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A transmission-line-type model for lightning return strokes with branches

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ABSTRACT

We examine the effect of channel branching on electric field waveforms produced by first return strokes in negative cloud-to-ground lightning using a modified transmission line model. From computed return stroke electric field waveforms it is found that the presence of an ungrounded branch results in sharper initial peak and a secondary peak in the falling part of the return stroke waveform. The time interval between the primary and secondary peaks depends upon the height of the branching point above ground and the speed at which the incident current wave moves upward from the ground. The presence of branch serves to slightly decrease the magnitude of the opposite polarity overshoot. The effects of the height of the branching point above ground, fraction of total channel current flowing to the branch, and current reflections from the branch unconnected end are illustrated.

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1. Introduction

Return-stroke models (e.g., Rakov and Uman [1]) are used to relate the channel base current to the current distribution along the channel, which, in turn, can be used to calculate return-stroke electric and magnetic fields. Specifically, the transmission line (TL) model (Uman and McLain [2]) has been demonstrated to work reasonably well in reproducing both close (e.g., Schoene et al. [3]) and relatively distant (e.g., Willett et al. [4]) fields for the first few microseconds of strokes in rocket-triggered lightning (which are thought to be similar to natural negative lightning subsequent strokes). Modifications to the TL model include a linear (MTLL, Rakov and Dulzon [5]) and exponential (MTLE, Nucci et al. [6]) current decay with height. Both models are able to reproduce in return stroke electric and magnetic fields the sharp initial peak and zero-crossing within tens of microseconds of the initial peak at about 50–200 km.

In this study, we examine the effect of channel branching on distant electric field waveforms produced by first return strokes in negative cloud-to-ground lightning using a modified transmission line model. Correlated high-speed video and electric field measurements for return strokes with channel branching have been reported by Stolzenburg et al. [7]. The effects of channel branches on return-stroke radiated fields have been theoretically studied by Le Vine and Meneghini [8], Vecchi et al. [9], Lupo et al. [10], and Zich and Vecchi [11]. One of the objectives of those studies was reproduction of pronounced fine structure observed in measured electric and magnetic fields of first return strokes. In this paper, we develop a simple model that allows us to examine the effects of a single branch, depending on its various parameters, with focus on individual features of field waveforms, as opposed to their overall appearance. Results of this study will help to improve our understanding of the relationship between field characteristics and source parameters needed, for example, in remote measurements of lightning currents.

2. Transmission line model

The transmission line (TL) model (Uman and McLain [2]) for return strokes involves a current wave injected at the bottom of the lightning channel traveling upward at constant speed v without attenuation or distortion. For the TL model the longitudinal current $i(z,t)$ at any height z and any time t is related to the current at the channel origin (which in this study is at ground level) is given by Eq. (1).

$$i(z,t) = i\left(0, t - \frac{z}{v}\right) \quad (1)$$

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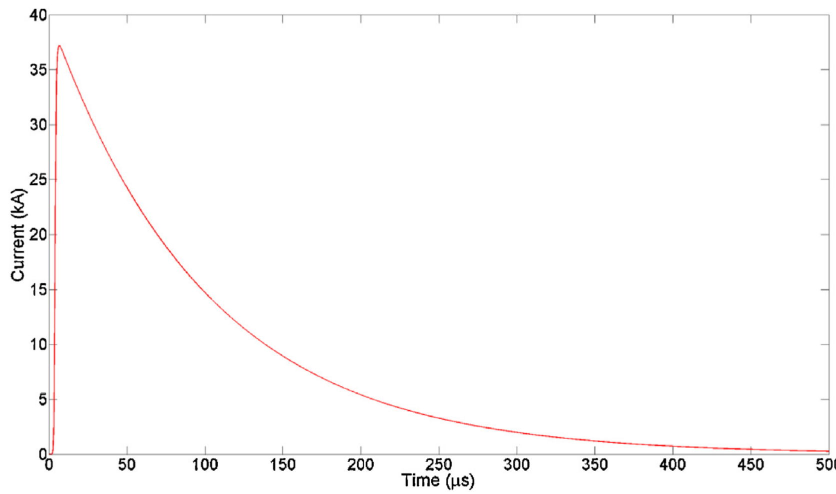

Fig. 1. The incident return stroke current waveform computed using the Heidler function that is used in this study, shown on a 500 μs timescale. The current peak is about 37 kA and the zero-to-peak risetime is 6.6 μs. The half-peak width is 72 μs. This current waveform is representative of negative first return strokes.

