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Evaluation of a first return stroke model considering the lightning channel tortuosity

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ABSTRACT

In this paper, the influence of the lightning channel tortuosity on the spatial and temporal return stroke current distribution, is evaluated. A return stroke model, developed with the current generation concept, has been used. The random tortuosity of the lightning channel is represented by a numerical model which also enables the linear charge density modeling. It is shown, that when the tortuosity of the lightning channel is taken into account, the return stroke current profile exhibits an amplitude attenuation and a time delay with respect to the current profile of the associated straight and vertical channel. It is worth pointing that the results presented in this paper are theoretical and obtained by means of numerical simulation, with exception of the linear charge density model, which was obtained using both, numerical simulation as well as experimental data obtained previously by other authors, as described in the paper.

1. Introduction

Nowadays there are a variety of lightning return stroke models provided in the literature. According to [1], most of the published models can be assigned to one or sometimes two of the following four classes: gas dynamic or physical models, electromagnetic models, distributed-circuit models and engineering models. Most of the return stroke models do not consider the tortuous geometry of the lightning channel, which is inherent to lightning, and most of them represent the lightning channel as straight and vertical to a flat ground, however, real lightning channels exhibit tortuous and branched geometries.

Some of the principal works conducted in order to analyze the effect of the random geometries of the lightning channel on the models for the different stages of the phenomena, have considered mainly the effect of the lightning channel geometry on the radiated electromagnetic fields [2,3,20,4–7], the effect of the tortuosity on the induced voltages [8], the characterization of tortuosity by means of laboratory experiments with short sparks [9] and the lightning propagation modeling by means of simulation [10]. One of the authors of the present paper has been involved with a research concerning the modeling of the lightning leader stage for channels with tortuosity and branching and as a result of this study, a new model has been developed. The model in question was proposed by Vargas and Torres and it is described in [11,12]. This model enables the calculation of the linear charge density and many other parameters, all of them considering the tortuosity of the lightning channel.

The model proposed by Vargas and Torres uses the total electric charge stored in the stepped leader channel and the relationship between the total charge in the leader and the return stroke peak current, obtained by Cooray et al. in [21], by means of experimental measurements of current waveforms measured by other authors. Cooray et al constructed an idealized model for the stepped leader, thundercloud, and ground, and solved this model numerically by means of the charge simulation method. The unknowns were the electrical charges along the stepped leader channel. In this way, Cooray et al. estimated the distribution of charge along the stepped leader, predicting a major accumulation of charge near the tip of the descending leader. For the complete description of the Cooray et at. model, please refer to [21].

The model of Vargas and Torres includes a methodology for the computer generation of stepped leader random geometries with a macroscale tortuousity similar to the one recorded in nature and is a model based on the bipolar and bidirectional concept of the leader channel. In this way, as opposed to the Cooray et al. model [21], which represented the leader channel as straight and vertical to a flat ground, the model of Vargas and Torres is able to represent the leader channel including random geometries with tortuosity and with or without branches. Using this more realistic representation of the leader channel, Vargas and Torres made use of the

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charge simulation method as well, in order to obtain the distribution of charge along the leader channel. Vargas and Torres also found that there is a major accumulation of charge near the tip of the descending leader. For a detailed description of the Vargas and Torres model, please refer to [11,12].

In this paper, the authors make use of the Vargas and Torres model [11,12], in order to simulate random lightning channels with a macroscale tortuosity similar to the one observed in nature [13–15], and then, these simulations are used to evaluate a return stroke model. In this manner, the authors compare the results obtained when the tortuosity of the channel is taken into account, with those that are obtained for the associated straight and vertical channel. The return stroke model used to evaluate the effect of the lightning channel geometry is a model that uses the concept of current generation and it is described in [16]. This work is an effort to comprehend the effect of lightning channel tortuosity on the linear charge distribution along the leader channel and on the distribution of currents along it.

