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Comment on "Return stroke transmission line model for stroke speed near and equal that of light" by R. Thottappillil, J. Schoene, and M. A. Uman

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[1] Electric fields on the ground 500 m, 5 km, and 50 km from the lightning channel base computed using the transmission line (TL) and antenna theory (AT) return-stroke models for a typical subsequent stroke current at the channel base and a return-stroke speed equal to the speed of light (v = c) are compared. The AT model gives a total electric field peak that is about 10% lower than the field peak predicted by the TL model. Optical measurements of the return-stroke speed within the bottom 100 m of the lightning channel are reviewed and found to be not supporting the assumption of v = c. *INDEX TERMS:* 3324 Meteorology and Atmospheric Dynamics: Lightning; 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 0609 Electromagnetics: Antennas; 0619 Electromagnetics: Electromagnetic theory; 0624 Electromagnetics: Guided waves

1. Introduction

[2] *Thottappillil et al.* [2001] analytically showed that for the Transmission Line (TL) model of the lightning return stroke the waveshapes of the electric and magnetic fields at all points in space and the waveshape of their causative current are identical, if the return-stroke speed, v, is assumed to be equal to the speed of light, c. The TL model assumes that a lightning return-stroke current pulse does not suffer any attenuation or distortion as it propagates along the channel. In this paper, we compare the electric fields predicted by the TL model with v = c and those predicted by the Antenna Theory (AT) model [*Moini et al.*, 2000] using the same channel-base current waveform. The AT model is based on the numerical solution of Maxwell's equations using the method of moments and thin-wire approximation [e.g., *Balanis*, 1997]. A detailed comparison of the TL and AT models is given in Table 1. In our view, the lightning channel geometry and the source in the AT model are more realistic than those in the TL model. Additionally, we review the optical measurements of the lightning return-stroke speed within the bottom 100 m of the channel to evaluate the applicability of the assumption of v = c to lightning.

2. Analysis and Results

[3] In comparing the electric fields predicted by the TL and AT models, we consider a straight and vertical lightning channel (of zero radius in the TL model and of 5-cm radius in the AT model) above a perfectly conducting ground and use the same lightning channel-base current waveform as that used by *Moini et al.* [2000]. This waveform [see Figure 2 of *Moini et al.*, 2000] is characterized by a peak value of about 11 kA and by a peak current rate of rise of about 105 kA/μs, which are typical for subsequent return strokes. For the TL model, we set v = c, and for the AT model we set R = 0 (no distributed resistance) and do not include the corona effect considered by *Moini et al.* [2000], so that for the AT model v is also essentially equal to c. Note that in the TL model the current waveform does not change as it propagates along the channel, while in the AT model the current waveform suffers appreciable attenuation and dispersion due to the radiation losses from the channel. Specifically, the current peak in the AT model decreases from about 11 kA to about 10 kA over the bottom 300 m of the channel.

[4] We computed the total electric fields and their individual components on perfectly conducting ground surface at three distances, 500 m, 5 km, and 50 km, from the channel base. For

Table 1. Comparison of the Transmission Line (TL) Model with v = c and the Antenna Theory (AT) Model

Model	Lightning Channel Geometry	Source	Current Distribution Along the Channel	Field Structure
TL	Infinitely conducting zero-radius cylinder (zero-angle inverted cone) above a perfectly conducting ground	Ideal current source producing spherical TEM wave (theta-directed E-field) at the base of the channel	No attenuation or dispersion	Guided spherical TEM wave, no radiation losses occur (analytical solution)
AT	Infinitely conducting cylinder of non-zero radius above a perfectly conducting ground	Delta-gap generator producing longitudinal E-field between the base of the channel and the ground	Attenuation and dispersion as the current wave propagates along the channel	Full wave (not pure TEM wave) numerical solution, radiation losses occur

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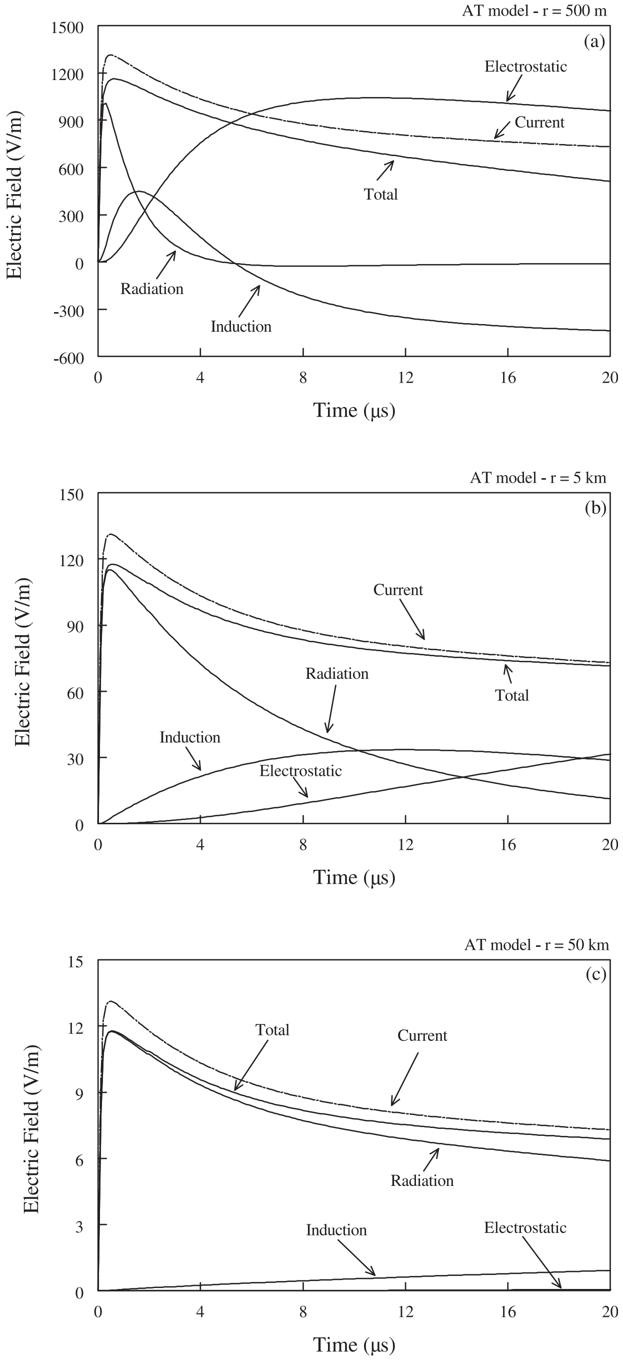

