Radiated Electromagnetic Field Analysis of Lightning in Presence of a two Layers of Vertically Stratified Ground

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Abstract - In this work we present an analysis of the electromagnetic field generated by a lightning stroke in presence of a complex geometry including a two layers' vertically stratified ground characterized by different values of the electrical conductivity. The simulation is carried out using the Finite Difference Time Domain (FDTD) method, in three Dimensions (3D) associated with an engineers' model for the representation of the spatiotemporal distribution of the return current along the lightning channel. A comparison between the results obtained by the implementation of the MTLL and MTLE models will be presented.

Keywords -Electromagnetic field, modeling, lightning, Finite-difference time-domain (FDTD) method, lightning return-stroke, vertical stratified ground.

I. INTRODUCTION

The lightning radiated electromagnetic field in the presence of a stratified ground has recently been the subject of research within the scientific community. The characterization of this field requires knowledge of the spatiotemporal distribution of the current along the lightning channel. The correct determination of this current distribution makes it possible to correctly evaluate the field generated by this phenomenon[1] [2].

This field was subsequently studied in the presence of a stratified soil (horizontal) based on the 2D-FDTD method [3], [6]. The lightning channel is represented by a distributed current sources (Model 7) along the channel and placed in the form of a vertical vector (Figure 1.)

The configuration is relative to a vertically stratified ground [4],[5]. The components of the electromagnetic field are rated above and below ground[6], [7].

The calculations are performed by the finite difference method in the three-dimensional time domain (3D-FDTD) [8], [9], [10]. Moreover, among the absorbing boundary conditions (1st order MUR, UPML (Uniaxial Perfectly Matched Layer), PML (Perfectly Matched Layers) and Liao conditions) [11], [12], we have retained the Mur absorbing boundary condition described in this section.

Indeed, a numerical calculation code has been developed on FORTRAN dedicated to the evaluation and analysis of lightning currents as well as to the determination of the electromagnetic disturbances radiated during a lightning strike in the presence of a ground. vertically stratified [13] [4].

II. CURRENT MODEL

The model used to represent the current at the base of the lightning channel is that of Heidler [14] (sum of the two functions-equation “(1)”). Using the lightning current parameters based on Table. I :

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

Where i_{01} and i_{02} are the current amplitudes, τ_{11} and τ_{12} are the front-time constants, and τ_{21} and τ_{22} are the decay time constants, while n_1 and n_2 are exponents.

$$\eta_1=\left[-\left(\frac{\tau_{11}}{\tau_{12}}\right)\left(n_1.\frac{\tau_{12}}{\tau_{11}}\right)^{\frac{1}{n_1}}\right] \quad (2)$$

$$\eta_2=\left[-\left(\frac{\tau_{21}}{\tau_{22}}\right)\left(n_2.\frac{\tau_{22}}{\tau_{21}}\right)^{\frac{1}{n_2}}\right] \quad (3)$$

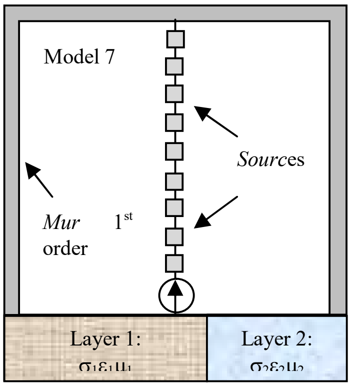


Fig 1. Schematic representation of the lightning channel and above a vertically stratified ground with two layers.

III. MODEL OF THE LIGHTNING CURRENT ALONG THE CHANNEL

The lightning channel is represented by distributed current sources (Model 7) along the channel and placed in the form of a vertical vector (Figure 1). Each current source is activated by the arrival of the current wave at the point concerned. The calculations are performed using the FDTD-3D method with a lightning current propagation speed along the channel equal to $1.5\ 10^8\ m/s$.
The current distribution in the lightning channel is represented by the TL model [15].

