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Location Accuracy Evaluation of ToA-Based Lightning Location Systems over Mountainous Terrain

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***Abstract*—In this paper, we analyze the location error of Time of Arrival (ToA)-based lightning location systems (LLSs) resulting from propagation over mountainous terrain. For the analysis, we have considered the region around the Säntis Tower, located in the Swiss Alps. The study is based on a full-wave finite-difference time-domain (FDTD) approach and the two-dimensional (2D) topographic maps along the direct path between the Säntis Tower and nearby sensor sites. The accuracy of the ToA lightning location results associated with times of arrival determined 1) as the time intercepts of straight lines passing through the peak of the return stroke pulse and different amplitude threshold crossing points, 2) as the time of the peak of the first derivative of the field and 3) as the time of occurrence of the peak value of the field are evaluated by using our full-wave FDTD method. The evaluated location errors associated with amplitude threshold crossing points of 10% and 20% of the initial rising amplitude of the field were found to be the lowest.**

Keywords—Lightning; Time of Arrival; FDTD; Säntis Tower; EUCLID

I. Introduction

Theoretical studies have shown that the location accuracy of the Time of Arrival (ToA) technique used in lightning location systems (LLSs) might be affected by propagation effects along a ground of finite conductivity (e.g., [*Cooray*, 2009; *Cooray et al.*, 2000; *Delfino et al.*, 2008a; *Delfino et al.*,

non-flat ground configurations (e.g.[*Cooray and Ming*, 1994; *Li et al.*, 2013; *Li et al.*, 2014; *Paknahad et al.*, 2014; *Schulz and Diendorfer*, 2000; *Zhang et al.*, 2012a; *Zhang et al.*, 2012b]). Several methods have been proposed to refine the algorithms for the estimation of the time of arrival associated with a measured waveform to minimize the effect of the lossy ground (e.g., [*Cooray*, 1987; *Honma et al.*, 1998]). Recently, *Li et al.* [2016] studied the propagation effects on lightning radiated electromagnetic fields over mountainous terrain by considering a pyramidal mountain and discussed the time delay error in the ToA technique currently used to locate lightning in detection networks.

In this paper, we go one step further and analyze the location error of ToA-based LLSs resulting from propagation over mountainous terrain and we discuss the effect of the choice of the amplitude threshold level on the lightning location accuracy in ToA according to the onset determination technique that will be described in Section II.

The presented analysis will be based on a full-wave FDTD approach and the two-dimensional (2D) topographic map along the direct path between the location of the lightning return stroke, assumed to be at the Säntis Tower and nearby sensor sites. The ground finite conductivity is taken into account in the numerical simulations. Section II contains the analysis method and calculation models. Section III presents simulation results and relevant discussion. Finally, conclusions are presented in Section IV.

II. Analysis Approach and Calculation Models

A. Definition of the Onset Time Associated with the ToA Technique

The time of arrival of a measured signal used by the ToA technique for calculating the lightning location can be evaluated using different methods (e.g., [*Lojou et al.*, 2011; *Schulz*, ... ds for the determination of ... (e.g., *Honma et al.* [2013]) resulting in better location accuracy.

In order to determine the time of arrival of a field pulse at a given sensor of a ToA-based LLS system, the so called onset time is used. It is assumed that this onset time provides the best reference point in the field waveforms seen by all the sensors at various distances and the fields being affected by different propagation paths conditions. The definition of the onset time t_{on} presented by *Schulz* [1997] and used in this paper is illustrated in Fig. 1.

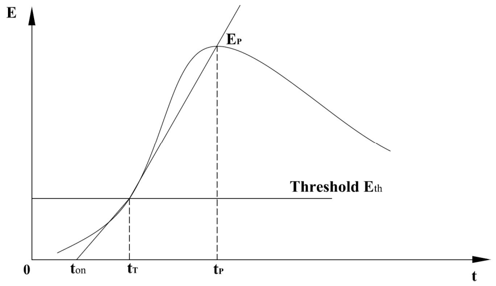

Fig. 1. Calculation of the signal onset time t_{on}

The onset time t_{on} can be calculated from the time t_T at which the signal exceeds an amplitude threshold E_{th}, the peak time t_p, the amplitude threshold value E_{th} and the peak value of the signal E_p using the following expression:

$$t_{on} = t_p - \frac{t_p - t_T}{E_p - E_{th}} E_p \tag{1}$$

In addition, two alternative methods will be used to estimate the reference point for the time of arrival: The time of the peak of the first derivative of the field [*Cooray*, 1987], and the time of the peak value of the field.

