On Lightning Electromagnetic Field Propagation Along an Irregular Terrain

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***Abstract*—In this paper, we present a theoretical analysis of the propagation effects of lightning electromagnetic fields over a mountainous terrain. The analysis is supported by experimental observations consisting of simultaneous records of lightning currents and electric fields associated with upward negative lightning flashes to the instrumented Säntis tower in Switzerland. The propagation of lightning electromagnetic fields along the mountainous region around the Säntis tower is simulated using a full-wave approach based on the finite-difference time-domain method and using the two-dimensional topographic map along the direct path between the tower and the field measurement station located at about 15 km from the tower. We show that, considering the real irregular terrain between the Säntis tower and the field measurement station, both the waveshape and amplitude of the simulated electric fields associated with return strokes and fast initial continuous current pulses are in excellent agreement with the measured waveforms. On the other hand, the assumption of a flat ground results in a significant underestimation of the peak electric field. Finally, we discuss the sensitivity of the obtained results to the assumed values for the return stroke speed and the ground conductivity, the adopted return stroke model, as well as the presence of the building on which the sensors were located.**

***Index Terms*—Finite-difference time-domain (FDTD), irregular terrain, lightning, Säntis tower.**

I. Introduction

THE problem of lightning electromagnetic field propagation along a lossy ground has been extensively studied in the literature (e.g., [1]–[5]). Moreover, inhomogeneous ground effects such as stratified and mixed path (e.g., [6]–[15]), frequency-dependent ground parameters (e.g., [16] and [17]), and more recently orography were also studied (e.g., [18]–[22]).

This study focuses on the effect of the propagation of lightning electromagnetic fields over a mountainous terrain. The topic has recently received some attention. Soto *et al.* [23], [24] presented finite-difference time-domain (FDTD) calculations of lightning electromagnetic fields for a lightning discharge striking the top of a cone-shaped mountain. Paknahad *et al.* [25] presented for a similar configuration, finite-element method (FEM) simulations for both aboveground and underground fields. These studies showed that lightning electromagnetic fields could be affected by a nonflat ground configuration. Schulz and Diendorfer [26] have attempted to consider a real terrain model by evaluating the length of the propagation path using the terrain model, and correcting the time errors related to the signal path elongation. They noted that the location accuracy of lightning location systems could be improved after considering such correction. More recently, Li *et al.* [27] analyzed the propagation effects on lightning radiated electromagnetic fields over hilly and mountainous terrain considering a pyramidal mountain. They also discussed the resulting systematic errors in algorithms currently used to locate lightning in detection networks, specifically the time delay error in the time-of-arrival technique.

All the studies considering a nonflat ground are based either on a fractal method to represent a rough surface or on simplified representations of the mountain (conical, pyramidal). To the best of our knowledge, the effects of a real irregular terrain on lightning electromagnetic fields have not been analyzed so far in the literature.

In this paper, we present a theoretical analysis of the propagation effects of lightning electromagnetic fields over a mountainous terrain. The analysis is supported by experimental observations consisting of simultaneous records of lightning currents measured at the Säntis tower in Switzerland and associated electric fields measured at a distance of 15 km or so from the tower. The propagation of lightning electromagnetic fields along the mountainous region is simulated using a full-wave approach based on the FDTD method and compared with the obtained experimental data.

The rest of this paper is organized as follows. Section II briefly presents the experimental setup and measuring stations. Section III presents the obtained data. Section IV describes the adopted models and computational methods, as well as FDTD parameters. Section V presents the numerical simulations and comparison with experimental data, along with relevant discussion. Summary and conclusions are given in Section VI.

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Fig. 1. Säntis tower in the northeast of Switzerland (47°14′57′′N, 9°20′32′′E).

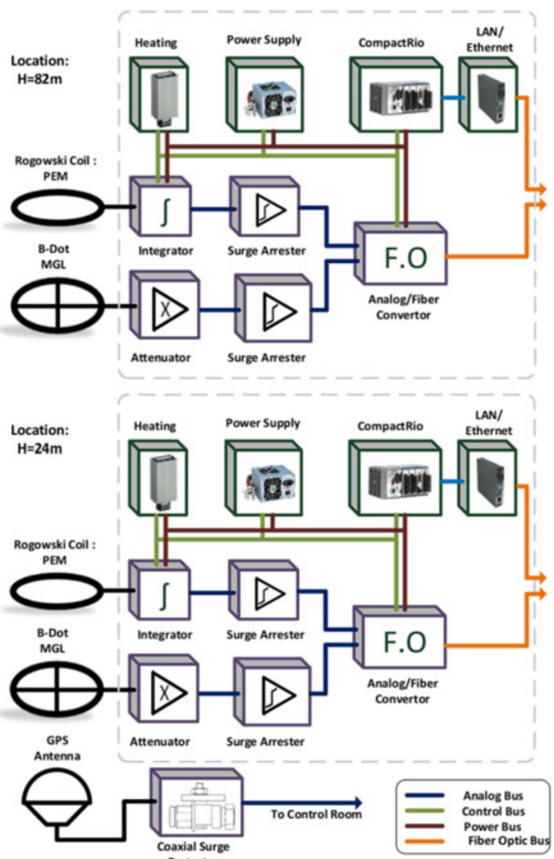

Fig. 2. Schematic diagram of the current measurement system installed at two different heights (24 and 82 m) along the Säntis Tower.

