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Importance of Taking Into Account the Soil Stratification in Reproducing the Late-Time Features of Distant Fields Radiated by Lightning

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***Abstract*—In this paper, we present an analysis of the propagation effect along a lossy ground on the characteristics of lightning-generated electric fields, using simultaneous observations of lightning currents and radiated fields measured at nine different distances associated with rocket-triggered lightning. The triggered-lightning site is located in Conghua (Guangdong, China). The electric field waveforms were measured using the sensors belonging to the Foshan three-dimensional lightning location system that are located at distances from the triggered-lightning site ranging from 69 to 126 km. The propagation path was over land and mainly over flat ground. The field sensors used had an overall bandwidth from 160 Hz to 1 MHz. It is shown that even though the early response of the field can be reproduced reasonably well by adjusting the ground electrical conductivity, the subsidiary peaks, and the late-time response of the fields cannot be satisfactorily reproduced assuming a homogeneous ground model. However, a two-layer soil model allows obtaining very good agreement between computed and measured waveforms for all the considered distances and events. Compared to the homogeneous ground case, the computed early-, intermediate-, and late-time response follows to a much better extent the experimental waveforms. We also provide a discussion on the influence of the computational model and parameters on the simulated results.**

***Index Terms*—Distant electric fields, ground losses, horizontally stratified ground, return stroke, triggered lightning.**

I. Introduction

THE characteristics of lightning return-stroke electromagnetic fields, especially for natural lightning, have extensively been reported in the literature (e.g., [1]–[4]) These characteristics (waveshape, risetime, duration, zero-crossing time, etc.) depend obviously on the lightning discharge electrical and geometrical parameters. However, the ground electrical parameters over which electromagnetic fields propagate play also an important role in the lightning electromagnetic field waveshapes (e.g., [5]–[9]).

In the past years, significant efforts have been made to model the effect of the ground on the propagation of lightning-radiated electromagnetic fields (see, e.g., [10], [11]). Compared with dedicated algorithms (e.g., [12]) or numerical methods (e.g., [13]) that can be costly in terms of computation time and memory requirements, the use of simplified approaches (e.g., [5]–[10]) is particularly interesting when the electromagnetic fields need to be evaluated at a significant number of points, for instance, when evaluating the electromagnetic coupling to power networks. One of the first simplified approximations for the electromagnetic fields due to a vertical dipole above a homogeneous lossy ground is done by Norton [14]–[15]. Wait [16] showed that the concept of attenuation function and surface impedance can be used to represent the effect of a multilayered soil. Wait [17]–[19] and Hill and Wait [20] derived the attenuation function for the vertical electric field propagating over a horizontally stratified ground. Shoory *et al*. [21] examined the accuracy of Wait's formulations for a horizontally stratified ground using a numerical technique and found that Wait's formula is able to reproduce the vertical electric field peak and waveform with a reasonably good accuracy at far distances from the lightning channel. Other studies have considered the effect of a mixed propagation path or vertically stratified ground (e.g., [22] and [23]).

The aim of this paper is to analyze the propagation effect on the characteristics of lightning-generated electric fields. In particular, the effect of soil stratification on the radiated electromagnetic fields is assessed. For the analysis, we will use simultaneous observations of lightning currents and radiated fields measured at different distances associated with rocket-triggered lightning [24]. The present study demonstrates the importance of considering the soil stratification in reproducing the late-time features of distant fields radiated by lightning.

The paper is organized as follows. Section II briefly presents the experimental setup and measuring stations, as well as the obtained data. Section III describes the models and computational methods adopted in this paper. Section IV presents numerical

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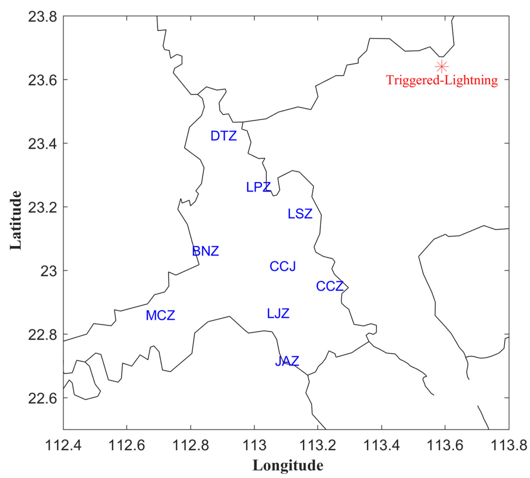

Fig. 1. Geographical location of the lightning triggering site in Conghua, Guangdong, and the nine sensors belonging to the lightning locating system in Foshan (FTLLS).

simulations and comparison with experimental data. The obtained results are commented and discussed in Section V. A summary and conclusions are given in Section VI.