B. *General Methodology*

In order to assess the location error of ToA-based lightning location systems resulting from propagation over mountainous terrain, we adopted the following approach.

First, we considered a return stroke to the Säntis Tower [*Romero et al.*, 2013] in Switzerland and we computed the generated electromagnetic fields at four positions which would correspond to LLS sensor sites. Fig. 2 presents the topographic map of the selected region based on the global digital elevation model data. S1, S2, S3 and S4 are the locations of four LLS sensors.

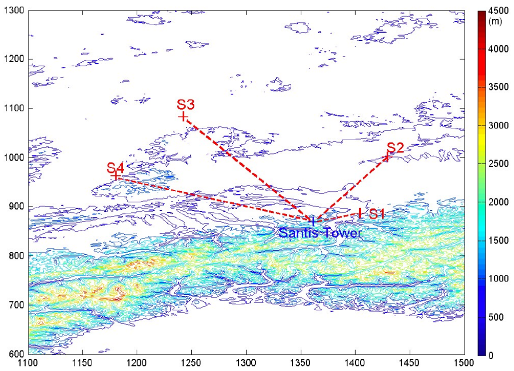

Fig. 2. Topographic map of the region of interest. A return stroke is assumed to strike the Säntis Tower (blue cross). The locations of the 4 hypothetical ToA-based LLS sensors are shown in the figures (S1, S2, S3 and S4).

As discussed in *Li et al.* [2015] a three-dimensional (3D) FDTD simulation would require prohibitive computation time and memory requirements. We have therefore considered in this work a two-dimensional (2D) axial symmetric model using the 2D cross sections of the topographic map along the direct path between the Säntis tower and the four sensor sites, as shown in Fig. 3, which were imported into our FDTD simulation code. To do this, the global digital elevation model version 2 (GDEM V2) from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) has been adopted and imported into our FDTD simulation code [*Li et al.*, 2015].

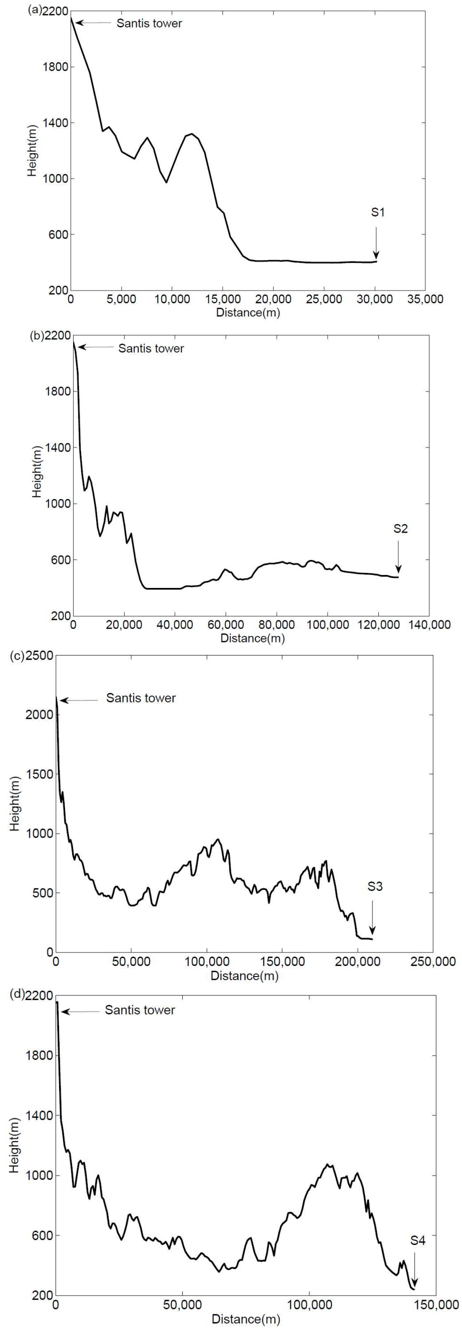

Fig. 3. 2D cross section of the topographic map along the direct path between the Säntis Tower and the four observation points (sensor sites) (a) S1, (b) S2, (c) S3 and (d) S4 (red dashed lines in Fig. 2).