II. Experimental Setup and Instrumentation

A. Current Measuement System at the Säntis Tower

The Säntis tower is located on the top of Mount Säntis, in the northeastern part of Switzerland (see Fig. 1). The tower (124-m tall) was instrumented in May 2010 and is serving as an experimental station for lightning observations. As of today, the tower is the highest direct lightning current measurement station [2500 m (above sea level)], with the highest lightning incidence (100+ times a year).

Fig. 3. Electric and magnetic field sensors on the roof of the Huber+Suhner building in Herisau.

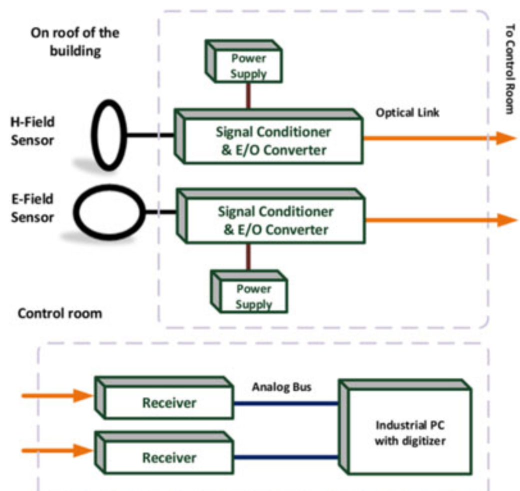

Fig. 4. Schematic diagram of the electric and magnetic field measurement system (adapted from Azadifar *et al.* [31]).

A schematic diagram of the current measurement system is shown in Fig. 2. Lightning current waveforms and their time-derivatives are recorded at two different heights [24-m and 82-m (above ground level)] using Rogowski coils and multigap B-dot sensors. The analog outputs of the sensors are relayed to a digitizing system by means of optical fiber links. The system allows an over-the-Internet remote maintenance, monitoring, and control. A PXI platform with a current sampling rate of 50MS/s was used to digitize and record measured waveforms. The lightning current is recorded over a 2.4-s time with a pretrigger delay of 960 ms.

More details on the measurement sensors and instrumentation system can be found in [28] and [29]. In 2013–2014, a certain number of updates were made to the overall measuring system, which are described in [30].

B. Electromagnetic Field Measurement Systems

On July 23, 2014, a wideband electric and magnetic field measuring system was installed in Herisau (47°23′N, 9°16′E),

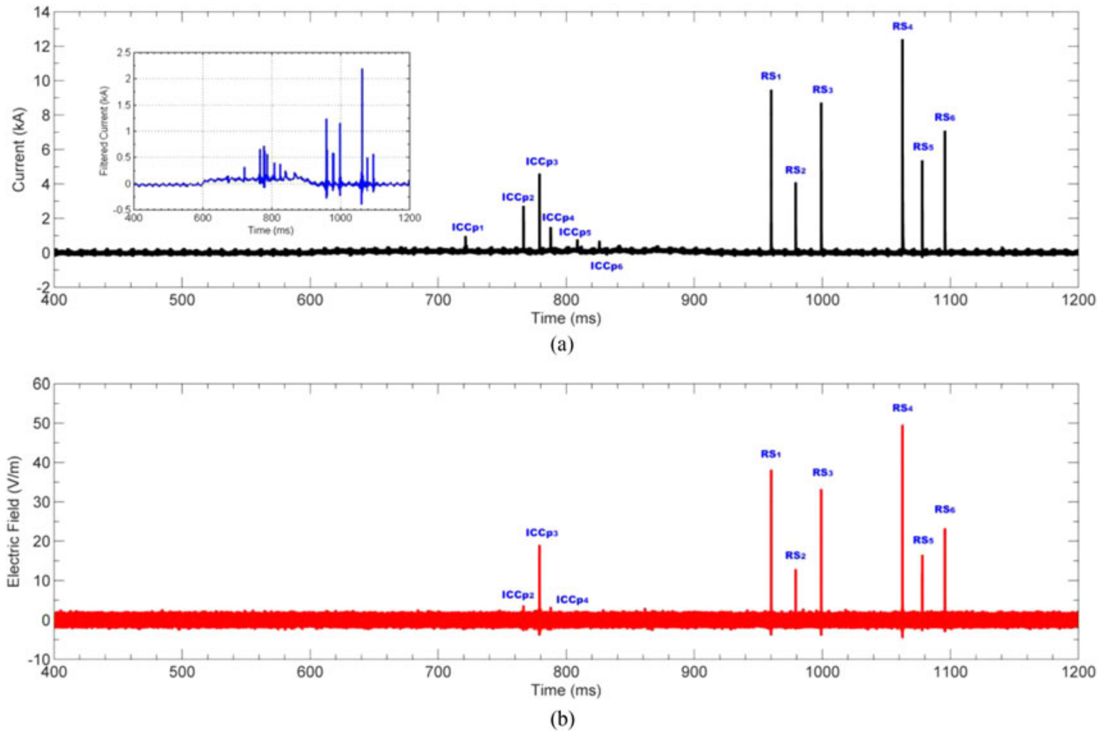

Fig. 5. Waveforms associated with a flash occurred on October 22 at 1:14 AM. (a) Current waveform. (b) E-field waveform at 15 km. The inset of Fig. 5(a) shows the current waveform filtered with a 1-kHz low-pass filter, in which the ICC is clearly discernible.

about 15 km away from the Säntis tower. The system uses Thales (former Thomson CSF) Mélopée chains, including sensor, conditioner, fiber optic connection, and receiver. The electric and magnetic field sensors were installed on the roof of a 25-m tall building belonging to the Huber+Suhner Company (see Fig. 3). The measured signals were relayed by optical link to the receiver. An industrial PC with a PCI 5122 digitizer card with a sampling rate of 50 MS/s was used as a data acquisition unit. The frequency bandwidth of the Mélopée system for the electric field is 1 kHz to 150 MHz, and that for the magnetic field is 2 kHz to 150 MHz. Fig. 4 shows a schematic diagram of the installed system. The field measuring system was operational until October 28, 2014.

