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Propagation effect of a fractal rough ground boundary on the lightning-radiated vertical electric field

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ABSTRACT

A two-dimension fractional Brown motion (fBm) model is presented for describing the nature rough ground surface. By using an effective surface impedance algorithm derived by Barrick reference, the propagation effects of a fractal rough ground surface on the vertical electric field generated by lightning return strokes are analyzed. The results show that the extra field attenuation increment caused by the roughness decreases with the decrease of the ground conductivity, when the ground conductivity is less than 0.001S/m, the propagation effect of the rough ground surface with a mean square height of less than 10 m is nearly as same as that of the smooth and finitely conducting ground. However, when the ground conductivity is larger than 0.1S/m (wet earth), the frequencies higher than about 2 MHz are attenuated significantly by a rough ground surface with a mean square height of 10 m. For the derivative of the vertical electric field in time domain, the field attenuation caused by a rough ground is significant, while for the peak of the vertical electric field, there is no obvious attenuation.

1. Introduction

The electric fields generated by lightning return strokes have submicrosecond components which play a major role in the interaction of these electric fields with structures such as power lines (Master and Uman, 1984; Cooray and Rosa, 1986; Rubinstein et al., 1989). Since the high frequencies are selectively attenuated, the finitely conductivity will cause the amplitude of the electromagnetic fields to decrease and its rise time to increase when the lightning electromagnetic fields propagate over finitely conducting ground (Rubinstein et al., 1989; Cooray et al., 2000, Cooray, 2008, 2009; Delfino et al., 2008a,b; Shoory et al., 2010). Therefore, the experimental investigations on the high frequency components in lightning-generated electric fields are usually conducted under maritime conditions where the propagation path of the electric fields is over seawater with a good conductivity of 4 S/m. Weidman and Krider (1980), Weidman et al. (1981) and Willett et al. (1990) found that the experimentally obtained spectrum is rapidly attenuated when the frequencies are higher than about 10 MHz. However, Ming and Cooray (1994) and Zhang et al. (in press) analyzed the propagation effect of the rough ocean surface on the lightning-generated electric fields, and found that for frequencies higher than about 10 MHz, the attenuation caused by the rough ocean surface is significant, and some of the feature spectrum observed by Weidman and Krider (1980) and Weidman et al. (1981) should be accounted for the errors introduced by the propagation effect of the roughness of the ocean surface.

Comparing with the rough ocean surface, the ground surface is less finitely conducting ground with more terrain irregularities. However, despite many researchers have

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analyzed the propagation effect of the electric fields generated by lightning return stroke along the ground, nearly all treatments of the subject took the earth surface as a smooth and finitely or perfectly conducting ground (Qie et al., 2007, 2009, 2011; Yang et al., 2008; Zhang et al., 2009, 2011a,b; Rubinstein, 1996; Cooray et al., 2000, Cooray, 2008, 2009; Shoory et al., 2010). In fact, the rough ground surface may have more significant effects on the electric fields generated by lightning return strokes, because the roughness of the ground surface can be expressed as an increase in the normalized surface impedance of the smooth ground, and the roughness of the ground surface decreases the apparent conductivity of the earth. Also, the experimental investigations on the lightning-generated electric field are often conducted under a rough ground conditions, however, the effect of rough ground surface on the lightning-generated electric field have been not well addressed (Shoory et al., 2005; Apaydin and Sevgi, 2010). Therefore, it is very valuable and necessary to study the propagation effect of the rough ground surface on the lightning-generated electric field.

As for the simulation of the rough ground surface, since natural ground surfaces are generally neither purely random nor purely periodic and often anisotropic, the introduction of fractal geometry provided a new tool for describing natural rough structures (Mandelbrot, 1982). A normalized two-dimension band-limited Weierstrass fractal function is usually used to model a rough surface, and this function shows a combination of both deterministic periodic and random rough structures. However, the Weierstrass fractal function is a fixed model and cannot be used to simulate any random rough ground. A viable fractal model for the rough surface description is the fractional Brownian motion (fBm) (Falconer, 1990), and the fBm is widely recognized as the most suitable fractal process to model the natural ground surfaces.

