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Locating Lightning Using Electromagnetic Time Reversal: Application of the Minimum Entropy Criterion

Hamidreza Karami[1], Amirhossein Mostajabi[1], Mohammad Azadifar[2], Zhaoyang Wang[1], Marcos Rubinstein[2], Farhad Rachidi[1]

1 Electromagnetic Compatibility Laboratory, Swiss Federal Institute of Technology (EPFL), 1015 Lausanne, Switzerland
2 University of Applied Sciences of Western Switzerland (HES-SO), 1400 Yverdon-les-Bains, Switzerland

***Abstract*—We present a new method based on Electromagnetic Time Reversal (EMTR) to locate lightning return strokes. The application of classical EMTR criteria such as the maximum field peak or the maximum energy to locate radiation sources would not work if the medium is inhomogeneous and/or has scatterers. The proposed method makes use of the fact that the spatial distribution of the field is characterized by a minimum entropy at the time at which the time-reversed back-injected waves reach the source. The focusing time is first determined by evaluating the entropy of the field as a function of time. The last local minimum of the entropy corresponds to the focusing time. The location of the source is determined by examining the spatial distribution of the electric field at the focusing time: the maximum value corresponds to the source location. The application of the proposed method is illustrated considering a 2D example including 4 scatterers and 4 sensors. The forward and reversed time simulations are performed using a 2D-FDTD model with PML boundary conditions.**

Keywords—Electromagnetic Time Reversal (EMTR); Entropy; Lightning Location Systems; Finite Difference Time Domain (FDTD).

I. INTRODUCTION

The knowledge of lightning parameters and of its point of impact are of key importance in lightning protection and detection. Lightning Location Systems (LLSs) provide important information on the lightning discharge, such as its geolocation, time of occurrence and return stroke peak current.

Time-of-arrival (ToA), Magnetic Direction Finding (MDF), and interferometry are the most widely used techniques by LLSs to locate lightning discharges [1]. More recently, electromagnetic time reversal (EMTR) was also proposed as a means to locate lightning discharges [2]-[7]. The application of EMTR to locate lightning includes four steps:

1) The electric or magnetic field waveforms due to the source (lightning strike) are measured by multiple sensors (forward time).

2) The obtained waveforms are time reversed.

3) The time-reversed signals are back-injected at the sensor locations into the location domain using a numerical simulator (reversed time).

4) A criterion is used to determine the location of the source (e.g., the maximum of the field peak or of the energy).

Indeed, the wavefronts generated by back-propagating the time-reversed fields will add up in phase at the lightning strike location [2], [3]. The original EMTR-based algorithm proposed by Mora et al. [3] to locate lightning discharges requires at least three field sensors. In [4], the proposed method in [2] and [3] was modified to include the effect of propagation along a lossy ground.

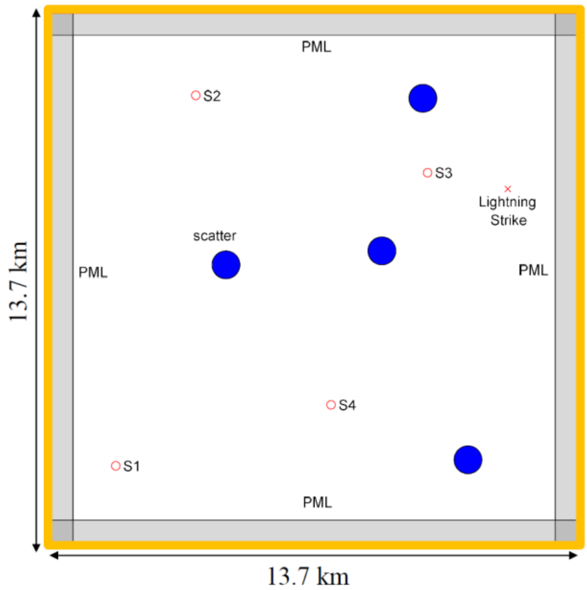

Fig. 1. Geometry of the problem. The lightning strike is shown with a red cross. The blue-filled circles represent scatterers (such as mountains). The red circles show the location of the sensors.