III. Obtained Data

During the operation of the field measurement station (July 23 to October 28, 2014), 21 upward negative flashes were recorded that included both the current at the Säntis Tower and the fields at the Herisau field station. Fig. 5 presents an example of current and electric field overall waveforms associated with an upward negative flash that occurred on October 22, 2014, at 1:14 AM. Note that the atmospheric electricity sign convention is used in this study for the electric field data. The current waveform is typical of upward negative flashes, with an initial stage comprising the so-called initial continuous current (ICC) which corresponds to an upward positive leader (see Rakov and Uman [32], ch. 6). Fast ICC pulses [labeled as $ICCp_1$ through $ICCp_6$ in Fig. 5 (a)] are superimposed to this ICC. After the extinction of the ICC, the waveform features six other pulses resulting from downward leader–return stroke sequences [labeled as RS_1 through RS_6 in Fig. 5 (a)].

IV. Adopted Models and Computational Method

A. Terrain Topography

In order to take into account the real geographical terrain between the Säntis Tower and the field measurement station, the global digital elevation model version 2 (GDEM V2) from advanced spaceborne thermal emission and reflection radiometer (ASTER) (henceforth referred to as "ASTER GDEM") has been adopted. ASTER GDEM was developed jointly by the U.S. National Aeronautics and Space Administration and Japan's Ministry of Economy, Trade, and Industry, which covers 99% of Earth's landmass and spans from 83°N to 83°S at a spatial resolution of 1 arc-second (approximately 30 m at the equator) [33]. The overall accuracy of ASTER GDEM V2 is about 17 m at the 95% confidence level evaluated by the ASTER GDEM validation team [33].

Fig. 6 shows the topographic map in the region of interest that includes the Säntis tower and the field measurement station. Fig. 7 shows the two-dimensional (2-D) cross-section of the topographic map along the direct path between the tower and the field measurement station (see red-dashed line in Fig. 6).

B. FDTD Modeling

Because of the distance between the Säntis tower and the field measurement station (about 15 km), a three-dimensional (3-D) FDTD simulation taking into account the topography would require prohibitive computation time and memory requirements. We have therefore considered in this study a 2-D axial symmetric model using the topographic data shown in Fig. 7, which was imported into our FDTD simulation code. The geometry of the

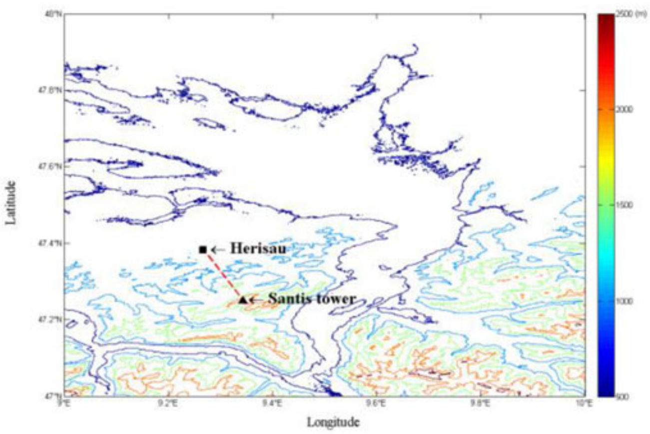

Fig. 6. Topographic map of the region of interest. Data from ASTER GDEM. The triangle designates the Säntis tower. Herisau is the location of the field measurement system.

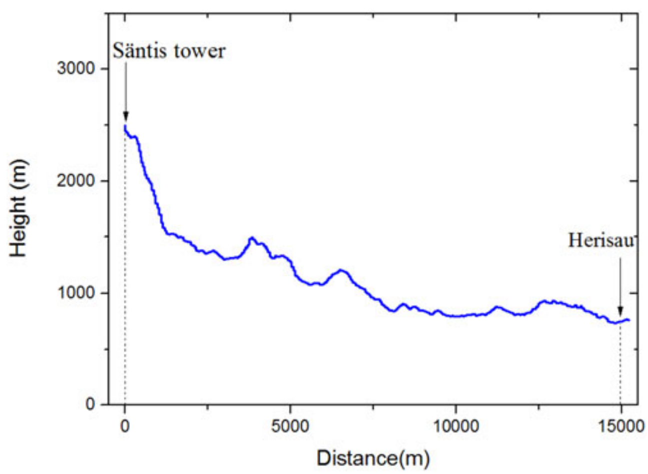

Fig. 7. Two-dimensional cross-section of the topographic map along the direct path between the tower and the field measurement station (red-dashed line in Fig. 6). Data from ASTER GDEM.

problem is shown in Fig. 8 (a). The adopted 2-D axial symmetric assumption appears to be reasonable since, in our case, the tower is located on the top of the Säntis Mountain, which is the highest point in the considered region [see Fig. 8 (a)]. Additionally, this assumption allows a significant reduction of the computational complexity of the problem.