Then, the location of the lightning discharge was determined using the ToA technique [*Cummins et al.*, 1998] and assuming a flat ground. The onset time of the fields at the sensors was calculated by using Equation (1) in Section II.A with the involved parameters (t_p, E_p, t_T), which were extracted from the numerical results obtained using our FDTD approach. Different values for the threshold time t_T presented in the literature [*Cooray*, 1987; *Honma et al.*, 1998; *Schulz and Diendorfer*, 2000] were considered to calculate the field onset time, which are the times corresponding to:

(a) 10% of the initial rising amplitude of the field,
(b) 20% of the initial rising amplitude of the field,
(c) 50% of the initial rising amplitude of the field [*Cooray*, 1987],

In addition, as mentioned in Section II.A, two alternative methods were also used to estimate the reference point for the time of arrival, namely:

(d) the peak derivative time [*Cooray*, 1987], and,
(e) the peak amplitude time.

Finally, the estimated locations were compared with the actual one (Säntis Tower).

III. Analysis, Simulation Results and Discussion

A. Calculation Parameters

For the FDTD analysis, the 2D cylindrical coordinates were adopted and the first-order Mur absorbing boundary conditions were employed to truncate the computational domain [*Mur*, 1981]. The simulation domain dimensions were 300 km × 15 km. The spatial discretization was $\Delta r=\Delta z=30$ m and the time increment was set to 50 ns. 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 2D 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) [*Nucci et al.*, 1988; *Rachidi and Nucci*, 1990], assuming a current decay constant λ = 2 km [*Nucci and Rachidi*, 1989]. The channel height was assumed to be $H = 7.5$ km and the return stroke speed was set to $v = 1.5\times10^8$ m/s. The ground conductivity and relative permittivity were assumed to be $\sigma_g = 0.001$ S/m and $\varepsilon_{rg}=10$, respectively. The channel-base current was represented using the sum of two Heidler's functions [*Heidler*, 1985], the parameters of which correspond to a typical subsequent return stroke [*Rachidi et al.*, 2001].

B. Simulation Results and Discussion

To illustrate the approach, Fig. 4 presents the results considering the ideal case of a flat, perfectly-conducting ground.

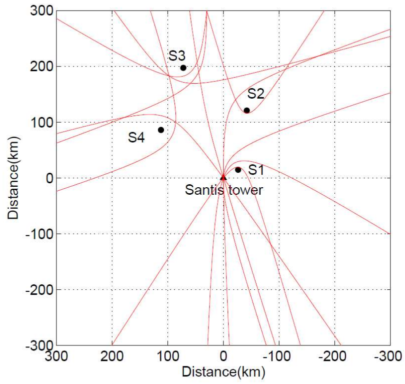

Fig. 4. Lightning location results evaluated by the ToA technique for the ideal case of a flat, perfectly-conducting ground. The presented area is 300 km× 300 km, centered around the Säntis Tower (triangle).