In all the above-mentioned studies [2]-[7], the $1/r$ dependence of the radiation field in the back-propagation step (step 3) was artificially removed in order to deal with the fact that the maximum peak field criterion might not be usable because the contribution of each sensor might become prohibitively small, and also because of the possible singularity at the source location. Back-propagating the fields by removing the $1/r$ dependence ensures that the fields coming from the sensors will be enhanced at the source location. Furthermore, the maximum constructive interference will necessarily occur at the source point because it is only at this location that the fields from each sensor arrive in phase.

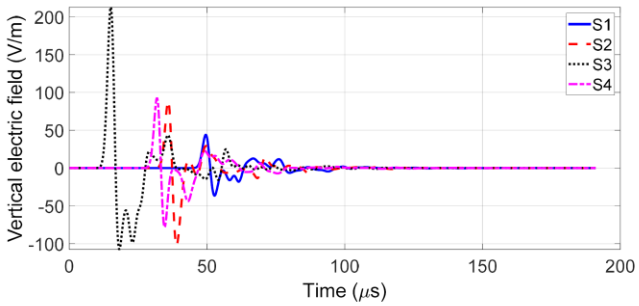

Fig. 2. Vertical electric fields captured by sensors due to the lightning strike corresponding to Fig. 1.

However, a constant amplitude assumption in the back-propagation phase presents at least two important disadvantages:

a) This assumption cannot be applied to numerical methods that are commonly used in many electromagnetic simulators, such as those in commercially available software.

b) The assumption is inapplicable in the case when the medium contains one or more scatterers in the computation domain.

In order to cope with this problem, an improved methodology based on the entropy criterion ([8] and [9]) is used in this paper. The presented simulation results for both forward and reversed times will be performed using the Two-Dimensional Finite Difference Time Domain (2D-FDTD) technique.

The use of the 2D-FDTD method allows the modeling of losses in the forward and backward propagation and it enables the modeling of complex structures that need to be considered in real applications, such as, for instance, mountains.

II. Geometry of the Problem

Fig. 1 shows the geometry of the problem and the 2D-FDTD computational domain. We consider a lightning strike at an arbitrary position shown by the red cross in the figure. The medium contains 4 scatterers (shown as blue circles) which represent, as a first approximation, mountains. Each scatterer has a radius of 250 m. Four sensors at which the generated fields are determined are considered and shown using red circles in Fig. 1. The relative permittivity and conductivity of the scatterers are assumed to be 10 and 0.05 S/m, respectively. Four Perfectly Matched Layers (PML) are used as boundary conditions in the 2D-FDTD model. Equally spaced cells are used to mesh the solution space. The length of each cell is 30 m and the time step is 63 ns.

A Gaussian 10-MHz bandwidth pulse is used as a source. Fig. 2 shows the calculated vertical electric field at each sensor. The electric field waveforms differ from each other by their amplitude and their respective time of arrival, both depending on the distance from the source. Oscillations due to reflections from the considered objects can also be observed in the late-time response of the field.

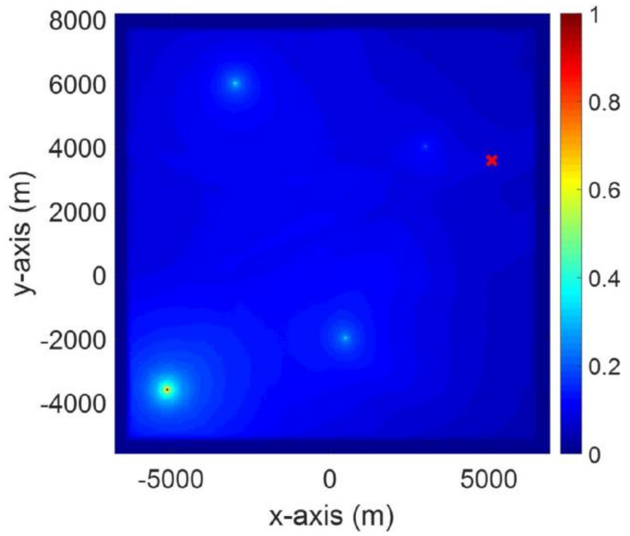

Fig. 3. Normalized maximun peak of electric field in the time-reversed phase. The red cross represents the location of the source.