Therefore, by using an effective surface impedance algorithm derived by Barrick (1971a,b), we will analyze the propagation effects of the fBm rough ground surface on the vertical electric field and its derivative generated by lightning return strokes.

2. Cooray approximation for the propagation effect of the lightning-generated vertical electric field along the rough ground

According to Cooray approximation (2008), the vertical electric field on the finitely conducting ground level is:

$$E_{v,\sigma}(j\omega,0,d) = E_{s,\infty}(j\omega,0,d) + E_{i,\infty}(j\omega,0,d) + E_{r,\infty}(j\omega,0,d)W(j\omega,0,d) \tag{1}$$

where, $E_{v,\sigma}(j\omega, 0, d)$ is the total vertical electric field in frequency domain on the finitely conducting ground, $E_{s,\infty}(j\omega, 0, d)$, $E_{i,\infty}(j\omega, 0, d)$ and $E_{r,\infty}(j\omega, 0, d)$ are the electrostatic field, the induction field and the radiation field in frequency domain, respectively, assuming the ground to be perfectly conducting.

$W(j\omega, 0, d)$ is the attenuation function corresponding to an electric dipole located at the lower end of the lightning channel. The attenuation function $W(j\omega, 0, d)$ is given by Wait (1956, 1974, 1998):

$$W(j\omega,0,d) = 1 - j\sqrt{\pi p}\exp(-p)erfc(j\sqrt{p}) \tag{2}$$

$$p = -\frac{j\omega d}{2c}\Delta_{eff}^2 \tag{3}$$

where, Δ_{eff} is the effective surface impedance corresponding to the rough ground,d is the horizontal distance from the observed point to the lightning channel on the ground level, ω is the radial frequency, c is the light speed, $j=\sqrt{-1}$, "erfc" is the complementary error function. Therefore, from Eqs. (1)-(3), we can see that the effective surface impedance Δ_{eff} is crucial for the propagation effect of the rough ground surface on the lightning electric fields.

3. Effective surface impedance and attenuation function of the rough ground

3.1. Two-dimension fractional Brown motion (fBm) model

In order to calculate the effective surface impedance Δ_{eff} of the fractal rough ground surface, the average height density spectral has to be firstly solved. For the 2D fBm model, the height spectral density is given by Falconer (1990):

$$V(\gamma,\eta) = V_0\left(\gamma^2+\eta^2\right)^{-a/2} \tag{4}$$

where, $V_0 = h^2/2\pi L$, $a = 8-2D$, D is the fractal dimension, L is the correlation length, h is the mean-square root of height, γ and η are the radial wave numbers (or spatial frequencies) along the x and y direction.

Fig. 1 shows the simulated fBm fractal ground surface by using the method of Monte Carlo, D = 2.3, L = 200 m, h = 5 m and 10 m, respectively. The detail simulation technique for the 2D fBm rough ground is referred to Guo and Wu (2001).

3.2. Effective surface impedance and attenuation function

Barrick (1971a,b) showed that the roughness of the ground surface can be expressed as an increase in the normalized surface impedance. For example, in the case of a rough ground surface the effective impedance Δ_{eff} is given by Ming and Cooray (1994):

$$\Delta_{eff} = \Delta + \Delta' \tag{5}$$

$$\Delta = \frac{k_0}{k}\left(1-\frac{k_0^2}{k^2}\right)^{1/2} \tag{6}$$

$$k = k_0(\varepsilon_r - j60\sigma\lambda_0)^{1/2} \tag{7}$$

$$k_0 = \omega(\mu_0\varepsilon_0)^{1/2} \tag{8}$$

where, Δ is the normalized surface impedance of the smooth ground with a conductivity σ and a dielectric constant $\varepsilon = \varepsilon_0\varepsilon_r$, ω is the radial frequency, ε_0 and μ_0 are the dielectric constant and magnetic permeability of free space,