Problem Geometry

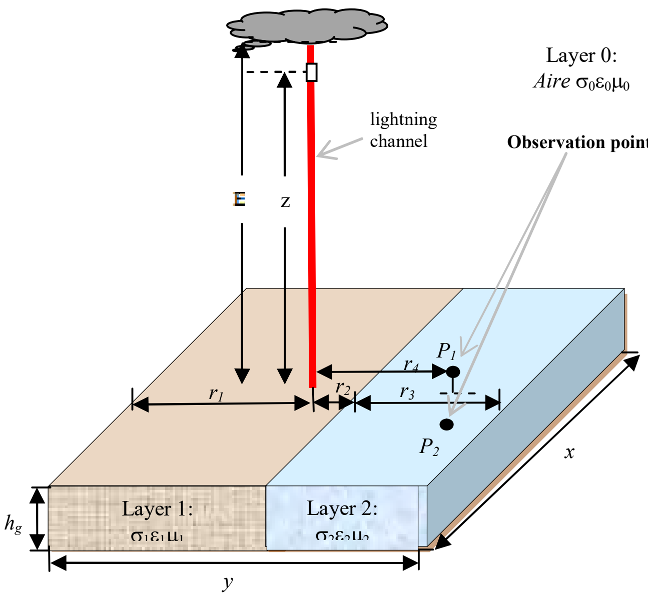
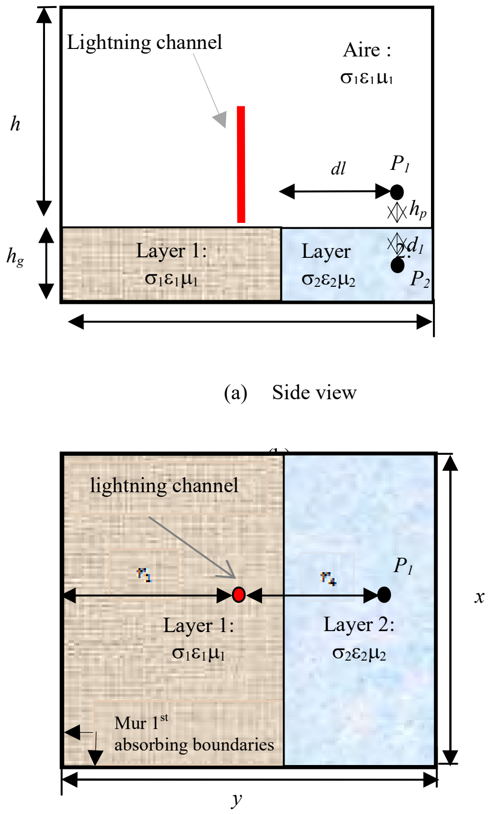


Fig. 2. Geometry adopted for the lightning electromagnetic fields computation



(a) Side view

(b) Top view

Fig. 3. Position of the observation points (a) side view and (b) Top view

This system is accommodated in working volumes with lengths : $x \times y \times z$. The computation of the electromagnetic fields is carried out by solving the Maxwell's equations using the three dimension finite difference time-domain method 3D-FDTD [1, 8, 10, 13, 16, 18].

This computation is based on the discretization of the working volume into cubic or parallelepiped parts with length Δx, Δy and Δz, and a time discretization of the time domain into time increments Δt. In this work the Mur absorbing boundary conditions are applied to the six limits of the working volume in order to avoid unwonted reflection.

Figure 2, presented above, describes the geometry of the problem studied in this part. The values of the various parameters of this figure will be given below in the phase of the simulation parameters.

IV. VALIDATION OF THE 3D-FDTD

This Validation is carried out by a comparison between a calculated waveform of the lightning current obtained using the simulation program, developed on FORTRAN and based on the 3D-FDTD method with those presented by Baba and Rakov [21]. In their work, Baba and Rakov evaluated the electromagnetic field generated by lightning using the

3D-FDTD method and Liao boundary conditions for homogeneous ground.

well as, current propagation velocity along the lightning channel is set to v = 0.5c and the light speed c = 3.108 m/s. The working volume of 2000 m × 2500 m × 3000 m is divided into 10 m × 10 m × 10 m cubic cells and surrounded by six planes of Liao's second-order absorbing boundary condition for the work of Baba and Rakov [21], and Mur absorbing boundary condition for our work. The spatiotemporal distribution of the current along the lightning channel is modeled using the transmission line (TL) model. The current source is computed using Heidler function [14] presented by "(1)" and associated with parameters of Table 1.

