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Development of a Lightning Location System Based on Electromagnetic Time Reversal: Technical Challenges and Expected Gain

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Abstract**—** The basic principles on which commercial Lightning Location Systems are based have not changed since their inception and the research and innovation efforts in the field have been essentially aimed at refining the location accuracy and at improving the discrimination and grouping algorithms of different types of lightning. Time Reversal is a promising technique that has recently received attention for source location and has been shown to be applicable to lightning location with improved performance. This paper describes the technique and the challenges involved in the development of such a system.

Keywords—component; formatting; style; styling; insert *(key words)*

I. Introduction

The basic principles on which commercial Lightning Location Systems are based have remained fundamentally unchanged since their inception and the research and innovation efforts in the field have been essentially aimed at refining the location accuracy and at improving the discrimination and grouping algorithms of different types of lightning. Current systems use one or a combination of three basic approaches: direction finding (e.g., [Krider et al., 1976]), time of arrival (e.g., [Lewis et al., 1960]), and interferometry (e.g., [Oetzel & Pierce, 1969]). The accuracy of the localization of these systems is limited by the fact that the real propagation of the lightning radiation takes place over a topographically and electrically complex medium and that the algorithms utilize only a subset of the characteristics of the fields at the sensor locations (e.g., the peak amplitude and the estimated onset time). In addition, the algorithms used to reduce the number of false positive detections have the unintended effect of reducing their detection efficiency.

Time Reversal has emerged as a very promising technique with applications in various fields of engineering [Rachidi et al., 2017]. It has received a great deal of attention in recent years in the field of acoustics, where it was first developed by Prof. Fink and his team in the 1990s (e.g., [Fink, 1992]). Recent studies carried out at the EPFL and the HES-SO have demonstrated that Electromagnetic Time Reversal (EMTR) can be used as a means to locate lightning strikes [Lugrin et al., 2014; Mora et al., 2012; Rubinstein & Rachidi, 2017]. The studies suggest that the technique can improve the performance of current lightning location networks, although its implementation requires overcoming a number of technological hurdles.

In this paper, we describe the challenges involved in the development of a system based EM time-reversal to locate lightning. For a near real-time LLS, these challenges include:

1) development of efficient simulation techniques and algorithms for EM back-propagation,

2) development of advanced location algorithms for EMTR lightning location,

3) tight time-synchronization, and

4) back-propagation of the waveforms in hardware

This paper is organized in 4 sections. After this introduction, Section II introduces the principle of operation of EMTR for lightning location. In Section III, each one of the challenges listed in the previous paragraph is discussed. Finally, Section IV contains a summary and conclusions.

II. SOURCE LOCATION BY EMTR

The Electromagnetic Time-Reversal method (EMTR) for source location is based on the *t*-symmetry of the wave equation. Assume that a radiation source is inside a cavity and that the system formed by the source, the cavity and the propagation medium is governed by time-reversal invariant physical laws. If the wavefront is recorded as it reaches the inside wall of the cavity, then time-reversed (substituting t by $-t$), and, after the time-reversal operation, retransmitted back into the cavity, the new wavefront would trace back the path followed by the original wave and it would concentrate at the location of the source.

The generation of the time-reversed, back-propagating wavefront would require a very large number of antennas distributed all over a cavity wall (ideally an infinite number) to record the expanding wavefront and to re-inject it so that it back-propagates and concentrates at the original source. A time-reversal cavity cannot be realized experimentally [Cassereau & Fink, 1992] due to the requirement on the number of transducers [Draeger & Fink, 1997]. In practice, the fields can only be measured using a limited number of sensors and the question arises whether the focusing property of time reversal remains intact. Draeger et al. [Draeger & Fink, 1997; "One-channel time-reversal in chaotic cavities," 1999] have shown that, in the case of acoustic waves, focusing is possible using even a single sensing element in a closed reflecting cavity with negligible absorption. The same focusing property has been obtained with electromagnetic waves (e.g., [Lerosey et al., 2004]). Derode et al. [Derode et al., 2000] have shown that, compared to a homogeneous medium, a higher focusing quality can be achieved in an inhomogeneous medium, as a result of multiple reflections and scattering.