II. Experimental Setup and Data

A. Experimental Setup

The triggered-lightning site, which is located in Conghua, Guangdong, China, has been operational for more than a decade. Information about the triggered-lightning site is available in [24]. The Foshan three-dimensional lightning location system (FTLLS) has been installed and started its operation in the summer of 2013 [25]–[27]. The network contains nine stations labeled in Fig. 1 as LSZ, LPZ, DTZ, CCJ, BNZ, CCZ, LJZ, JAZ, and MCZ. The stations are located at distances from the triggered-lightning site of, respectively, 69, 73, 74, 85, 87, 100, 101, 112, and 126 km. The triggering site, also shown in Fig. 1, is located on the northeast of the nine sensors. The propagation path is over land and mainly over flat ground [26].

Wideband electric field measuring systems with a 3 dB bandwidth from 160 Hz to 1 MHz are employed to measure the lightning electromagnetic fields at each station. The systems are equipped with analog integrators with a 1 ms decay time constant. Electric field signals produced by triggered-lightning discharges were digitized with a 10-MS/s sampling rate, 12-bit resolution, digital high-speed data acquisition card.

B. Data

The dataset is composed of simultaneous recordings of currents and multistation electric field waveforms associated with one negative triggered-lightning flash that occurred on June 3, 2014, at 6:43 AM (local time). The flash contains five return strokes, three of which (RS1, RS4, and RS5) were considered in this study.

III. Analysis Method

A. Return-Stroke Model

The modified transmission line model with exponential decay (MTLE) model was adopted for the analysis [28], [29]. The current decay constant along the channel was assumed to be $\lambda = 2$ km and a return-stroke speed of $= 1.5 \times 10^8$ m/s was adopted in all the simulations. The adopted value for the current decay constant was inferred using experimental data [30]. This value is used in most of the studies using this model (e.g., [31]–[36]). The measured channel-base current waveform was represented using the sum of two Heidler's functions [37]

$$i(0,t) = \frac{I_{01}}{\eta_1}\frac{\left(\frac{t}{\tau_{11}}\right)^{n1}}{\left(\frac{t}{\tau_{11}}\right)^{n1}+1}e^{-\frac{t}{\tau_{12}}} + \frac{I_{02}}{\eta_2}\frac{\left(\frac{t}{\tau_{11}}\right)^{n2}}{\left(\frac{t}{\tau_{21}}\right)^{n2}+1}e^{-\frac{t}{\tau_{22}}}$$
$$\eta_1 = \exp\left(-\frac{\tau_{11}}{\tau_{12}}\left(n_1\frac{\tau_{12}}{\tau_{11}}\right)^{1/n_1}\right)$$
$$\eta_2 = \exp\left(-\frac{\tau_{21}}{\tau_{22}}\left(n_1\frac{\tau_{22}}{\tau_{21}}\right)^{1/n_2}\right). \quad (1)$$

The parameters of (1) were determined for each return stroke using a genetic algorithm [38]. The reason why the measured current was represented by analytical functions is that the use of the raw data, which includes noise could cause numerical issues. Fig. 2 presents the measured current waveforms associated with the three considered return-stroke pulses along (to which we refer in this study as RS1, RS4, and RS5) with their analytical representations using Heidler's functions. The determined parameters of the functions for each waveform are given in Table I.

B. Electric Field Computation Model

Three different approaches will be used in this study to model the ground plane in the computation of the electric fields at various distances: a perfectly conducting ground plane, a homogeneous finitely conducting ground plane, and a two-layer stratified ground.

1) Perfectly Conducting Ground: Fig. 3 presents the geometry adopted for the calculation of lightning electric field. The expression for the vertical electric field radiated by a vertical channel above a perfectly conducting ground is given by (e.g., [10])

$$e_{z,p}(d,z,t) = \frac{1}{2\pi\varepsilon^\circ}\int_0^{H(d,z,\varphi,t)} \times \left[\begin{array}{l} \frac{2(z-z')^2-d^2}{R^5(z')}\int_{R(z')/c+z'/c}^{t} i\left(z',\tau-\frac{R}{c}\right)d\tau \\ +\frac{2(z-z')^2-d^2}{cR^4(z')} i\left(z',t-R(z')/c\right) \\ -\frac{d^2}{c^2R^3(z')}\frac{\partial i\left(z',t-R(z')/c\right)}{\partial t} \end{array}\right] dz'$$
$$-\frac{1}{2\pi\varepsilon^\circ}\frac{d^2}{c^2R^3H(d,z,\varphi,t)} \times i\left(H(d,z,\varphi,t),\frac{H(d,z,\varphi,t)}{v}\right)\frac{dH(d,z,\varphi,t)}{dt} \quad (2)$$