This section of validation is devoted to lightning current spatiotemporal distribution along the lightning channel . Cette partie de validation est consacrée à la distribution spatio-temporelle du courant de foudre le long du canal de foudre.

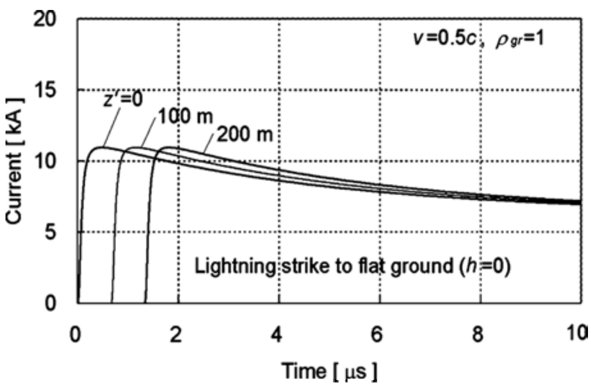
A) Current at the base of the lightning channel

The current at the base of the lightning channel is simulated using the sum of the two Heidler functions [14] "(1)" and the current parameters are recorded in table I.

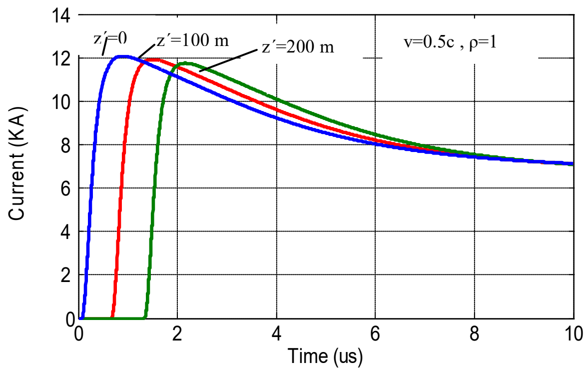
Table 1: Parameters relating to the two Heidler functions with $n_1 = 2$.

Table 1: Parameters of the lighting current source**.**

Parameter	value
i_{01}	10.7 kA
τ_{11}	0.25 µs
τ_{12}	2.5 µs
i_{02}	6.5 kA
τ_{21}	2.1 µs
τ_{22}	230 µs
n_1	2
n_2	2



(a)



(b)

Fig 4 : Current waveforms for a lightning strike to a ground-level (h = 0,v = 0.5c, and ρ = 1) at different heights z′= 0, 100, or 200 m along the lightning channel,
(a) Results taken from [21],
(b) Our results.

In Fig. 4, we present the lightning current waveforms corresponding to different heights from a ground namely: 0 m on ground surface , 100 m , 200 m from the ground surface in the lightning channel. Fig. 4(a) presents the results carried out by Baba and Rakov [21]. Fig. 4(b) shows the waveforms obtained by the 3D-FDTD simulation considering the TL model . The obtained results present a satisfactory agreement in comparison with those obtained by Baba and Rakov. Furthermore, the high magnitude of the lightning current is that calculated , because it presents the sum of the wave current along the lightning channel. In addition, the waveforms of the current obtained at an altitude of z' = 100 m and z' = 200 m from the ground surface.

V. SIMULATION SETTINGS

The vertical lightning channel having an altitude of 7 km is located at the center of the horizontal xy plane above the ground surface,The observation point has a distance r_4=70 m from the lightning channel,Volume of the workspace of 150 m×200×7122. Parallelepipedic air discretization cells: 2.5×2.5×10 m, Parallelepipedic discretization cells for the ground: 2.5×2.5×0.5 m, for a depth of 2 m below the ground surface, and 2.5×2.5×10 m for the rest of the depth. Time step : 1 ns,Horizontal distance between the left limit of the second layer and the calculation point: dl=20 m.The parameters relating to the current are recorded in table 1, with v = 130 m/µs.The spatiotemporal distribution of the return arc current is carried out using the MTLL model (with H = 7500 m), as well as the MTLE model (with λ = 2000 m),The soil conductivity values are recorded in Table 2.