2. Linear charge density modeling

2.1. Data description

In order to model the linear charge density along a tortuous lightning channel, the Vargas and Torres model was used. First, 2000 random lightning channels with tortuous geometries were generated and then, the model was used to calculate the linear charge density on each segment of each channel. The data obtained consist of the following variables:

1. ρ_{ij}: The linear charge density, for the segment *j*, in channel number *i*.
2. Q_i: The total electric charge stored in the complete channel number *i*.
3. $x_{s_{ij}}, y_{s_{ij}}, z_{s_{ij}}$: The Cartesian coordinates for the starting or initial point of the segment *j* in the channel *i*.
4. $x_{f_{ij}}, y_{f_{ij}}, z_{f_{ij}}$: the Cartesian coordinates for the final point of the segment *j* in the channel *i*.
5. γ_{ij}: The total distance along the tortuous channel from ground to the center of the segment *j* in the channel *i*.

According to this notation, the limits for the variables *i* and *j* are the following: $1 \leq i \leq 1000$, $1 \leq j \leq p$. Where *p* is the number of segments composing the tortuous channel.

2.2. General definition and calculation for γ

From the above definitions, and for a specific tortuous channel (constant value for *i*), the variable γ can be related to a height *z* over the associated straight channel. Thus, the variable γ is a function of height *z* ($\gamma = f(z)$). This means that for each point in a straight channel, there is an equivalent point on the tortuous channel which has the same height and can be calculated as follows:

$$\gamma(z) = \left[\sum_{j=1}^{M-1} \sqrt{(x_{f_j} - x_{s_j})^2 + (y_{f_j} - y_{s_j})^2 + (z_{f_j} - z_{s_j})^2}\right] + \sqrt{(x - x_{s_M})^2 + (y - y_{s_M})^2 + (z - z_{s_M})^2} \quad (1)$$

where *M* is the channel segment number that satisfies the condition $z_{f_M} \geq z$. The *x* and *y* can be calculated from the symmetric equations for a line in space:

$$x = \frac{(z - z_{s_M})(x_{f_M} - x_{s_M})}{(z_{f_M} - z_{s_M})} + x_{s_M} \quad (2)$$

$$y = \frac{(z - z_{s_M})(y_{f_M} - y_{s_M})}{(z_{f_M} - z_{s_M})} + y_{s_M} \quad (3)$$

For this case the variable γ is the total distance along the tortuous channel from ground to the point with height *z*.

2.3. Regression analysis

With the previous definitions, the data of 1000 of the simulated channels were used to produce an equation by means of nonlinear regression analysis [17], and the remainder data of the other 1000 channels were used to test the validity of the model. A strong correlation was found between the linear charge density, ρ, and the variables *Q* (total charge stored on each channel) and γ (the coordinate defined above). The results obtained are presented in Section 4.1.

3. Return stroke model

The first return stroke model presented in [16] has been selected in order to compute the current profile due to a lightning channel with tortuosity. This model enables the inclusion of different charge density profiles and it also enables the calculation of currents for a lightning channel with a known geometry, inasmuch as this model describes some physical aspects of the return stroke process. Following is a description of the assumptions made in order to include the lightning channel geometry in the model and the mathematical modeling needed to compute the currents according to these assumptions.

3.1. Assumptions for a tortuous channel

The assumptions presented in [16] for a straight channel, remain for the tortuous channel but with the following modifications:

(a) The linear charge density of the descending leader is variable and it depends on the γ coordinate, according to Eq. (10).
(b) All the physical events which depend on *z* in a straight channel, are dependent on γ in a tortuous channel.

3.2. Mathematical modeling

Since for the tortuous channel, all the physical events described in [16] depend on the γ coordinate, the mathematical modeling presented there, has to be expressed in terms of this variable. Thus, the velocity of the connecting leader can be expressed as:

$$v_c(\gamma) = v_0 e^{(\gamma/\lambda_c)} \quad (4)$$

The velocity of the return stroke can be represented by:

$$v_r(\gamma) = v_i e^{(-\gamma - l_c/\lambda_r)} \quad (5)$$

The current per unit length injected into the channel at a given point, with γ coordinate can be represented for the tortuous channel by:

$$I_c(\gamma, t) = \frac{\rho(\gamma, Q)}{\tau(\gamma)} e^{(-t/\tau(\gamma))} \quad (6)$$

Where the charge per unit length $\rho(\gamma, Q)$ is modeled by Eq. (10).

The variables $v_0, v_i, \lambda_c, \lambda_r$ and l_c can be calculated for the tortuous channel according to the procedure presented in [16] and using the equations described above.