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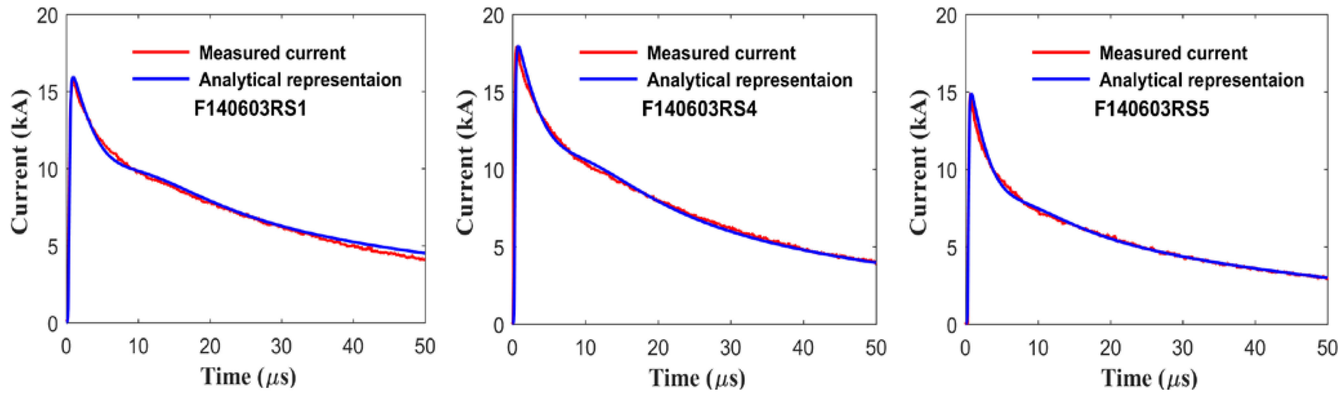

(a) (b) (c)

Fig. 2. Measured current waveforms associated with the three selected return stokes (solid blue line) and their analytical representations using Heidler's functions (solid red line). (a) RS1. (b) RS4. (c) RS5.

TABLE I
PARAMETERS OF HEIDLER'S FUNCTIONS USED TO REPRESENT THE RETURN STROKE CURRENT WAVEFORMS

Lightning return stroke	$I_{01}(kA)$	$\tau_{11}(\mu s)$	$\tau_{12}(\mu s)$	n_1	$I_{02}(kA)$	$\tau_{21}(\mu s)$	$\tau_{22}(\mu s)$	n_2
RS1	16.0	0.501	9.6	5	5.6	10.0	77	3
RS4	18.0	0.359	8.9	5	5.9	9.5	60	3
RS5	15.0	0.417	6.1	6	5.0	8.0	55	3

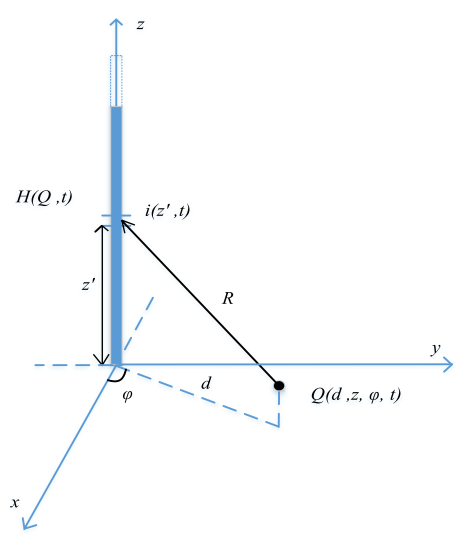

Fig. 3. Geometry for the calculation of the lightning electromagnetic field.

where $i(z', t)$ is the current in the return-stroke channel, $H(d, z, \varphi, t)$ is the apparent height of the wavefront as seen by an observer at Q at time t. R is the distance from a channel segment dz' at height z' to the observation point, d is the horizontal distance between the channel base and the observation point, c is the speed of light, v is return-stroke speed, and ε_0 is the permittivity of free space. The second subscript p holds for the field above a perfect ground. The last term in (2) is the so-called turn-on term field component accounting for a possible discontinuity at the return-stroke wavefront, as introduced and discussed by Le Vine and Meneghini [39], Rubinstein and Uman [40], [41], Le Vine and Willett [42], Thottappillil and Rakov [43], [44], Thottappillil *et al*. [45], [46], and Pavanello *et al*. [47]. The current distribution predicted by the MTLE model we are using in this paper does not feature any discontinuity at the wavefront, and therefore, this last term is equal to zero.

2) Homogeneous Finitely Conducting Ground: The vertical electric field above a homogeneous lossy ground can be written in the time domain as (e.g., [10])

$$e_z(d, z, t) = e_{z,p}(d, z, t) * f(t) \tag{3}$$

where $f(t)$ is the attenuation function accounting for the propagation effects along a lossy half-space. Expressions for the attenuation function and ground surface impedance can be obtained in the frequency domain and the corresponding time-domain expression can be derived using inverse Fourier transforms, i.e.,

$$f(t) = F^{-1}[F(j\omega)] \tag{4}$$

where ω is the angular frequency. Equation (3) can be equivalently expressed in the frequency domain as

$$E_z(d, z, j\omega) = E_{z,p}(d, z, j\omega)F(j\omega). \tag{5}$$

The expression for the attenuation function above a homogeneous ground derived by Wait [18] is as follows:

$$F(j\omega) = 1 - j\sqrt{\pi p}e^{-p}erfc(j\sqrt{p}) \tag{6}$$

where $erfc$ is the complementary error function [19] and p is the numerical distance defined as

$$p = -0.5\gamma_0 d\Delta^2 \tag{7}$$

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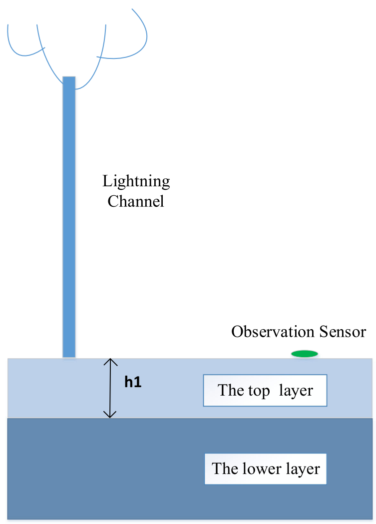

Fig. 4. Geometry for the calculation of the lightning electromagnetic field above a two-layer soil.

in which γ_0 is the free-space wavenumber defined as

$$\gamma_0 = j\omega\sqrt{\mu_0\varepsilon_0} \tag{8}$$

where μ_0 is the permeability of vacuum. Δ is the normalized surface impedance of the homogeneous ground given by

$$\Delta = \frac{Z(j\omega)}{\sqrt{\mu_0/\varepsilon_0}} \tag{9}$$

in which the homogeneous ground surface impedance is given by

$$Z(j\omega) = \sqrt{\frac{j\omega\mu_0}{\sigma + j\omega\varepsilon_0\varepsilon_r}}. \tag{10}$$

3) Two-Layer Stratified Ground: Fig. 4 shows the geometry of a two-layer stratified soil. The first layer is characterized by a vertical depth $h1$, and electrical parameters σ_1 and ε_{r1}. The second layer is characterized by electrical parameters σ_2 and ε_{r2}.

Wait *et al.* [10]–[16] derived the expression for the attenuation function of a stratified ground given by

$$F_{str}(j\omega) = 1 - j\sqrt{\pi p_{str}}e^{-p_{str}}erfc(j\sqrt{p_{str}}) \tag{11}$$

in which the numerical distance p_{str} is defined as

$$p_{str} = -0.5\gamma_0 d\Delta_{str}^2 \tag{12}$$

In (12), Δ_{str} is the normalized surface impedance of the two-layer ground given by

$$\Delta_{str} = \frac{Z_{str}(j\omega)}{\sqrt{(\mu_0/\varepsilon_0)}} \tag{13}$$

where

$$Z_{str} = \sqrt{\frac{\varepsilon_0}{\mu_0}}K_1\frac{K_2 + K_1\tanh(u_1h_1)}{K_1 + K_2\tanh(u_1h_1)} \tag{14}$$

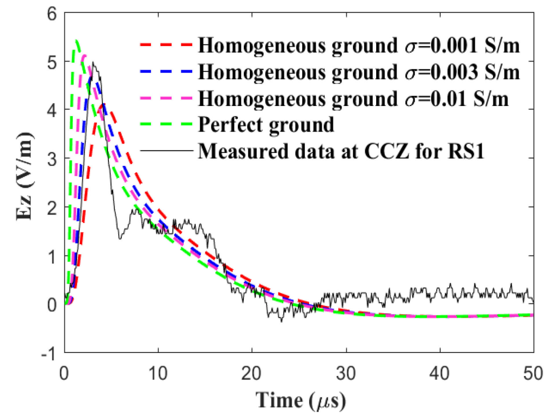

Fig. 5. Dashed color lines describe the simulation results for the homogeneous and for the perfect ground cases. The black solid line indicates the measured vertical fields at station of CCZ for the first return-stroke in flash F140603.

is the surface impedance of a two-layer horizontally stratified ground, and

$$K_1 = \frac{u_1}{\sigma_1 + j\omega\varepsilon_0\varepsilon_{r1}} \tag{15}$$

$$K_2 = \frac{u_2}{\sigma_2 + j\omega\varepsilon_0\varepsilon_{r2}} \tag{16}$$

$$u_1 = \sqrt{\gamma_1^2 - \gamma_0^2} \tag{17}$$

$$u_2 = \sqrt{\gamma_2^2 - \gamma_0^2}. \tag{18}$$

In (17) and (18), the wave numbers in each ground layer are given by

$$\gamma_1 = \sqrt{j\omega\mu_0(\sigma_1 + j\omega\varepsilon_0\varepsilon_{r1})} \tag{19}$$

and

$$\gamma_2 = \sqrt{j\omega\mu_0(\sigma_2 + j\omega\varepsilon_0\varepsilon_{r2})}. \tag{20}$$

IV. Simulation and Comparison With Experiment Data

We consider the lightning flash occurred on June 3, 2014, at 6:43 AM, as shown in Fig. 2. We have selected three return strokes (labeled RS1, RS4, and RS5) for the analysis. Similar simulations were performed for the two other strokes but they were not shown for the sake of brevity.