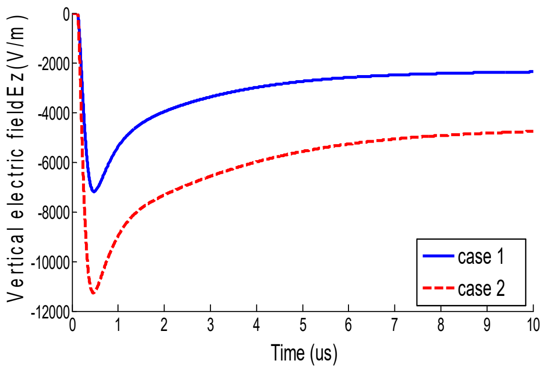
Table 2 Eectrical parameters relative to the ground two-layer stratified vertical stratification.

	Layer 1		Layer 2	
	Settings	Values	Settings	Values
Case1	$\sigma\,(s/m)$	0.001s /m	$\sigma\,(s/m)$	0.01
	ε_r	10	ε_r	10
Case 2	$\sigma\,(s/m)$	0.01s /m	$\sigma\,(s/m)$	0.001
	ε_r	10	ε_r	10

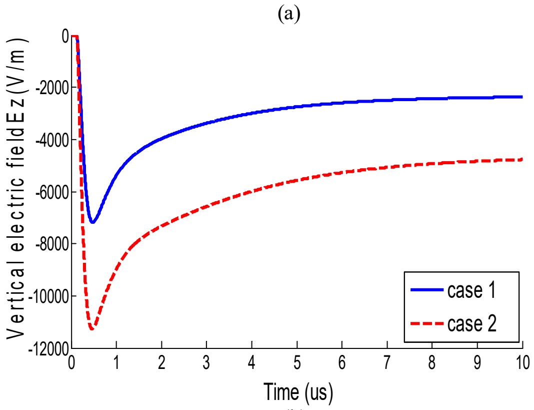
VI. SIMULATION RESULTS

A) Electromagnetic field calculated above the ground

The waveforms of time variations of vertical electric field, horizontal electric field and azimuth magnetic field are shown in Figure 5, 6 and 7 respectively.

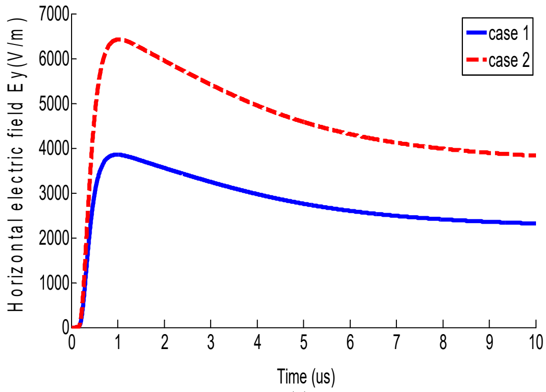


(a)



(b)

Fig. 5. Temporal variations of the vertical electric field : (a) MTLE model, (b) MTLL model



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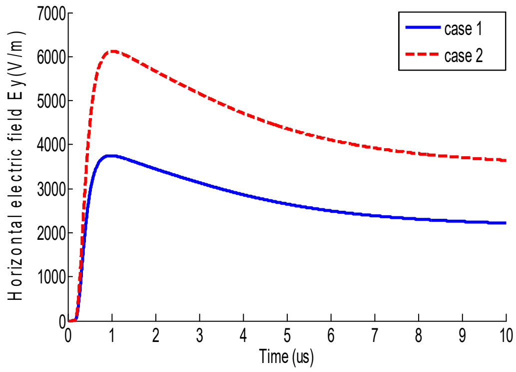
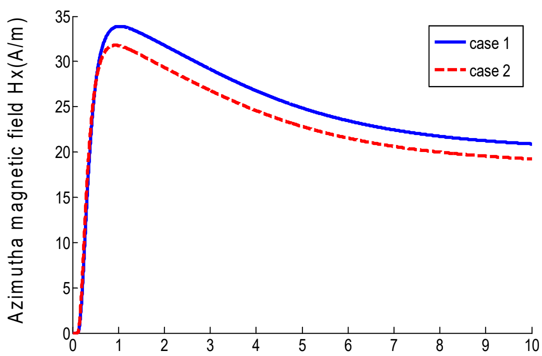


(b)

Fig. 6. Temporal variations of the horizontal electric field (a) MTLE model, (b) MTLL model.