In order to analyze the effect of the field propagation along an irregular terrain, we also considered the commonly used assumption of a flat ground as shown in Fig. 8(b). Note that, in our case, the effect of the presence of the Säntis tower can be neglected, due to the small round-trip time along the tower relative to the risetime of current waveforms (e.g., [34] and [35]). As already mentioned in Section II, the field sensors were located on the roof of a building. As discussed in the literature (e.g., [36]–[38]), the presence of the building might result in an enhancement of the electric field. This issue will be discussed in Section V.

For the FDTD analysis, the cylindrical coordinates are adopted and the first-order Mur absorbing boundary conditions are employed to truncate the computational domain [39]. The

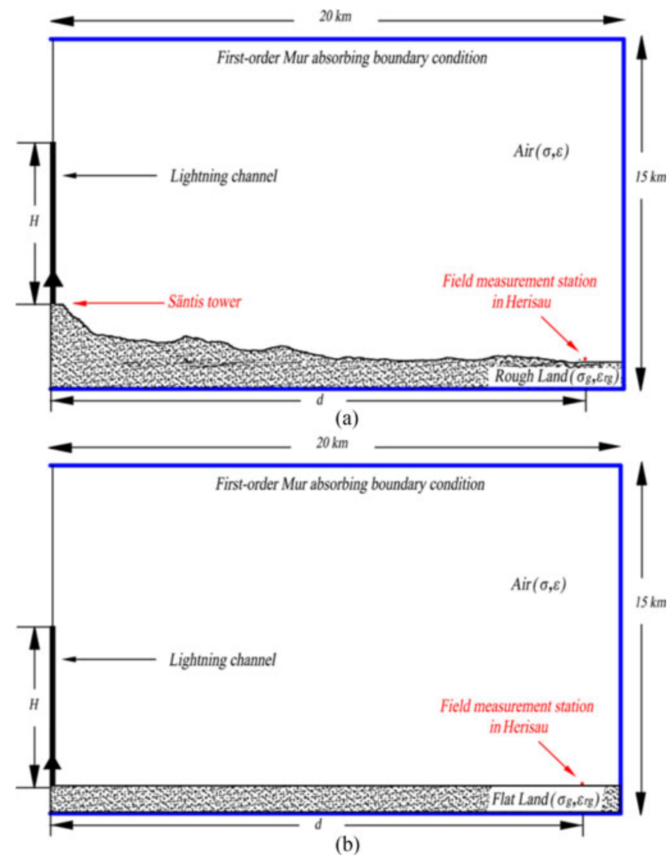

Fig. 8. Geometry for the FDTD simulation domain. (a) Taking into account the 2-D topography of the terrain. (b) Assuming a flat ground.

air and the ground are both represented by Yee's grid units [40]. The FDTD simulation domain of 20 km $\times$ 15 km is illustrated in Fig. 8. The spatial discretization was $\Delta r = \Delta z = 10$ m and the time increment was set to 19.2 ns, which satisfies the time and space stability condition for FDTD. The ground was characterized by a conductivity σ_g and a relative permittivity ε_{rg}. The lightning channel was set in the symmetry axis of the 2-D axial symmetric model and the current distribution along the return stroke channel was specified according to the modified transmission line model with exponential decay (MTLE) [41, 42], assuming a current decay constant $\lambda = 2$ km [43]. The channel height is assumed to be $H = 7.5$ km and the return stroke speed was set to $v = 1.5 \times 10^8$ m/s. A discussion on the influence of the return stroke model and the adopted value for the return stroke speed will be given in Section V. The simulations were carried out on a computer with an Intel Xeon E5450 processor and 32 GB of available memory.

The developed FDTD simulation code has been thoroughly validated against results obtained using FEMs [44].

V. Simulations and Comparison With Experimental Data

We consider the lightning flash occurred on October 22, 2014, at 1 :14 AM, presented in Fig. 5. We have selected three return strokes (labeled as RS_2, RS_5, and RS_6) and one ICC pulse (labeled as $ICCp_3$) for the analysis.

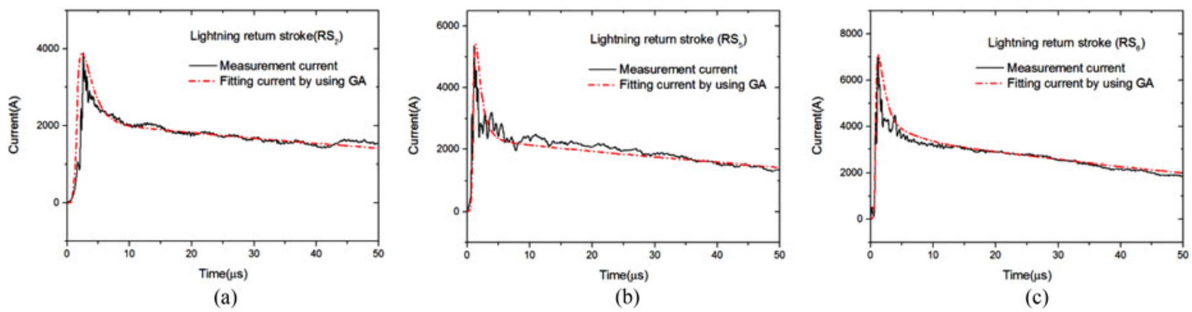

Fig. 9. Measured current waveforms associated with the three selected return stokes (solid line) and their analytical representations using Heidler's functions (dashed line). (a) Case1: RS_2. (b) Case2 : RS_5. (c) Case3 : RS_6.

