtained using the proposed models. The model of Goldhirsh produces lower attenuation results. As the visibility improves, better conformity and agreement of all the models is noticed.

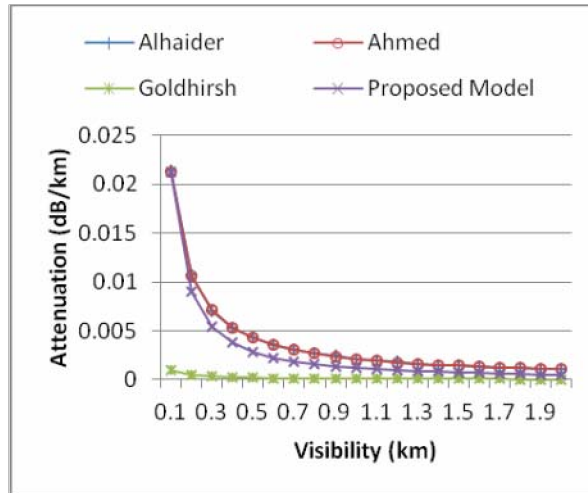
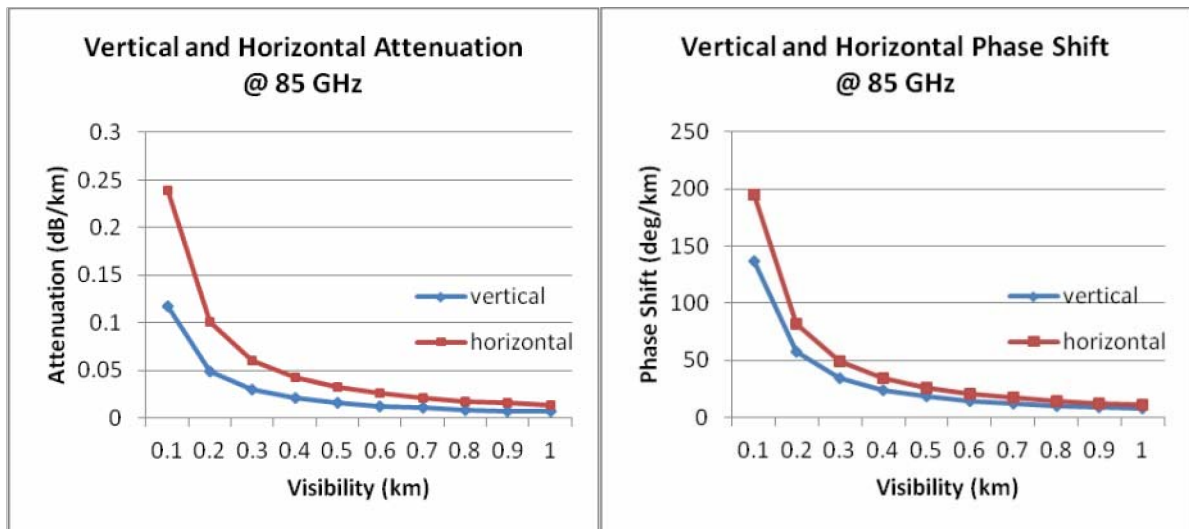


Figure 1: Proposed model validation.

After proposed models have been validated, we implement the attenuation and the phase rotation components. The values of $l_1 = 0.2$, $l_2 = 0.3$ and $l_3 = 0.5$ are adopted for the ellipsoidal particles (Bashir, 2019). The results are shown in Figure 2 for different values of frequency and visibility. In Figure 2(a) and Figure 2(b), the attenuation and the phase rotation of horizontal polarized waves and vertical polarized waves at 85 GHz as a function visibility are shown. The results indicate a dependence relation that is linear with the frequency and the visibility during storm. Attenuation decreases as the visibility gets better. The lowest attenuation, i.e., very negligible, is when the visibility is 1 km. Conversely, as the visibility gets worsened, around 1 m for instance, the attenuation also gets poorer.

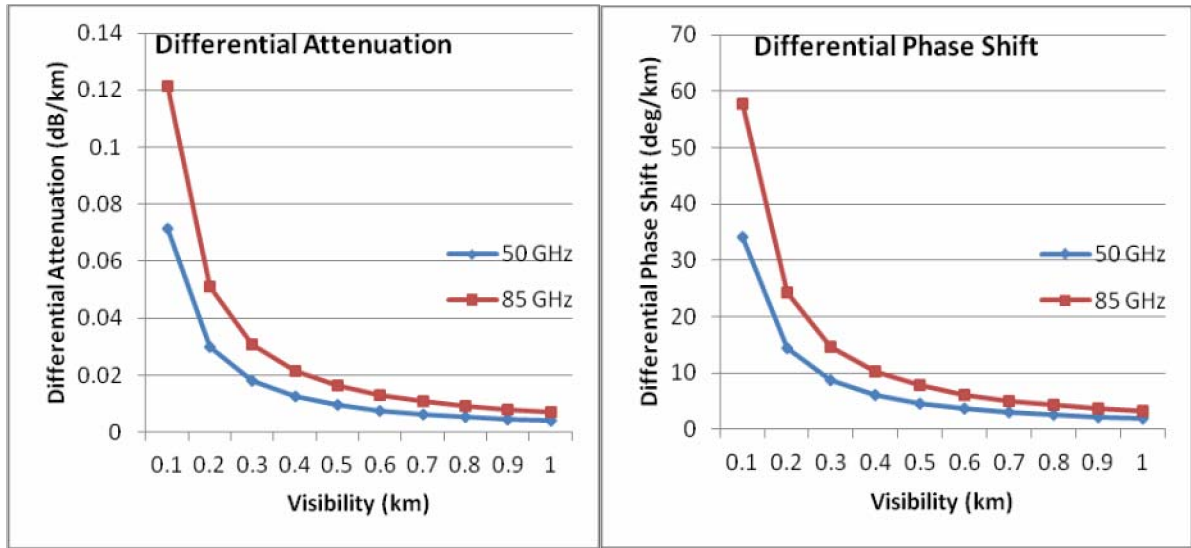


a. Vertical & horizontal attenuation

b. Vertical & horizontal phase rotation

Figure 2: Attenuation and phase rotation of polarized waves @ 85 GHz.