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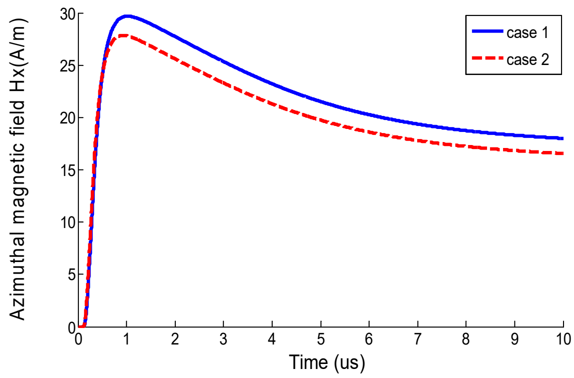


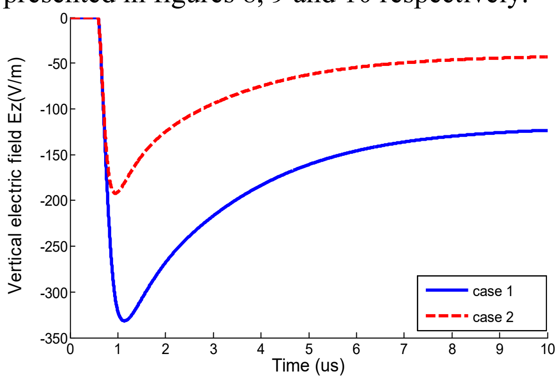
(b)

Fig. 7. Temporal variations Azimuthal magnetic field: (a) MTLE model, (b) MTLL model

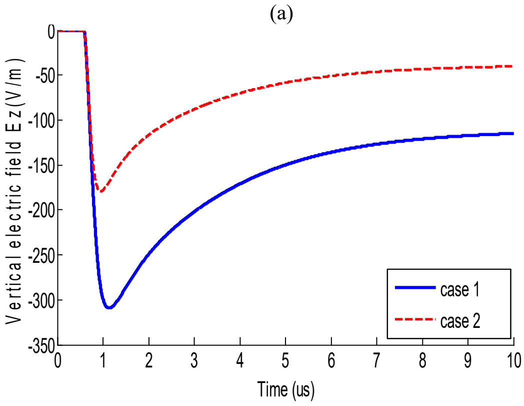
According results presented in figures 5, 6 and 7, it can be noted that the electromagnetic field components calculated above a vertically stratified ground [17], at a height of 10 m and at a distance of 70 meters from the lightning channel, are affected by the change in conductivity of the two vertical layers of the ground. In addition, the components of the vertical and horizontal electric fields are the most affected by this change in conductivity. The maximum amplitudes of these fields obtained in case 1 are greater than those obtained in case 2. In order for the results of the magnetic field to be less affected by the stratification of the soil, there is a slight influence of the evolution of the conductivity of the soil. ground on these two components. Thus, if we compare the results obtained using the two models (MTLL and MTLE), it can be said that both waveforms are identical with different amplitudes.

B) Electromagnetic field calculated below ground

The temporal variations of the vertical and horizontal components of the electric field, as well as that of the azimuthal component of the magnetic field [20], calculated at a depth equal to 1 m below the ground are presented in figures 8, 9 and 10 respectively.

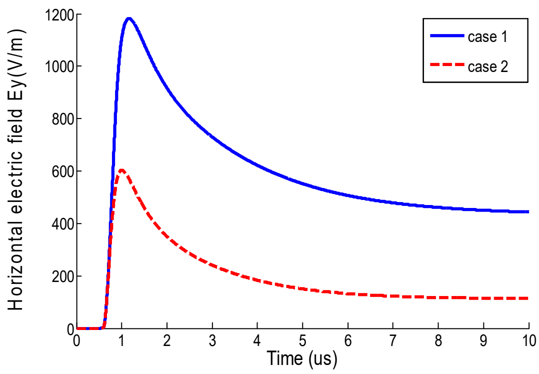


(a)