The use of EMTR to locate cloud-to-ground lightning can be summarized as follows. When lightning strikes, simultaneous, synchronized recordings are carried out of the electric and/or the magnetic field waveforms at several EM-field sensors. The recorded waveforms are then transmitted to a central server that numerically time-reverses them and lets these time-reversed versions back-propagate into the location domain by simulation. It can be shown, both mathematically and by simulations [Lugrin et al., 2014], that the back-propagated fields add up in phase at the lightning strike location and that the maximum constructive interference can therefore be used as a criterion to determine the lightning strike location. Experimental tests have also been successfully carried out on the use of EMTR for fault location in power systems (e.g., [Razzaghi et al., 2013, 2017; Wang et al., 2018]).

Since the back propagation in EMTR uses the complete field waveforms (within bandwidth limits of the system) and the real topological and electrical parameters of the propagation path, the accuracy of the location can be greatly improved compared to classical systems.

Propagation in the case of distant lightning takes place over a non-perfectly conducting ground, a case in which Maxwell's equations are not time-reversal invariant (e.g., [Rachidi et al., 2017]). This problem can be addressed by using techniques such as the ones presented in [Lugrin et al., 2014] or by using the concept of time-reversal invariance in the soft sense introduced in [Rubinstein et al., 2017].

III. CHALLENGES

The development of a real-time, high-quality EMTR-based lightning location system requires solving a number of theoretical challenges and overcoming various technological difficulties related to electromagnetic theory, computer science, hardware acceleration, and testing. The following subsections discuss some of the salient problems that need to be solved.

A. Development of efficient simulation techniques and algorithms for EM back-propagation

Lightning location by time reversal requires simulations of back-propagation over large simulation domains with appreciable complexity, involving different kinds of scatterers and a complex terrain profile. Compared to a homogeneous medium, a higher EMTR focusing quality can be achieved in an inhomogeneous medium as a result of multiple reflections and scattering. Therefore, a more accurate simulation of the back-propagation phase taking into account terrain complexity will result in higher performance in EMTR. Efficient codes running on fast computers with large memory resources are a requirement for lightning location using this technique due to the needed numerical simulations. Efficient computing techniques need to be developed enabling the use of complex models in EMTR back-propagation simulations in quasi real-time.

The propagation effects of lightning electromagnetic fields along irregular terrain have been the subject of recent investigation (e.g., [Zhang et al., 2012; Li et al., 2013]). Specifically, it has been shown that the location accuracy of time-of-arrival lightning location systems can be strongly affected by propagation effects along an irregular and lossy terrain (e.g., [Li et al., 2016]).

Acceleration techniques exist that can be used to accurately simulate the EMTR back-propagation phase of the EMTR in quasi-real-time. These techniques include:

- Domain decomposition methods, such as Huygens' theorem that can be implemented for the efficient calculation the EM fields over long distances and terrain profiles [Oikawa et al., 2012]. Other innovative scattering methods, such as the Method of Auxiliary Sources (MAS) can also be used to speed the resolution of the simulations.

- Parallelization techniques implementation and optimization of simulation algorithms on graphics processing units (GPUs), e.g. [Pyrialakos et al., 2015].

- Multiresolution [Jiang et al., 2014] and hybrid numerical techniques, for instance the FDTD and Method of Moments [Huang et al., 1999].

- The Equivalence Theorem to allow the use of pre-calculated Green's functions from each sensor to reduce the required computational resources.

The developed computational algorithms need to consider the fact that the electromagnetic propagation involving a dissipative medium is not time reversal invariant in the strict sense unless an inverted-loss medium is considered for the reverse times.

Acceleration of the numerical simulations by the application of a 2-step approach: in the first step, the location of the lightning discharge is determined applying the classical Time of Arrival or Direction Finding techniques. Then, an area corresponding to the location accuracy for individual strokes of the classical ToA or DF systems (typically a few kilometers) can be considered. The definition of this area would considerably reduce the computational domain for the back-propagation. This approach can, in principle, be combined with any of the above-mentioned simulation techniques.