Fig. 5 presents the simulation results obtained assuming either a perfect or a homogeneous lossy ground with different ground electrical conductivities, and their comparison with the corresponding measured waveforms. In Fig. 5, the presented waveforms correspond to the field at Station CCZ that is located at a distance of 85 km with respect to the stroke location. It can be seen that, even though the early response of the field can be reproduced reasonably well by adjusting the ground electrical conductivity, the subsidiary peaks and the late-time response of the field cannot be satisfactorily reproduced assuming a homogeneous ground model.

The simulation results assuming a two-layer model for the ground are shown in Fig. 6 for all the stations and all the three return strokes. Each column presents the results for one return

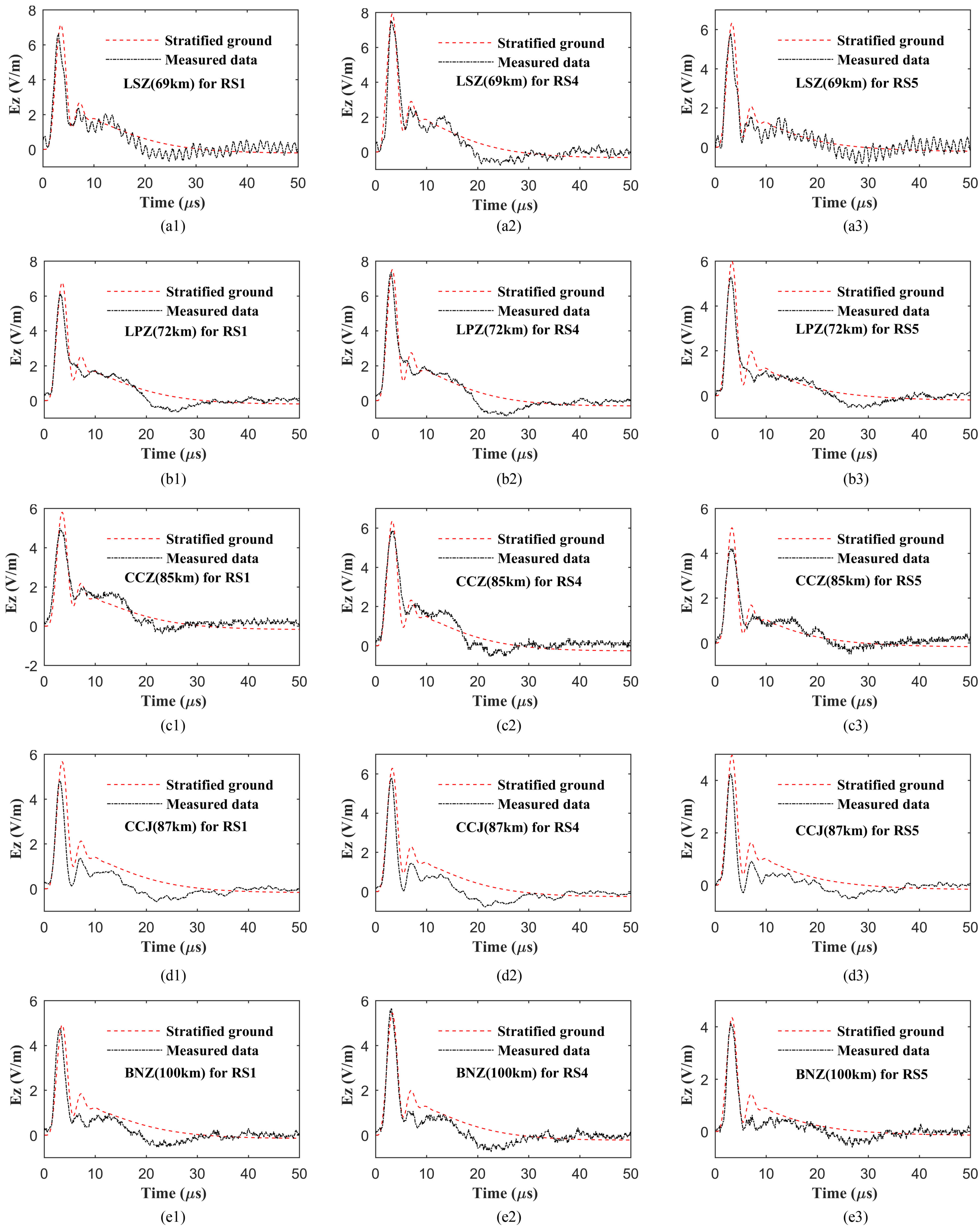

Fig. 6. Simulation results from the two-layer soil for the three considered cases. The dashed red line and black dotted line represent the stratified ground simulation and measured data, respectively. (a1)–(g1) Left-hand column present simulation results from multiple stations for RS1 for RS1 in flash F140603. (a2)–(g2) Middle column corresponds to RS4. (a3)–(g3) Right-hand column corresponds to RS5.