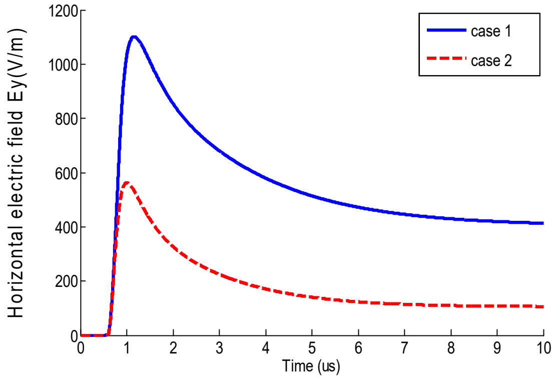


(b)

Fig 8: Temporal variations of the vertical electric field
(a) MTLE model (b) MTLL Model

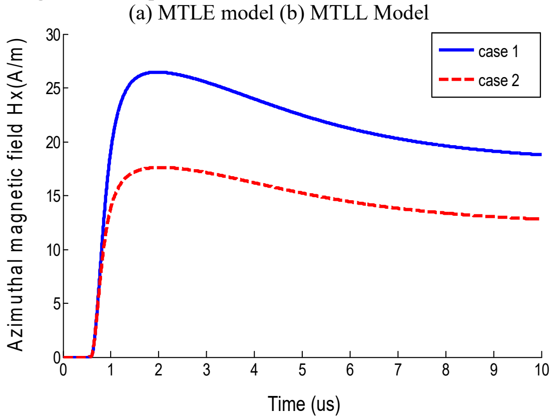


(a)



(b)

Figure 9 : Temporal variations of the horizontal electric field
(a) MTLE model (b) MTLL Model



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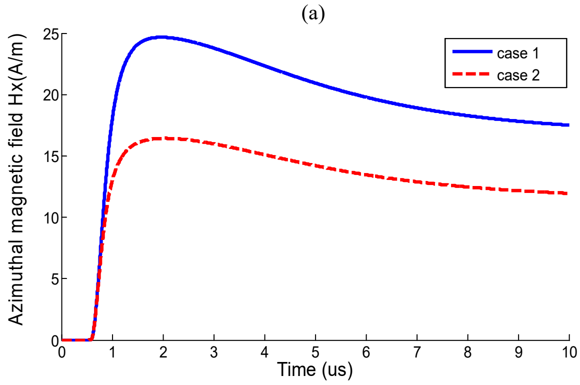

(b)

Fig 10 : Temporal variations of the azimuth magnetic field
(a) MTLE model, (b) MTLL model

The analysis of the various results obtained shows that the components of the field calculated using the MTLL model have a maximum amplitude lower than that corresponding to the MTLE model. One can clearly notice the significant influence of the variation of the values of the conductivity between the two vertical layers of the ground. Thus, the values of the maximum amplitudes corresponding to case 2 (drawn in dotted red lines) are lower than those obtained for case 1.

VII. CONCLUSION

In this paper, the calculation of the electromagnetic field generated by lightning was presented by a new study in the presence of a vertically stratified soil and a lightning channel. This study was carried out by a three-dimensional fine-difference method in the time domain (3D-FDTD). The spatio-temporal distribution of the lightning current along the lightning channel was modeled and calculated using sources of distributed currents (Model 7). In addition, we developed a calculation code on FORTRAN and based on the 3D-FDTD method associated with the MUR absorbing boundary conditions. Finally, we have performed a comparison between the lightning current spatiotemporal distribution along the lightning channel and the electromagnetic field obtained by the implementation of the model MTLE and MTLL.

As a comparison, we can note that our simulation results, in particular the waveforms of the vertical electric field and the magnetic field, resulting from the 3D-FDTD calculation, agree satisfactory on the amplitude plane and the waveform plane.
Otherwise from these results obtained by implementing the FDTD-3D approach, we conclude THAT from the influence of the vertically stratified soil on the components of the electromagnetic field, the vertical and horizontal components of the electric field above the soil are more affected by vertical soil stratification. Moreover, the azimuthal magnetic field is slightly affected by this change in the conductivity value by the presence of two vertically stratified soil layers. In the case below the ground, the components of the vertical and horizontal electric field most affected by the stratification of the ground and the component of the magnetic field least affected by this change in the value of the conductivity of the ground.

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