To investigate the cross-polarization discrimination, the attenuation and the phase rotation differentials are determined. If the DUSA particles are considered to be of ellipsoid, they (the DUSA particles) will align with the shortest axis, vertical, when air conditions are in stationary. With such orientation of particles, cross-polarization is induced. The cross-polarization discrimination's inputs, i.e. the attenuation and the phase rotation differentials are then evaluated using the expressions in (21) as well as (22). In Figure 3(a) and Figure 3(b), the attenuation and the phase rotation differentials at both 50 GHz as well as 85 GHz for a range of visibility are presented.



a. Attenuation differential

b. Phase rotation differential

Figure 3: Attenuation and phase rotation differentials of polarized waves (@ 50 GHz & 85 GHz).

Furthermore, the induced cross-polarization discrimination by DUSA storms at millimeter wave is determined using (15) and (16) and the results from the proposed models for the attenuation and the phase rotation prediction. The results, calculated at 1 km propagation path length and a range of frequency, are as presented in Figure 4.

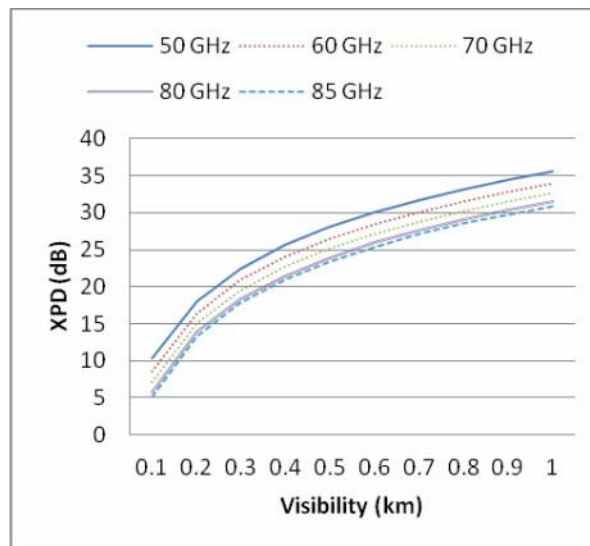


Figure 4: Cross-polarization discrimination.

It can be seen that DUSA storms induced cross-polarization discrimination depends on dielectric constant, wave frequency and visibility. There is a linear relation between the cross-polarization differentiation (i.e. discrimination) and the visibility as any increment of visibility gives rise to increment in the cross-polarization discrimination. Also, frequency increase leads to increase in attenuation. This in turn, produces low cross-polarization discrimination values. The cross-polarization in such situation is said to be severe and the severity worsens as the path length is increased.

5. Conclusions

In spite of the existing methods of propagating two different polarizations (linear or circular) while the same carrier frequency is used to increase the channel capacity, the effects of the cross-polarization on propagation link performance during DUSA storms have not been well tackled at the millimeter wave bands. In this work, cross-polarization discriminations in DUSA storms have been investigated at millimeter wave. The discrimination is a function of both attenuation and phase rotation. Cross-polarization is induced because the attenuation constant and the phase rotation constant for horizontal and vertical polarizations are different.

The work validated the Rayleigh approximation technique for obtaining the scattering of DUSA particles that are ellipsoidal for some millimeter wave. It also developed and proposed mathematical models, derived in terms of dielectric constant, frequency and visibility, to evaluate attenuation and phase rotation of linearly polarized waves. The proposed models are benchmarked with some existing models and their results agree well perfectly. The attenuation and phase rotation vary directly with the dielectric constant and frequency, but they vary inversely with the visibility. The attenuation becomes significant during severe sand and dust storms, but it is negligible during non-severe storms.

Besides, the results are applied as inputs for prediction of cross-polarization discrimination. The attenuation, phase rotation and cross-polarization discrimination caused by dry DUSA storms have been calculated for different visibilities scenarios. At a frequency of 50 GHz, attenuation rises from 0.004 dB/km to 0.07 dB/km when the value of visibility reduces to 100 m from 1 km. Similarly, at 85 GHz, the attenuation rises from 0.07 dB/km to 0.12 dB/km when the value of visibility reduces to 100 m from 1 km.

Lastly, it is found that the cross-polarization (circular and 45° linear) values will not be a major challenge even when visibility is at 100 m during sand and dust storms in dry regions. However, it becomes a major challenge when the visibility reduces to less than 100 m over around 10 km link path (or visibility reduces to less than 10 m over around 1 km path length). Cross-polarization discrimination of 10.3 dB is predicted at frequency of 50 GHz, 100 m visibility and 1,000 m propagation path length. A definite conclusion that can be drawn from the investigation of the millimeter wave's cross polarization in DUSA storms is that the differentiation or discrimination is reasonably acceptable to be used and applied in systems that dual polarization based.

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