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

Lightning return stroke	I_{01} (kA)	τ_{11} (μs)	τ_{12} (μs)	n_1	I_{02} (kA)	τ_{21} (μs)	τ_{22} (μs)	n_2
Case 1:RS_2	2.6	2.0	1.5	2.0	2.1	1.0	120	9.0
Case 2:RS_5	4.0	0.1	1.0	7.0	2.3	1.0	100	6.0
Case 3:RS_6	7.3	0.8	3.0	7.0	3.0	5.0	80	3.0

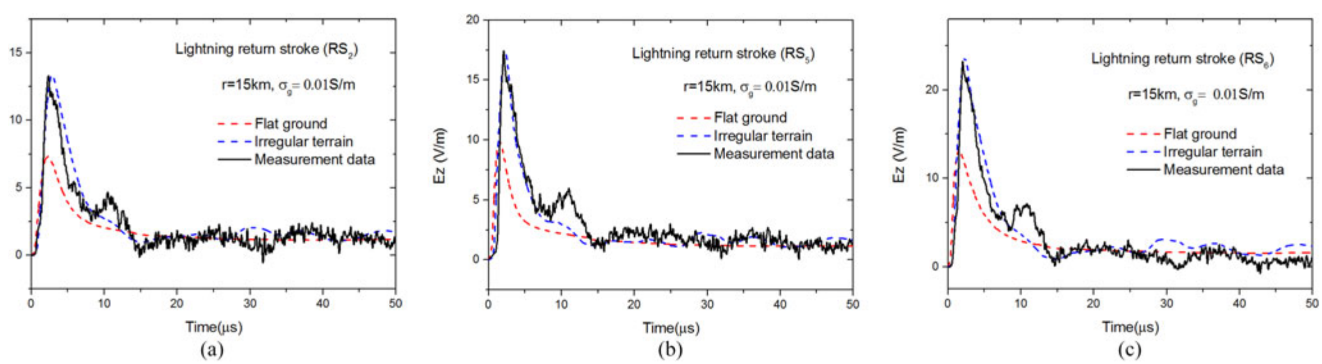

Fig. 10. Vertical electric fields at 15 km associated with return stroke pulses shown in Fig. 9. Solid line : Measured waveforms; Red dashed lines : simulated waveforms assuming a flat ground; Blue dashed lines : simulated waveforms taking into account the terrain profile. (a) Case 1: RS_2. (b) Case 2 : RS_5. (c) Case 3 : RS_6. Ground parameters : $\sigma_g = 0.01$ S/m and $\varepsilon_{rg} = 10$.

A. Return Stroke Pulses

The channel base currents associated with the considered return strokes were not directly used in the FDTD simulations because of the superimposed noise. Instead, they were represented using the sum of two Heidler's functions [45]

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

The parameters of function (1) were determined using a genetic algorithm (GA) [46]. Fig. 9 presents the measured current waveforms associated with the three considered return stroke pulses along with their analytical representations using Heidler's functions. The determined parameters of the functions for each waveform are given in Table I.

Fig. 10 presents a comparison between FDTD simulation results and the obtained experimental data for the vertical electric fields generated by the three return strokes. For the comparison, we have considered the two terrain profiles illustrated in Fig. 8, namely an irregular ground model based on a 2-D representation of the topographic map [see Fig. 8 (a)], and a flat ground [see Fig. 8 (b)]. The conductivity and the relative permittivity of the ground were set to $\sigma_g = 0.01$ S/m and $\varepsilon_{rg} = 10$, respectively. A discussion on the influence of the ground conductivity will be given in Section V.

It can be seen that, considering the real irregular terrain between the Säntis tower and the field measurement station, both the waveshape and amplitude of the simulated electric fields are in excellent agreement with the measured waveforms. On the other hand, the assumption of a flat ground results in a significant underestimation of the peak electric field. It is interesting to note that the obtained results are consistent with a recent study on the performance analysis of the European lightning detection network (EUCLID) presented in [31], in which it was shown that the peak current estimates provided by the EUCLID network were about 1.8 times higher than those from

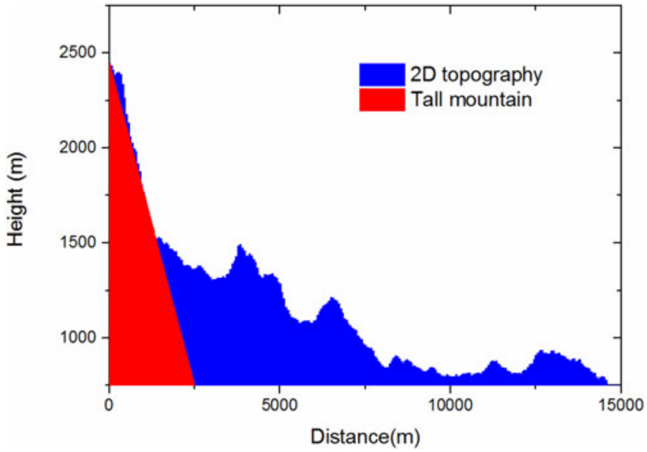

Fig. 11. Analysis of the effect of the enhancement. Red profile: approximation of the mountain using a cone over a flat ground. Blue profile: 2-D topography of the terrain.