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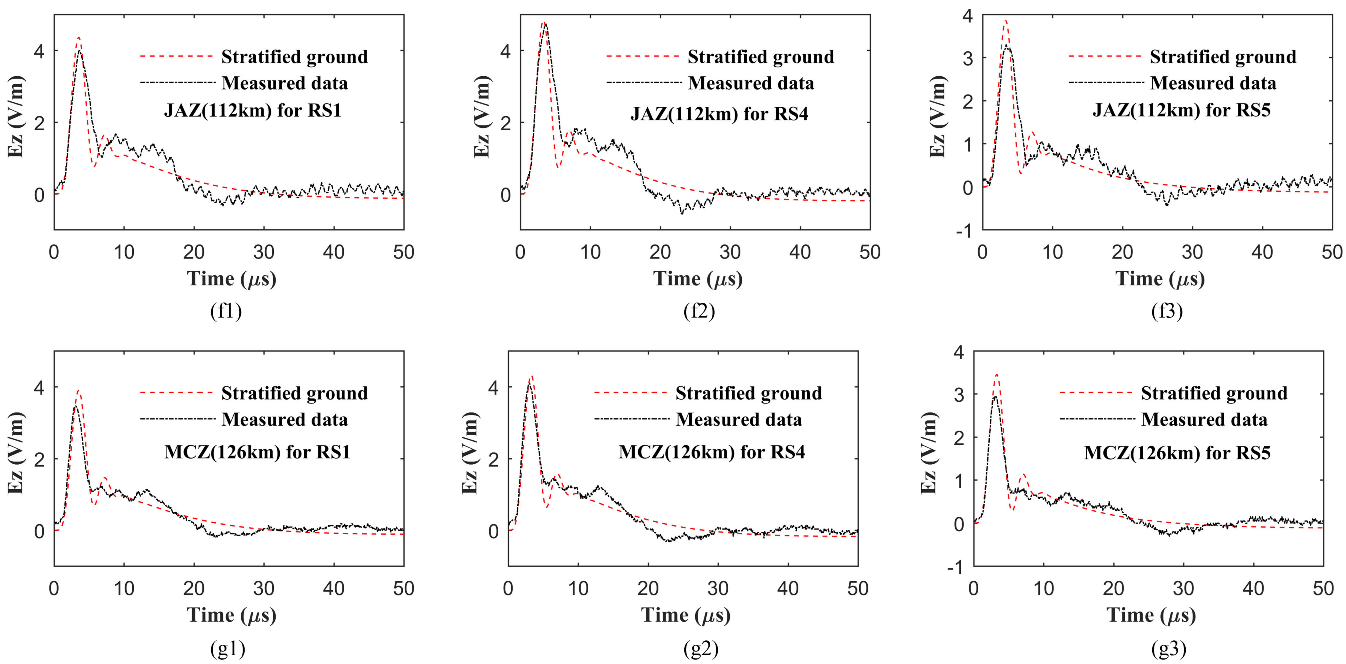

Fig. 6. Continued.

stroke, for which electric field waveforms (calculated and measured) are presented for stations LSZ, LPZ, CCZ, CCJ, BNZ, JAZ, and MCZ (shortest to farthest) from the top to the bottom. The ground parameters σ_1, σ_2, ε_{r1}, ε_{r2}, and the height of the top layer $h1$ were, respectively, set to 0.001 S/m, 4, 5, 80, and 15.5 m, for all the considered observation points. These values were determined in order to obtain the best match with the experimental data. The inferred parameters can be considered as reasonable. Indeed, evidence of a multilayer structure of the soil in China can be found in [48]. Similar parameters have been adopted in other studies considering the same geographical region [49]. However, this point calls for further research. Considering the same ground parameters along the path of propagation for each site is certainly an approximation. In reality, a better knowledge of the ground electrical parameters should be gained for each field measurement site. Note also that the adopted value for the top layer conductivity (0.001 S/m) is consistent with available data [50].

It can be seen that a two-layer soil model allows obtaining very good agreement between computed and measured waveforms for all the considered distances and events. Compared to the homogeneous ground case, the computed early-, intermediate-, and late-time response follows to a much better extent the experimental waveforms. The observed discrepancies (for example at CCJ and BNZ stations) might be due to the variation of the soil electrical parameters along the considered paths.

V. Discussion

A discussion is in order on the influence of various parameters adopted for the simulations, namely the adopted return-stroke model, the values for the ground conductivity of the top and lower layer, depth of the top layer, and the return-stroke speed.

