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Electromagnetic wave attenuation due to the charged particles in dust&sand (DUSA) storms

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ABSTRACT

In this paper, we calculated the attenuation of the electromagnetic waves (EMWs) propagating through the dust&sand (DUSA) storms using the predicting model based on Mie theory, in which the charges carried on the DUSA particles, the ambient relative humidity (RH) and the particle size distribution are considered simultaneously. It can be found that the charges carried on the DUSA particles and the RH can change the value of the absorption and scattering efficiency, but they can't change the domain attenuation mechanism caused by the DUSA storms in the EMWs frequency regions (3 GHz, 4 GHz), (8 GHz, 40 GHz) and (75 GHz, 100 GHz). Whatever the DUSA storms are formed by equal-size particles or the mixed-size particles, the charge carried on the particle surface and the RH have a significant impact on the attenuation caused by the DUSA storms, and the change ratio of the attenuation caused by the charge or RH depends on the particle size. By the comparison of the calculated attenuation with the measured one, we found that the charges carried on the particles and the RH will be important factors to affect the attenuation of the EMWs.

1. Introduction

The signal of the electromagnetic waves (EMWs) is affected in terms of the attenuation when it propagates through the dust&sand (DUSA) storms [1,2], resulting in weakening the intensity of the signal and shortening the transmission distance, which attracts many researchers' interest because the signal is easily affected in the utilization of the satellite telecommunications and its application in the regions where encounter DUSA storms frequently, such as Middle East, Africa, China and some parts of South America etc. [2]. The attenuation is mainly caused by two mechanisms, scattering and absorption of the DUSA particles [3–5]. The scattering and absorption have a relation with the particle size, dielectric constant, the charges carried on the surface of the particles and the relative humidity (RH) etc. [6,7]. The total effect combining the scattering and absorption of EMWs by particular system can be investigated by the extinction, which is the algebraic sum of the scattering and the absorption [8,9]. The attenuation signal of the EMWs by DUSA storms is direct proportionally to the extinction.

The research on the attenuation of the EMWs by DUSA storms can be dated back from 1940s [8]. A series of studies about the attenuation of the EMWs have been conducted out. Based on the Rayleigh approximation, the attenuation of the EMWs is calculated [9,10], and it is found that the Rayleigh approximation could be used to predict the attenuation at lower frequency, that is to say, it can only calculated the scattering of particle, which radius is much smaller than the wavelength of the incident EMWs [11]. But as frequency increases, it is invalid to calculate the attenuation because of its inherent assumption [12]. In case of the high frequency of EMWs, the attenuation predicting model is established based on the Mie theory [13–17], it was found that the attenuation is related to the visibility, the frequency of the incident electromagnetic wave and the particle size distribution. The charge on the particles' surface can also affect the scattering field of the EMWs [18–29], leading to increase the attenuation. The effect of charges on the attenuation by the DUSA storms is firstly investigated by Zhou et al. considering net charges partly covering sand particle's surface, and it was found that net charges carried on the sand particle surface make the EMWs signals attenuated significantly [18], which explained why the experimental result is much lower than the calculated one without considering the electrical effect reported by Haddad et al. [6]. In addition, many results indicate that the RH has a significant effect on the dielectric constant [30–32], and further affects the attenuation of EMWs, and the particles' size and distribution could also affect the scattering/absorption efficiency of the EMWs [14,33,34]. Actually, all these factors

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mentioned above exist in any DUSA storm, and what is the effect of all these factors considering simultaneously on the attenuation of the EMWs?

For this purpose, the attenuation caused by the DUSA storm in this paper is investigated by considering the relative humidity, the charge carried on the particles, and the particles' size. In Section 2, we introduced the predicting model and the principle of parameters chosen in this paper. The calculated results are displayed in Section 3, and we also discussed these factors' influence on the attenuation, respectively. In Section 4, we compared the calculated with the measured attenuation.

2. Prediction model of attenuation due to DUSA storms

A linearly plane EMWs polarized in x-axis direction propagate through the DUSA storm along z-axis shown as in Fig. 1, in which the DUSA particles are assumed as spheres with uniform net charges over covering the surface. The surface charge density carried on the particles is denoted as σ. The attenuation of the EMW in unit distance, the attenuation coefficient A_P in dB/km, can be calculated by the formula proposed by Hulst as following [35],

$$A_P = 4.343 \times 10^3 \int_{R_{min}}^{R_{max}} C_{ext}(R)N(R)dR \tag{1}$$

in which $C_{ext}(R)$ is the extinction cross section of the spherical particle with the radius R. R_{max} and R_{min} are the maximum radius and the minimum radius of the particles in the DUSA storms, respectively. $N(R)dR$ is the total number of the particles in the unit volume with the radius from R to $R+dR$.

In case of a single particle with the radius R, the particle's extinction/scattering/absorption cross section can be calculated by formula (2) which is deduced out in Ref. [3],

$$\begin{aligned} C_{ext} &= \frac{2\pi}{k^2}\sum_{n=1}^{\infty}(2n+1)\mathrm{Re}(a_n+b_n) \\ C_{sca} &= \frac{2\pi}{k^2}\sum_{n=1}^{\infty}(2n+1)\left(|a_n|^2+|b_n|^2\right) \\ C_{abs} &= C_{ext}-C_{sca} \end{aligned} \tag{2}$$

where $\mathrm{Re}(\cdot)$ represents the real part of a complex number, and a_n and b_n are the Mie coefficients of the scattering filed of the EMWs by a surface charged spherical particle, which can be got by solving the Maxwell equations with the boundary conditions to refer to Refs. [21–24], regardless of the magnetism of the particles,