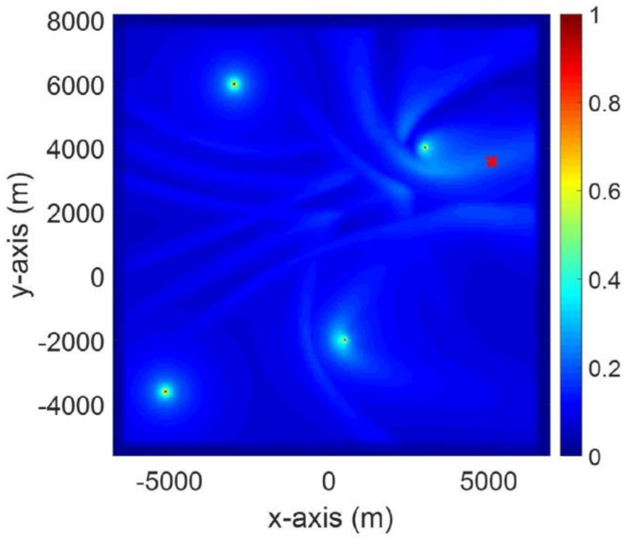

Fig. 4. Normalized energy of the electric field in the time-reversed phase. The red cross represents the location of the source.

III. Application of the EMTR Technique to Locate the Source

All four steps in the EMTR methodology described in Section I were applied to locate the source. The electric fields at each sensor were time reversed and back injected into the solution space using the 2D-FDTD method. In the following, we discuss the selection of various criteria in the fourth step of the EMTR method.

A. *Maximum field peak and maximum energy criteria*

Figs. 3 and 4 present, respectively, the normalized maximum field peak and the normalized energy over the solution space obtained by 2D-FDTD method. In these figures, the maximum peak field and the maximum energy are not obviously located at the lightning source, which is shown with the red cross in these figures. Indeed, as a result of the $1/r$ attenuation in the backward propagation, these two criteria cannot be used to locate the source. As discussed earlier, the $1/r$ dependence in the back-propagation phase cannot be artificially removed due to the presence of scatterers in the medium.

B. Minimum entropy criterion

The main problem with the use of the two criteria discussed in the previous section is the fact that they are defined over the whole time interval. If we consider, however, the exact time at which the time-reversed back-injected waves reach the source, they are expected to produce a sharp peak at the target location at that exact instant, since they all arrive in phase. As noted in [8], such a distribution is characterized by a small entropy. Therefore, a criterion based on the minimum of entropy can be used to identify first the time at which the waves focus back to the source. The maximum field peak at this identified instant can be then used to locate the source.

At each time, the entropy of the electric field is calculated using

$$Entropy(n) = \left[\sum_{i,j} E_z^2(i,j)\right]^2 / \sum_{i,j} E_z^4(i,j) \qquad (1)$$

in which E_z is the z-component of electric field, (i,j) are the grid cell coordinates, and the summation is performed over the solution space.

As discussed in [8]-[10], the last local minimum of the entropy corresponds to the focusing time. The location at which we get the maximum electric field at the focusing time is the source location.

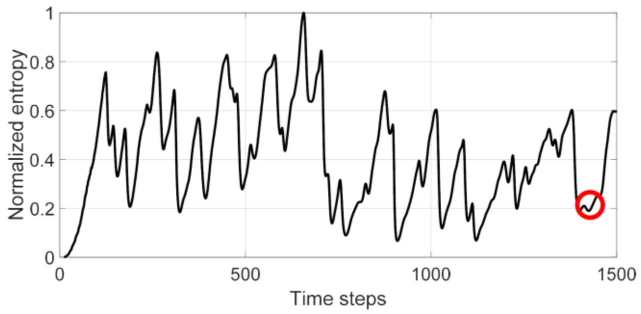

Fig. 5. Entropy criterion [7] used to determine the optimal time at which all the time-reversed back-injected waves focus at the source location. The optimal time corresponds to the last local minimum, shown by the red circle.