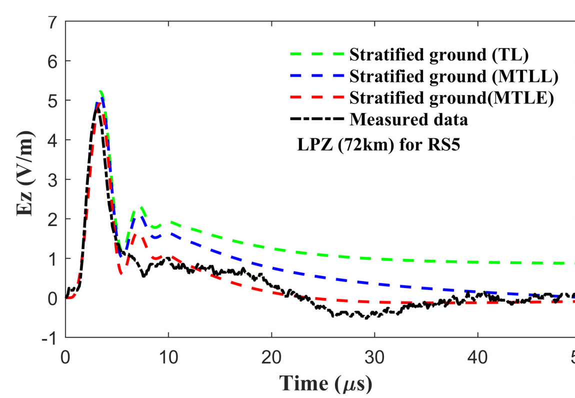

Fig. 7. Influence of the return-stroke models on simulated results. $\varepsilon_{r1} = 5, \varepsilon_{r2} = 80$, $\sigma_1 = 0.001$ S/m, $\sigma_2 = 4\,\text{S/m}, \text{h1} = 15.5\,\text{m}$.

1) *Return-stroke model:* Fig. 7 shows the simulation results for the station LPZ using three different return-stroke models: MTLE [28]–[29], TL [51], and MTLL [52]. It can be seen that, as far as the early-time response of the field is concerned, the three models provide very similar results. The fact that the TL model fails in reproducing the late-time response is well known and is due to the absence of any attenuation of the current pulse along the channel (e.g., [53]). In summary, it can be said that the adopted return-stroke model will affect to some extent the results.
2) *Conductivity of the top layer:* Fig. 8 shows the simulation results considering three different conductivities for the top ground layer associated with return-stroke RS5 in Fig. 2(c). The relative permittivity was set to $\varepsilon_{r1} = 5$. The conductivity and the relative permittivity of the second

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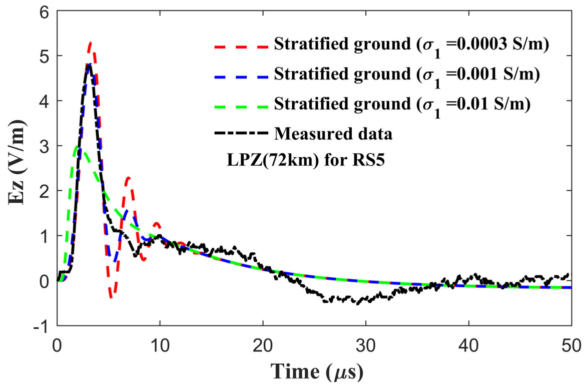

Fig. 8. Influence of the conductivity of the top layer on simulated results. $\varepsilon_{r1} = 5, \varepsilon_{r2} = 80$, $\sigma_2 = 4$ S/m, $h_1 = 15.5$ m.

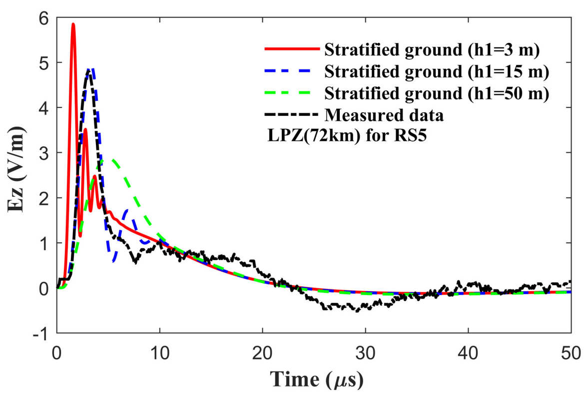

Fig. 9. Influence of the depth of the top layer on simulated results. $\varepsilon_{r1} = 5, \varepsilon_{r2} = 80$, $\sigma_1 = 0.001\,\text{S/m}$, $\sigma_2 = 4\,\text{S/m}$.

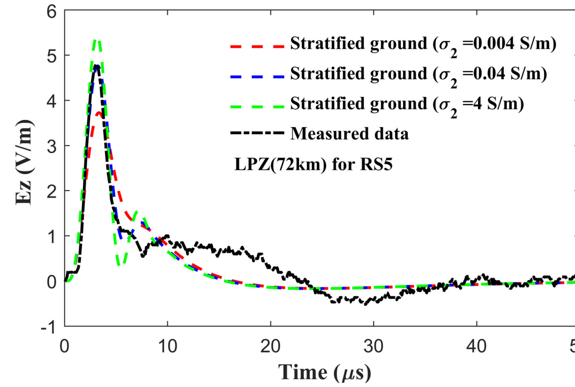

Fig. 10. Influence of the conductivity of the lower layer on simulated results. $\varepsilon_{r1} = 5, \varepsilon_{r2} = 80, \sigma_2 = 4\,\text{S/m}, \text{h1} = 15.5\,\text{m}$.