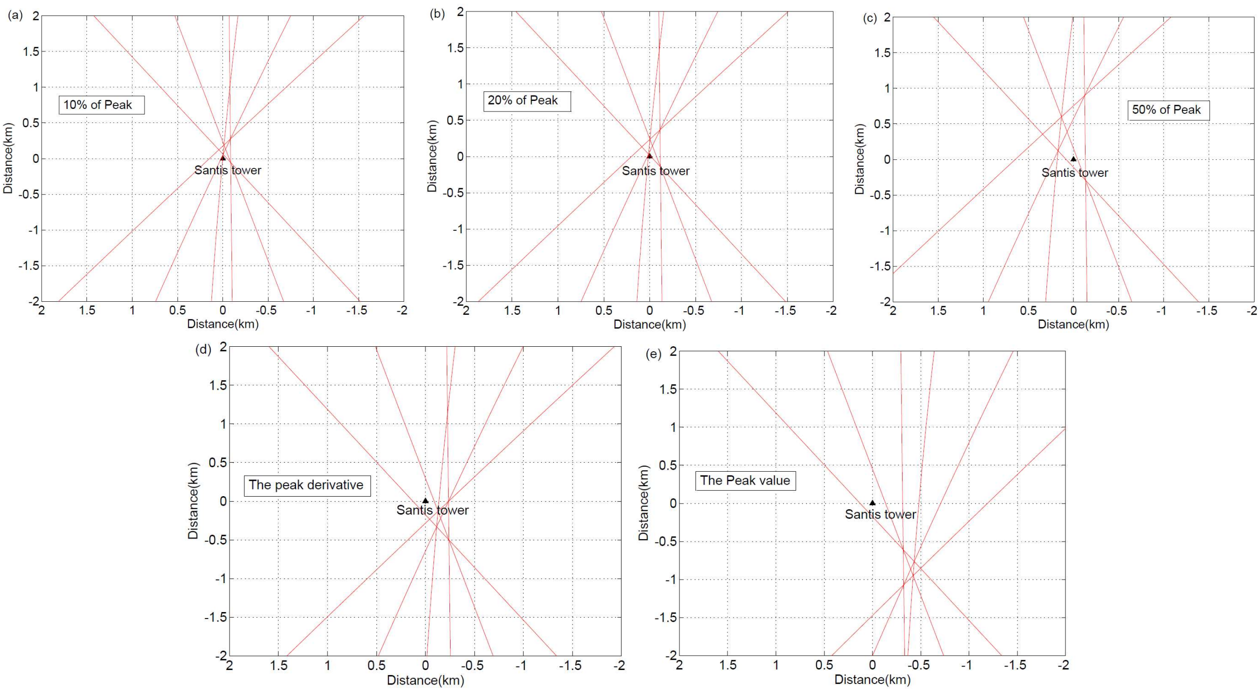

Fig. 5 Lightning location results evaluated by the ToA technique considering different reference points for the time of arrival: (a) Using (1) with an amplitude threshold of 10% of the initial rising amplitude of the field; (b) Using (1) with an amplitude threshold of 20% of the initial rising amplitude of the field; (c) Using (1) with an amplitude threshold of 50% of the initial rising amplitude of the field; (d) The peak derivative time of the field; and (e) The peak field time. The presented area is 2 km×2 km, centered around the Säntis Tower (triangle).

In this figure, pairs of hyperbolas associated with the differences in time of arrival between each pair of observation points (sensors) are shown. As can be seen from the figure, the ToA-predicted location coincides perfectly with the Säntis Tower. For the perfectly-conducting ground case, the result is independent of the choice of the amplitude threshold in the determination of the onset time.

Fig. 5 presents the plot of pairs of hyperbolas associated with the differences in time of arrival between each pair of observation points, in this case taking into account the terrain profile and the finite conductivity of the ground. In this case, the resulting hyperbolas strongly depend on the adopted method to estimate the reference point for the time of arrival, as can be seen by comparing Figs. 5a, b, c, d and e.

The evaluated location errors associated with amplitude thresholds of 10% and 20% of the initial rising amplitude of the field appear to be the lowest.

IV. CONCLUSIONS

In this paper, we analyzed the location error of Time of Arrival (ToA)-based lightning location systems resulting from propagation over mountainous terrain. For the analysis, we have considered the region around the Säntis Tower, located in the Swiss Alps. The study was based on a full-wave finite-difference time-domain (FDTD) approach and the two-dimensional (2D) topographic maps along the direct path between the Säntis Tower and nearby sensor sites.

The accuracy of ToA lightning location results associated with onset times determined from different amplitude thresholds were evaluated using our full-wave FDTD method. The evaluated location errors associated with time of arrivals estimated using thresholds of 10% and 20% of the initial rising amplitude of the field were found to be the lowest. It is worth noting that the finite ground conductivity was also taken into account in the FDTD simulations and, therefore, the resulting changes in the estimated time of arrivals are a combination of the effect of the terrain profile and of the ground conductivity.

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