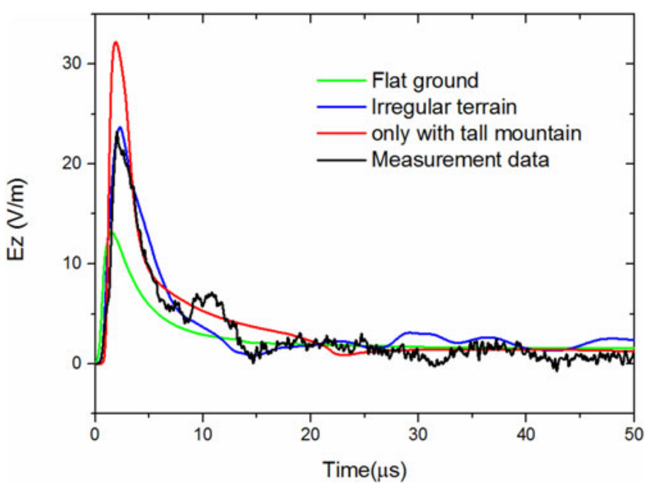

Fig. 12. Comparison between simulated fields associated with a flat ground (green line), irregular terrain (see blue profile in Fig 11), and the ground with a tall mountain (see red profile in Fig. 11). The black curve corresponds to the measured waveform.

direct measurements. This overestimation can be attributed to the enhancement of the radiated electromagnetic fields associated with the presence of the irregular, mountainous terrain around the Säntis Tower.

A discussion is in order on the observed enhancement of the electric field. It is well known that a tall tower struck by lightning results in an enhancement of the radiated electromagnetic fields (e.g., [47]–[49]). As mentioned earlier, the effect of the presence of the Säntis tower on the radiated field is negligible because of the small round-trip time along the tower relative to the risetime of the current waveforms. The question, however, is whether the observed enhancement in this case is due to the presence of the tall mountain on which the tower is sitting. To address this question, we have considered an alternative profile in which we have approximated the mountain by a cone over a flat ground (red shape in Fig. 11), and compared it with the results considering the irregular terrain (represented in blue in the same figure). Fig. 12 shows the simulated fields for the two profiles, along with the measured waveform. It can be seen that

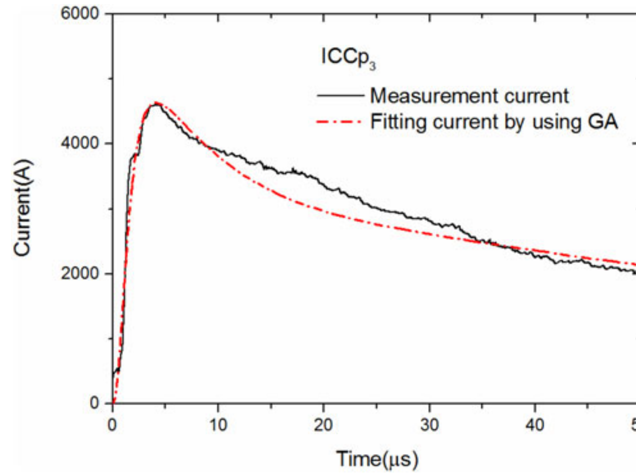

Fig. 13. Measured current waveform associated with the selected ICC pulse ($ICCp_3$ in Fig. 5) in solid line, and its analytical representations using Heidler's functions in dashed line.

the red profile results in a significant enhancement effect on the field, which, to some extent, can be considered as similar to the presence of a tall strike object. On the other hand, the propagation along the irregular terrain around the tall mountain appears to produce a counterweight to this effect, resulting in a simulated electric field which is in excellent agreement with the measured one.

B. ICC Pulses

The characteristics of pulses superimposed on the ICC of upward discharges (ICC pulses) have been analyzed in several studies on rocket-triggered and tower-initiated lightning flashes (see, e.g., a review in [50]). According to [51], pulses with short risetimes (lower than about 8 μs) are indicative of the leader-return stroke mode of charge transfer to ground, while those with longer risetimes are associated with the M-component mode of charge transfer to ground [51].

In this section, we present simulation results for the electric fields associated with an ICC pulse labeled $ICCp_3$ in Fig. 5. This ICC current pulse is characterized by a 10–90% risetime of 2.26 μs and a peak amplitude of 4.6 kA. As for the return stroke waveforms, the ICC current pulse was represented by the sum of two Heidler's functions whose parameters were determined using a GA approach, with $I_{01} = 4.2$ kA, $\tau_{11} = 2.0\ \mu$s, $\tau_{12} = 6.0\ \mu$s, $n_1 = 2.0$ and $I_{02} = 2.5$ kA, $\tau_{21} = 8.0\ \mu$s, $\tau_{22} = 90.0\ \mu$s, $n_2 = 2.0$. Fig. 13 presents the measured current waveform associated with $ICCp_3$ (solid line). In the same figure, the analytical representation is also shown in dashed line.