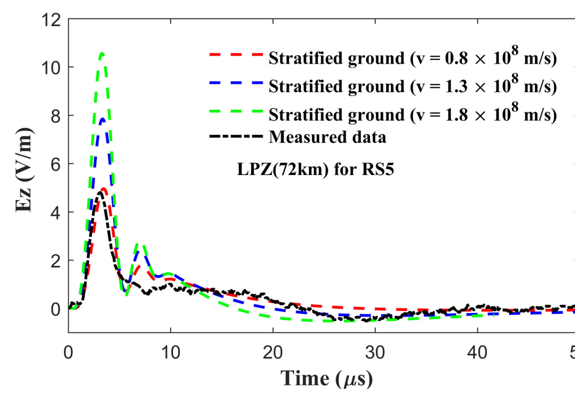

Fig. 11. Influence of the return-stroke speed on simulated results. $\varepsilon_{r1} = 5, \varepsilon_{r2} = 80$, $\sigma_1 = 0.001\,\text{S/m}$, $\sigma_2 = 4\,\text{S/m}, \text{h1} = 15.5\,\text{m}$.

layer were set, respectively, to $\sigma_2 = 4\,\text{S/m}$ and $\varepsilon_{r2} = 80$. The depth of first layer was set to $h1 = 15.5\,\text{m}$. As expected, it can be seen that the conductivity of the top layer affects essentially the early-time and intermediate-time response of the field. A decrease of the conductivity results in an increase of the peak electric field, which can be higher than the peak corresponding to the perfectly ground case. In addition, for low conductivities, the field waveform has an oscillatory behavior featuring subsidiary peaks. These results are consistent with previous studies (e.g., Shoory *et al*. [21]). As discussed in [5], when the conductivity of the top layer is lower than that of the lower layer, the attenuation function can be larger than unity for certain frequencies.

3) *Depth of the top layer:* The effect of the depth of the top layer is illustrated in Fig. 9, in which the electric field was evaluated considering three different values for this parameter, namely 3, 15, and 50 m. The ground electrical parameters are $\varepsilon_{r1} = 5, \varepsilon_{r2} = 80$, $\sigma_1 = 0.001\,\text{S/m}$, and $\sigma_2 = 4\,\text{S/m}$. It can be seen that the frequency of oscillations and the field peaks depend strongly on the depth of the top layer. The larger the depth, the smaller the peak and the oscillation frequency. For large values of the top layer depth (50 m or higher), the oscillation disappears. In this case, the depth of the top layer is much larger than the skin depth for the relevant frequencies, and the stratified ground behaves as a homogeneous ground with upper layer parameters [5].

4) *Conductivity of the lower layer:* Fig. 10 shows the simulations considering three different conductivities for the lower layer, namely 0.0004, 0.04, and 4 S/m. In agreement with [5], it can be seen that the subsidiary peaks resulting from the oscillatory behavior appear only when the conductivity of the lower layer is greater than that of the top layer.

5) *Return-stroke speed:* The effect of the return-stroke speed is illustrated in Fig. 11, considering three different values, namely 0.8×10^8, 1.3×10^8, and 1.8×10^8 m/s. It can be seen that the return-stroke speed affects essentially the early-time response of the field and its peak value. At the considered distant location, the peak field is essentially proportional to the value of the return-stroke speed [54].

It is worth noting that the late-time features of the distant electric fields may also be influenced by other effects, such as attenuation and dispersion of the propagating current along the lightning channel as discussed in Shao *et al*. [55] and Shoory *et al*. [35], channel tortuosity [56], return-stroke speed, and return-stroke model inaccuracies. Furthermore, the fact that other factors such as local effects at the field-measuring stations could affect the subsidiary peaks cannot be completely ruled out. However, the fact that a two-layer soil model allows us to reproduce reasonably well the fields measured at nine different stations located in different geographical locations is an indication that the stratified soil plays at least an important role in the late-time response of the field.

VI. Summary and Conclusion

We presented an analysis of the propagation effect along a lossy ground on the characteristics of lightning-generated electric fields, using simultaneous observations of lightning return-stroke currents and vertical radiated fields measured at nine different distances from rocket-triggered lightning. The triggered-lightning site was located in Conghua (Guangdong, China). The electric field waveforms were measured using the sensors belonging to the FTLLS, which were located at distances from the triggered-lightning site ranging from 69 to 126 km. The propagation path is over land and mainly over flat ground. The field sensors have an overall bandwidth from 160 Hz to 1 MHz.

It was shown that, even though the early response of the fields can be reproduced reasonably well by adjusting the ground electrical conductivity of a single-layer ground model, the subsidiary peaks and the late-time response of the fields cannot be satisfactorily reproduced assuming a homogeneous ground model. However, it was shown that a two-layer soil model allows obtaining very good agreement between computed and measured waveforms for all the considered distances and events. Compared to the homogeneous ground case, the computed early-, intermediate-, and late-time response follows to a much better extent the experimental waveforms. We also provided a discussion on the influence of computational model and parameters on the simulated results.

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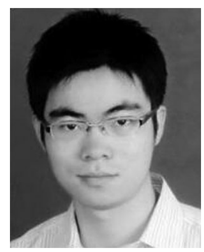

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