$$\begin{cases} a_n = \dfrac{\psi_n(x)\psi_n'(mx) - m\psi_n'(x)\psi_n(mx) - i\omega k^{-1}\mu_0^{-1}\sigma_s\psi_n'(x)\psi_n'(mx)}{\xi_n(x)\psi_n'(mx) - m\xi_n'(x)\psi_n(mx) - i\omega k^{-1}\mu_0^{-1}\sigma_s\xi_n'(x)\psi_n'(mx)} \\ b_n = \dfrac{\psi_n'(x)\psi_n(mx) - m\psi_n(x)\psi_n'(mx) + i\omega k^{-1}\mu_0^{-1}\sigma_s\psi_n(x)\psi_n(mx)}{\xi_n'(x)\psi_n(mx) - m\xi_n(x)\psi_n'(mx) + i\omega k^{-1}\mu_0^{-1}\sigma_s\xi_n(x)\psi_n(mx)} \end{cases} \tag{3}$$

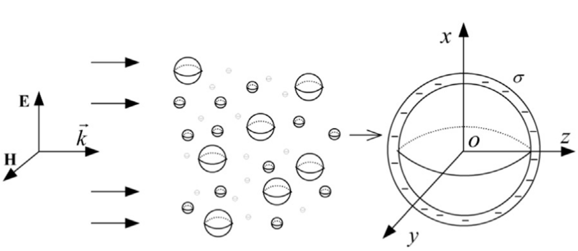

Fig. 1. Schematic of the plane electromagnetic waves with x-axis polarization propagates through a DUSA storm along the z-axis. The particles in the DUSA storms are electrified and carry net charges on the surface, and the surface charge density is denoted as σ. $\boldsymbol{k}$, **E** and **H** is the EMWs propagating direction, the electric field and the magnetic field.

where $\psi_n(x) = xj_n(x)$ and $\xi_n(x) = xh_n^{(1)}(x)$ ($j_n(x)$ is the spherical Bessel function, $h_n^{(1)}(x)$ is the spherical Hankel function); $x = \frac{2\pi Rf}{c}$ is the size parameter, in which $c=3.0\times10^8$ m/s, and f is the frequency of the incident EMWs; $m = \sqrt{\varepsilon_r(RH)}$ is the relative refractive index, where $\varepsilon_r(RH)$ is the relative dielectric constant; μ_0 is the permeability of vacuum; $k = \frac{2\pi f}{c}$ is the wave number, and σ_s is the surface conductivity, which is used to describe the charges on the surface of the particle [36]. The relationship of the surface conductivity with the surface charge density is firstly proposed by Bohren and Hunt [36], and later, Klačka and Kocifaj made a detailed introduction to the surface electrical conductivity, which can be further expressed by temperature and potential [23,24], shown as in formula (4),

$$\sigma_s = \frac{i\sigma e/m_e}{2\pi f + ik_bT/\hbar} \tag{4}$$

Here T is the temperature of the particle in K. $e=1.602\times10^{-19}$ C and $m_e=9.109\times10^{-31}$ kg, are the amount of element charge and the electron mass; $k_b=1.38\times10^{-23}$ JK^{-1} is Boltzmann's constant and $\hbar=1.0546\times10^{-34}$ Js is the reduced Planck's constant.

As mentioned above, the relative refractive index can be inversely derived by the dielectric constant. However the dielectric constant will be affected by the chemical composition of the DUSA particles, the frequency of the incident electromagnetic wave and the relativity humidity in air [37,38]. Some experimental results about the relative constant are shown that the real part, ε', of the complex dielectric constant first increases and then decreases with the increase of the frequency, while the imaginary part, ε'', increases with the increase of the frequency [39–42], shown as in the Table 1, also refer to the Refs. [16,32]. In addition, according to the measured dielectric constant by Sharif in Khartoum, Sudan [43], the relationship of the relative dielectric constant with the RH is proposed by Sharif [32,43], shown as in formula (5),

$$\begin{cases} \varepsilon_r'(RH) = \varepsilon' + 0.04RH - 7.78\times10^{-4}RH^2 + 5.56\times10^{-6}RH^3 \\ \varepsilon_r''(RH) = \varepsilon'' + 0.02RH - 3.71\times10^{-4}RH^2 + 2.76\times10^{-6}RH^3 \end{cases} \tag{5}$$

where, $\varepsilon_r = \varepsilon' - i\varepsilon''$ denotes the dry DUSA particles' relative dielectric constant; $\varepsilon_r(RH) = \varepsilon_r'(RH) - i\varepsilon_r''(RH)$ denotes the DUSA particles' relative dielectric constant related to the RH.

In addition, usually the visibility V in km is used to describe the sand particles concentration of the DUSA, which can be empirically expressed by the number of the total sand particles, N_T, per unit volume, presented by Goldhirsh [24], as following,

$$N_T = \frac{5.5\times10^{-4}}{VR_e^2} \tag{6}$$

where R_e is the equivalent radius of the distribution particle size, which can be calculated by $R_e = \left[\int p(R)\cdot R^3dR\right]^{1/3}$[44], in which $p(R)$ represents the distribution function of the particle size.

Table 1
The dust dielectric constant measured under different EMWs frequencies.

Frequency Band (GHz)	ε'	ε''	Reference
S-Band (3–4 GHz)	4.56	0.251	Ghobrial [41]
X-Band (8–12 GHz)	5.73	0.415	Sharif et al. [42]
Ku-Band (12–18 GHz)	5.50	1.300	Ruike et al. [40]
K-Band (18–27 GHz)	5.10	1.400	Ruike et al. [40]
Ka-Band (27–40 GHz)	4.00	1.325	Ruike et al. [40]
W-Band (75–110 GHz)	3.50	1.640	Ruike et al. [40]