The vertical electric field associated with the ICC pulse was determined following the same approach as the one used for the return stroke pulses. The same model (MTLE) and the same parameters for the return stroke speed were also adopted. Fig. 14 presents the comparison between FDTD E-field simulation results and the obtained experimental data. It can be seen that the simulation results taking into account the terrain profile are in reasonable agreement with the measured data, suggesting that the hypothesis of Flache *et al.* [51] on the charge transfer

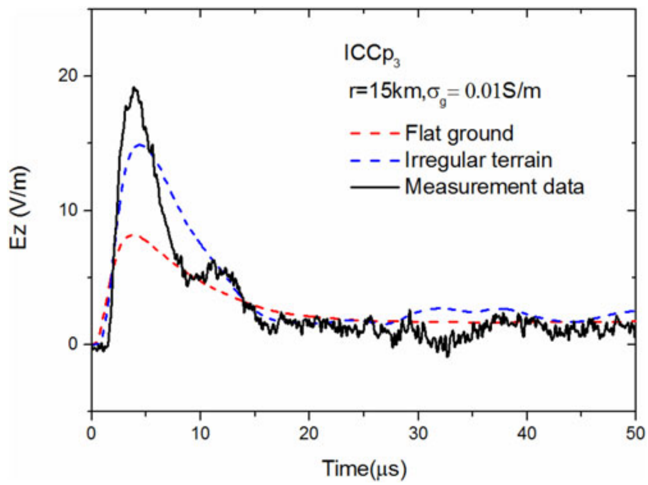

Fig. 14. Vertical electric fields at 15 km associated with the ICC pulse shown in Fig. 11. Solid line: Measured waveforms. Red dashed lines: simulated waveforms assuming a flat ground. Blue dashed lines: simulated waveforms taking into account the terrain profile. Ground parameters : $\sigma_g = 0.01$ S/m and $\varepsilon_{rg} = 10$.

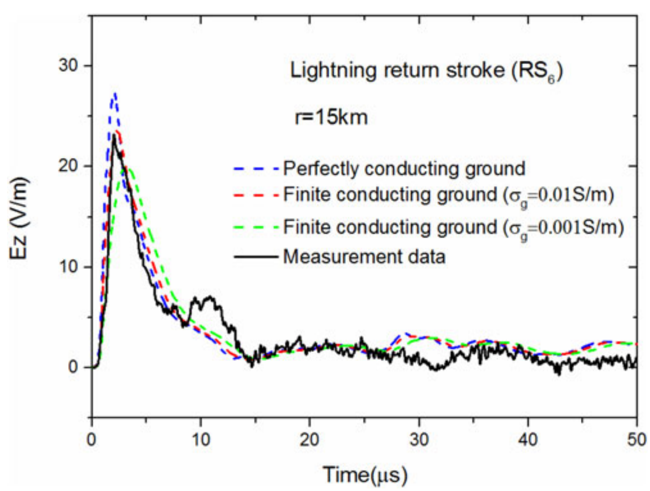

Fig. 15. Effect of the finite conductivity on the vertical electric field at a distance of 15 km from the lightning channel and along the irregular path. Case 3: RS_6.

mechanism is appropriate. Further studies, however, are needed to confirm this hypothesis. The observed difference in the peak value of the field is about 21%. Similar to the results obtained for the return strokes, it can be seen that the assumption of a flat ground results in a significant underestimation of the peak electric field associated with the ICC pulse.

C. Discussion

A discussion is in order on the influence of various parameters adopted for the simulations, namely the ground conductivity, the return stroke speed, the adopted return stroke model, and the presence of the building on which the field sensors were located.

1) Ground Conductivity: Fig. 15 shows the FDTD simulations considering three different conductivities for the ground associated with the return stroke (RS_6) in Fig. 5: 1) perfectly conducting, 2) $\sigma_g = 0.01$ S/m, and 3) $\sigma_g = 0.001$ S/m. The relative permittivity was set to $\varepsilon_{rg} = 10$ in all cases.

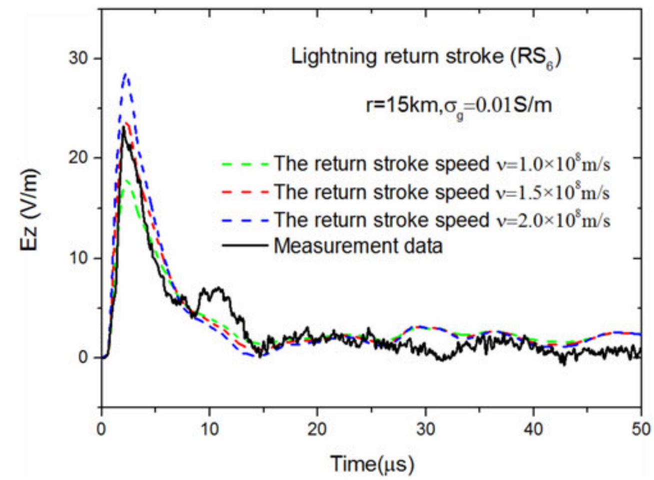

Fig. 16. Effect of the return stroke speed on the vertical electric field at a distance of 15 km from the lightning channel and along the irregular path. Case 3: RS_6.