Figure 1. Electric field on the ground and its components (electrostatic, induction, and radiation) calculated using the AT model (a) 500 m, (b) 5 km, and (c) 50 km from the lightning channel. Also shown is the channel-base current waveform scaled so that it also represents the total electric field predicted by the TL model with v = c.

the TL model the waveshapes of the total electric fields at all three distances considered are identical to each other (although the individual field components are different) and to the waveshape of the channel-base current, consistent with the findings of *Thottappillil et al.* [2001]. For the AT model (see Figures 1a, 1b, and 1c), the waveshapes of the total electric fields, computed at the three distances, differ from the waveshape of the channel-base current after the peak (after the initial some hundreds of nanoseconds). Further, the AT-model-predicted total electric fields are smaller than the corresponding TL-model-predicted fields, the latter being represented in Figures 1a, 1b, and 1c by the channel-base current waveforms. Specifically, the total field peaks predicted by the AT model are about 10% lower than the corresponding field peaks predicted by the TL model.

3. Discussion

[5] The differences between the predictions of the AT and TL models are due to a decrease of current peak and an increase of current risetime as the return stroke propagates along the channel in the AT model and no such effects in the TL model. The current attenuation and dispersion in the AT model are associated with the radiation losses that necessarily occur when a non-zero radius wire is excited by a non-TEM-wave source (see Table 1).

[6] We now review the optical measurements of the lightning return-stroke speed within the bottom 100 m or so of the channel in order to evaluate the applicability of the assumption of v = c to lightning. *Wang et al.* [1999b] reported on two-dimensional speed profiles within 400 m of the ground for two return strokes in triggered lightning. The return-stroke speeds within the bottom 60 m of the channel were found to be 1.3×10^8 and 1.5×10^8 m/s. Further, *Weidman* [1998] reported mean return-stroke speeds in the lowest 100 m of the lightning channel of 8.8×10^7 and 7.8×10^7 m/s for 14 triggered and 9 natural lightning strokes, respectively. Finally, Doug Jordan (personal communication, 1998) measured propagation speed of the optical front for one return stroke in triggered lightning that was approximately one-third of the speed of light between heights of 24 and 36 m above the lightning attachment point, similar to the speeds reported by *Wang et al.* [1999b] and by *Weidman* [1998] within the bottom 60 and 100 m, respectively. Thus the optical measurements of the return-stroke speed, although limited, do not support the suggestion of *Thottappillil et al.* [2001] that v = c for the bottom 30 m or so of the lightning channel, which implies that v abruptly decreases (more than a factor of two to three) over the next few tens of meters. Clearly, additional optical measurements of v for the bottom few tens of meters of the lightning channel are needed.

4. Concluding Remarks

[7] We summarize the results of our comparison of the TL model with v = c and the AT model by answering the following two questions:

1. Does an infinitely-conducting, traveling-wave vertical wire antenna above a perfectly-conducting ground have radiation losses so that current along the antenna is attenuated? In our view, the answer depends on the type of source (explicitly specified, as in the AT model, or implied, as in the TL model). The answer is "no" for the case of an ideal current source producing a spherical TEM wave, as in the TL model, and it is "yes" for the case of a longitudinal electric field source, as in the AT model (see Table 1).
2. Can the current attenuation predicted by the AT model be primarily due to unjustified model assumptions or/and computational errors? We think not, because similar attenuation of a current wave propagating along an infinitely-conducting vertical wire above a perfectly-conducting plane is predicted by the frequency-domain Numerical Electromagnetic Code NEC2 [*Bantin*, 2001; Baba and Ishii, personal communication, 2001]. NEC2 uses, similar to the AT model, the method of moments and thin-wire approximation and has been successfully tested against experimental data [e.g., *Lee and Hayakawa*, 2001]. Unfortunately, no analytical solution is possible for the physically realistic case of a non-zero radius wire excited by a longitudinal-electric-field source.

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comments on the manuscript, although they do not necessarily agree with all the results presented in the paper.

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