B. *Development of advanced location algorithms for EMTR lightning location*

Lugrin et al. [Lugrin et al., 2014] pointed out that, in the EMTR location technique, the back-propagation of the fields leads to very small field values that can be the source of numerical errors during the back-propagation calculations. A second potential problem, also identified in [Lugrin et al., 2014], is the appearance of singularities in the calculations in the vicinity of the original electromagnetic radiation source. Lugrin et al. proposed to normalize the back-propagated waveforms to address these two problems. As an unintended consequence, the loss of the information contained in the relative amplitudes of the waveforms in the simulation domain may decrease the achievable accuracy. Algorithms must be investigated that, while still using the phase information to determine the point of maximum constructive interference, include also the amplitude information. In addition, algorithms to optimize the location obtained with time reversal combining them with other methods to increase the localization speed and the accuracy could further improve the performance of the EMTR system.

C. *Time synchronization*

Since sensors are distributed in space, the waveforms arrive at them at different times, with different amplitudes due to different propagation path lengths. In addition, the waveshapes exhibit differences due to propagation effects over ground with a finite conductivity. This, and possible differences in the trigger levels introduce synchronization errors that must be taken into account. The following approaches to reduce the timing error should be investigated:

- Using precision GPS timing modules. Currently, the most precise GPS timing modules guarantee time resolutions smaller than 60 ns. Improvements should become available with the upcoming improvements to current navigational systems and with the put in operation of new ones..
- Using high-frequency on-board clocks and recording the number of cycles elapsed between the moment the lightning is detected and the moment the time is read from the GPS module.
- Using pre-trigger recording: continuously sampling the measured field, and buffering a number of data samples so that they are saved at the time of the trigger. Hence, a sensor transmits a history of the signal prior to the lightning waveform detection. This may enable error-correction at the central unit.

D. *Back-propagation in hardware*

It the most intuitive way, to estimate the location of the lightning strike, the remote processing unit should use the locations of sensors and received field-waveforms as follows: from the location of each sensor, the field recorded by that sensor is first time-reversed and then computationally propagated in all directions. After some time, the fields would start overlapping. The computation of all fields would continue until the complete geographical area is covered. Finally, the location of the maximum field level would be found, as it is this point that corresponds to the lightning strike location.

However, given the size of the area covered by the sensors (a radius of tens or hundreds of kilometers), this way of calculation would require prohibitively long computation time and enormous amount of processing power and storage (all the field values would have to be kept, so that in the end the maximum could be looked for). More efficient approaches need to be explored. Two possible approaches are presented here.

Approach 1: High-parallelization opportunities offered by Field-Programmable Gate Arrays (FPGAs) must be explored. A programmable hardware accelerator, either (1) composed of hundreds of simultaneously running hardware state machines or (2) composed of hundreds of small soft-cores (such as Nios II, or recent experimental FPGA multi-core solutions [Gray, 2016; Kumar HB et al., 2017]), can be designed. This would require developing novel strategies on the parallelization of the EMTR algorithm: decisions on the splitting of the computation into smaller tasks, ensuring validity of data at any point of calculation and ensuring deterministic results. This may require completely novel techniques to parallelize two-dimensional electromagnetic-field calculations.

Approach 2: This approach is applicable to back propagation in hardware but also to point A. in this section, in which it was also mentioned. Every sensor could transmit recorded waveforms along with the time when the recording started. The processing unit would then use this timing information to first apply a conventional Time-Difference of Arrival (TDoA) method and thereby obtain an estimate of the region in which the lightning strike location lies. Hence, the area in which fields would have to be calculated would be dramatically reduced.

Besides accelerating the EM-field calculation, compression and decompression of data could be parallelized. Efficient and accurate compression methods based on the matrix pencil method (MPM) [Sarkar & Pereira, 1995] could be utilized. In this method, the measured waveform is represented by a sum of exponential functions, each characterized by two complex-valued parameters (poles and residues). On the sensor side, data would be compressed, i.e., the poles and residues would be calculated. On the processing unit side, data would be decompressed, i.e., exponential functions would be derived based on the received poles and residues.

IV. Summary and Conclusions

Time Reversal is a promising technique that has recently received attention for source location and has been shown to be applicable to lightning location with improved performance.

In this paper, we described the challenges involved in the development of a system on based EM time-reversal to locate lightning. These challenges include the development of efficient simulation techniques and algorithms for EM back-propagation, the development of advanced location algorithms for EMTR lightning location, tight time-synchronization, and back-propagation of the waveforms in hardware.

We also proposed different ideas and approaches to address these challenges in view of a future deployment of a lightning location system based on time reversal.

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