It can be seen that the ground conductivity affects essentially the early-time behavior of the vertical electric field (see [52] for a review on the effect of propagation along a lossy ground). A decrease of the conductivity from 0.01 S/m to 0.001 S/m results in a decrease of the peak electric field of about 15%. The effect of the ground conductivity appears therefore to be less significant compared to the effect of the propagation over the considered rough terrain. Note that we have considered a simple, homogeneous model for the ground with constant, frequency-independent electrical parameters. A more thorough analysis taking into account the soil inhomogeneity (e.g., [7] and [13]) and frequency dependence (e.g., [17], [34], and [53]) is beyond the scope of this paper.

2) Return Stroke Speed: The return stroke speed is an important parameter that can vary from one stroke to another [54]. At distant observation points at which the field is essentially determined by its radiation component, the field peak is nearly proportional to the return stroke speed [55]. On the other hand, at shorter distances, an increase of the return stroke speed might result in a slight reduction of the electric field [56]. The effect of the return stroke speed is illustrated in Fig. 16. In the analysis, we have considered three different values for the return stroke speed, namely 1.0×10^8 m/s, 1.5×10^8 m/s, and 2.0×10^8 m/s. It can be seen that an increase of the return stroke speed from 1 to 1.5×10^8 m/s, and from 1.5 to $2{\times}10^8$ m/s will result in an increase of about 20% of the peak electric field.

3) Return Stroke Model: Fig. 17 shows the simulated results using three different return stroke models: MTLE [41], [42], TL [57], and MTLL [58]. 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 due to the absence of any attenuation of the current pulse along the channel (e.g., [59]). In summary, it can be said that the adopted return stroke model will affect to some extent the results (see also [60]). However, the general conclusion that the propagation along the considered irregular terrain results in an overall enhancement of the field remains valid regardless of the used model.

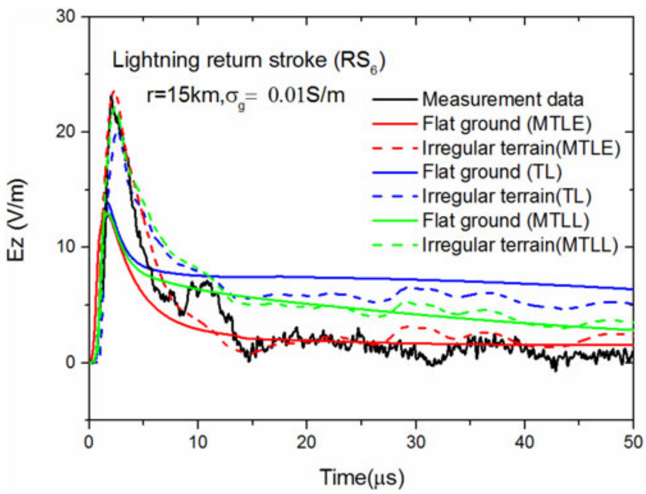

Fig. 17. Effect of the return stroke model on the vertical electric field at a distance of 15 km from the lightning channel and along the irregular path. Case3 : RS_6.

4) Presence of the Building on Which the Field Sensor is Located.: Finally, it is well known that the presence of the building on which the field sensors are located might affect the measured waveform (e.g., [37] and [38]). In particular, the electric field measured on the roof of a building might experience an enhancement that depends on several factors related to the building (shape, material, presence of conducting beams, etc.) and on the position of the field sensor. Representing the building by a conducting block with a conductivity equal to that of the ground would result in an enhancement of the peak electric field of about 25%. However, in the present configuration, the building on which the field sensors were located is surrounded by several other buildings which makes it difficult to evaluate the enhancement effect, either by measurement or by simulation.

VI. Summary and Conclusion

In this paper, we presented a theoretical and experimental analysis of the propagation effects of lightning electromagnetic fields over a mountainous terrain. First, we presented simultaneous records of lightning currents and electric fields associated with upward negative lightning flashes to the instrumented Säntis tower in Switzerland. Second, the propagation of lightning electromagnetic fields along the mountainous region was simulated using a full-wave approach based on the FDTD method. Because of the large distance between the Säntis tower and the field measuring station (about 15 km), a 3-D-FDTD simulation taking into account the exact topography would require a prohibitive computation time and memory requirements. We have considered in this study a 2-D axial symmetric model using the cross-section of the topographic map along the direct path between the tower and the field measurement station. The data were extracted from the GDEM V2 and imported in our FDTD simulation code.

It was shown that, considering the real irregular terrain between the Säntis tower and the field measurement station, both the waveshape and amplitude of the simulated electric fields associated with return strokes were in excellent agreement with the measured waveforms. On the other hand, the assumption of a flat ground resulted in a significant underestimation of the peak electric field. The obtained results were found to be consistent with the recent study on the performance analysis of the EUCLID presented in [31], in which, it was shown that the peak current estimates provided by the EUCLID network were about 1.8 times higher than those from direct measurements. This overestimation can be attributed to the enhancement of the radiated electromagnetic fields associated with the presence of the irregular, mountainous terrain around the Säntis Tower.

Furthermore, we presented simulation results for the electric field associated with a fast ICC pulse (pulse superimposed to the ICC of the flash). Assuming that fast ICC pulses are associated with the leader-return stroke mode of charge transfer to ground, the electric field was determined following the same approach as the one used for the return stroke pulses. It was found that the simulation results taking into account the terrain profile are in reasonable agreement with the measured data, suggesting that the hypothesis on charge transfer mechanism is appropriate.

Finally, we discussed the sensitivity of the obtained results to the assumed values for the return stroke speed and the ground conductivity, the adopted return stroke model, as well as the presence of the building on which the sensors were located.

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