Fig. 5 shows the normalized entropy over the time for the geometry of Fig. 1. As shown in this figure, the focusing time is identified as the last local minimum of the entropy.

Fig. 6 shows the distribution of the electric field intensity at the optimal time determined using the minimum entropy criterion. As can be seen, the proposed entropy criterion provides a very good geolocation of the lightning strike. Fig. 7 presents an expanded view of the field distribution around the exact lightning location. As can be seen from this figure, the distance between the estimated impact point and the correct location of the lightning strike is 2.5 mesh cells. This means that the location error is less than 75 m.

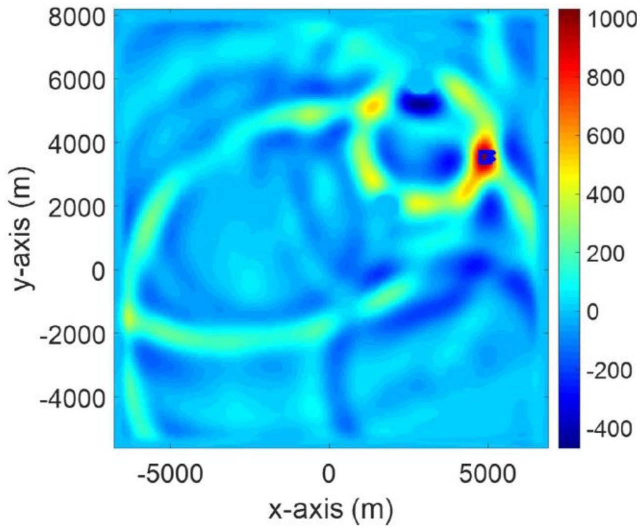

Fig. 6. Distrubution of the electric field amplitude over the calculation domain at the optimal time obtained using the minimum entropy criterion.

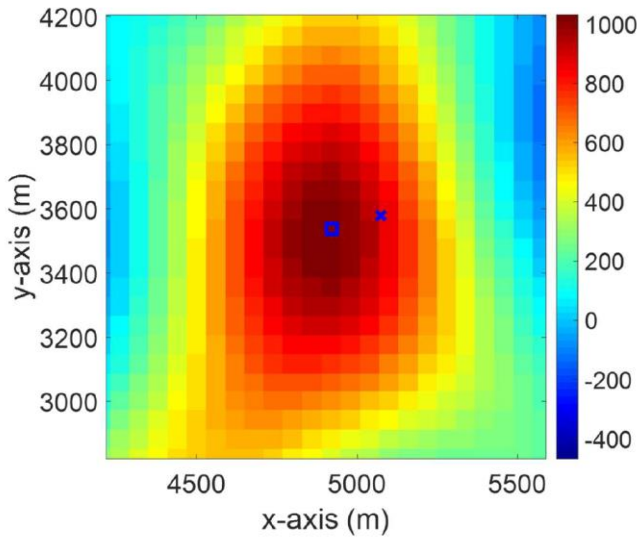

Fig. 7. Expanded view of Fig. 6 around the source location (shown by the blue cross). The estimated location by the proposed method is shown by the blue square.

IV. Conclusion

We presented a new method based on Electromagnetic Time Reversal (EMTR) to locate lightning return strokes. The application of classical EMTR approaches that use criteria such as the maximum field peak or the maximum energy would not work if the medium is inhomogeneous and/or has scatterers.

The proposed method makes use of the fact that, at the time at which the time-reversed back-injected waves reach the source, the field spatial distribution is characterized by a minimum entropy. The focusing time is first determined by evaluating the entropy of the field as a function of time. The last local minimum of the entropy corresponds to the focusing time. The location of the source can be determined by examining the spatial distribution of the electric field at the focusing time: The maximum value corresponds to the source location.

The proposed method was illustrated considering a 2D example including 4 scatterers and 4 sensors. The forward and reversed time simulations were performed using a 2D-FDTD model with PML boundary conditions. The proposed method was able to locate the source with an accuracy of 2.5 mesh cells (75 m).

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