The current decay with height in the MTLL and MTLE models is represented by Eqs. (2) and (3), respectively.

$$i(z,t) = \left(1 - \frac{z}{H}\right) i\left(0, t - \frac{z}{v}\right) \tag{2}$$

$$i(z,t) = e^{-z/\lambda} i\left(0, t - \frac{z}{v}\right) \tag{3}$$

H in Eq. (2) is the assumed vertical channel length and λ in Eq. (3) is the assumed decay height constant. The overall electric field waveforms at close distances are best reproduced by the MTLL model. However, for the initial few microseconds all three models predict essentially the same fields.

The general time-domain equation for computing the vertical electric field dE_z due to a vertical differential current element idz (channel segment of length dz carrying a uniform current $i(t)$) at a height z above a perfectly conducting ground plane for the case of an observation point P on the plane at a horizontal distance r from the dipole is given by (e.g., Uman [12]):

$$dE_z(r,t) = \frac{1}{2\pi\varepsilon_0}\left[\frac{(2z^2 - r^2)}{R^5(z)} dz \int_0^t i\left(z, \tau - \frac{R(z)}{c}\right) d\tau + \frac{(2z^2 - r^2)}{cR^4(z)} i\left(z, t - \frac{R(z)}{c}\right) dz - \frac{r^2}{c^2 R^3(z)} \frac{di(z, t - (R(z)/c))}{dt} dz\right] \tag{4}$$

where ε_0 is the electric permittivity of free space, R is the inclined distance from the dipole to the observation point, which is given by $R = \sqrt{z^2 + r^2}$.

From Eq. (4), the total electric field at the observation point for a finite-length vertical channel whose lower and upper ends are at

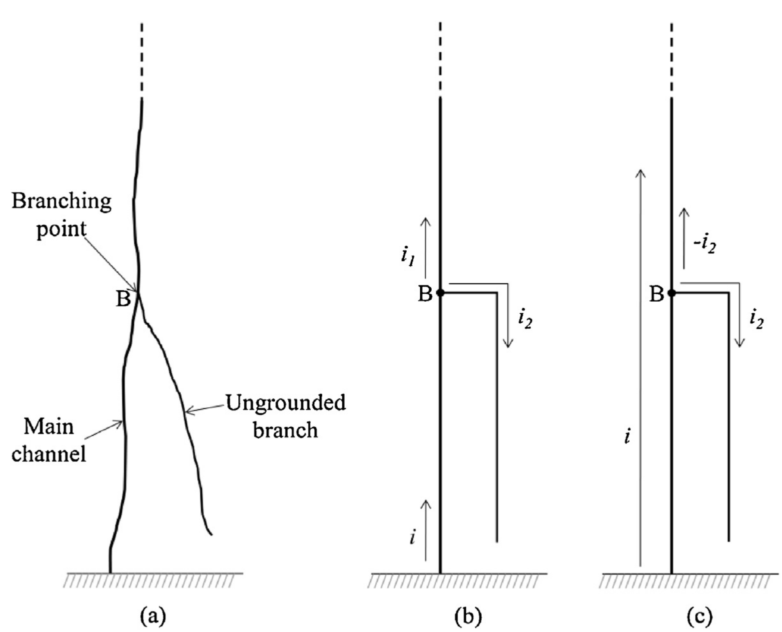

Fig. 2. (a) The geometry of the lightning channel considered in this paper. The channel consists of a main channel that extends between the ground and the cloud charge source region, and additionally, includes an ungrounded branch. (b) The simplified version of the channel geometry shown in (a). Both the main channel and the branch are considered to be vertical and separated by a short horizontal channel segment. (c) Configuration equivalent to (b) that was used in computing fields. See text for details.

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