3D Generalized Finite-Difference modeling of time reversal for localization of dielectric obstacles — the impact of dipole array density

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***Abstract*—This paper presents a 3D full time-domain modeling of the time reversal process for the localization of an obstacle in free space using an array of transceivers made of electric dipoles. The main purpose of this study is to analyze the influence of the density of dipoles in the array on the accuracy of the localization in a given electromagnetic configuration. A Generalized Finite Difference (GFD) method and a leapfrog time discretization are used to get the numerical results.**

I. Introduction

Time Reversal (TR) techniques have firstly been used in an acoustic context [1] and more recently have been applied to several electromagnetic applications such as wireless communication [2], generation of high-field intensity pulses [3], and localization of scatterers [4]. In a lossless medium Maxwell's equations are time-symmetric, so a time-reversed electromagnetic field should be expected to go back towards the sources. Since an obstacle illuminated by a given EM wave can be considered as a set of secondary sources within it (or at its surface), it is then expected that the TR of the scattered field is to converge towards the obstacle (in some sense, to be considered further). The presently studied TR process consists in several steps: 1) illuminating the obstacle by a propagating source pulse, 2) recording the scattered field on an array of electric dipoles, 3) using this array (as a TR mirror) to emit the TR of the recorded signals in free space, 4) getting a picture of the field distribution when focusing occurs. For a given configuration, the picture obtained, and hence the accuracy of the localization, should in particular depend upon the polarization and the density of the dipoles in the array, usually spaced of the order of half-a-wavelength [5] (main theoretical results, to our knowledge, however appear to rely on the assumption of a high number of finely-spaced sources). In the time domain, to the best of our knowledge, this issue has not been investigated yet. Here we propose a numerical full 3D time-domain analysis of this subject.

II. Generalized Finite Difference Model

GFD [6] provides a general framework for mesh-based numerical methods such as finite-element (FE) or finite-integration techniques (FIT) [7], enabling us to handle unstructured meshes. Using unstructured meshes with GFD then leads to better dispersion properties compared to classical Finite Difference Time Domain (FDTD) as employed in most 3D time-domain simulations [4],[8]. A leapfrog scheme is used for the time-domain discretization, and truncation of the computational domain via perfectly matched layers yields simulation of the infinite free space. In practice, the box containing the obstacle and the surrounding free space is spatially discretized on an unstructured tetrahedral mesh (the same mesh will be used for all configurations considered in the analysis here). One face of the box is meshed with structured triangles in order to model the array of dipoles: any edge of this mesh could be chosen as an active dipole of the array, and density and polarization managed by appropriate choice of a set of active edges. When simulating the direct problem, some edges of the array are used to generate the EM pulse. Active ones are then used to collect the signals received. The signal corresponding to the scattered field is computed by difference of the signals received in two configurations: free space, and obstacle embedded in it. The TR field in free space follows by emitting the TR of the received signals (corresponding to the scattered field) from all active edges, using the same time scheme as in the direct simulation.

III. Problem configuration

A dielectric ellipsoid with relative permittivity $\epsilon_r = 5$ centered at $(0.075\,m, 0, 0)$ and of semi-axes $r_x = 0.3\,m$, $r_y = r_z = 0.2\,m$ is illuminated by an y-polarized electric dipole set at the center of the transceiver array (on a centered surface Φ of the $x = 2.25\,m$ plane, see Fig. 1). A Gaussian ElectroMotive Force (EMF) defined by

$$T_s = T_{max}\, exp(-(c_0(t-t_0)^2), \quad (1)$$

letting $c_0 = 3\ 10^8\,m/s$ and $t_0 = \frac{6}{c_0}$, is applied along the dipole. Several distribution densities of y-polarized dipoles are considered (Tab. I).

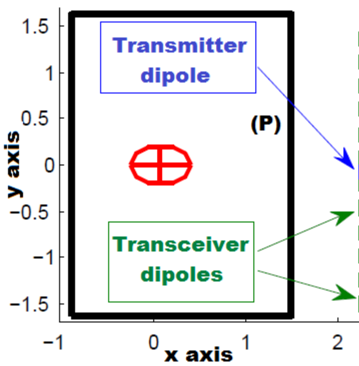

Fig. 1. 2D configuration

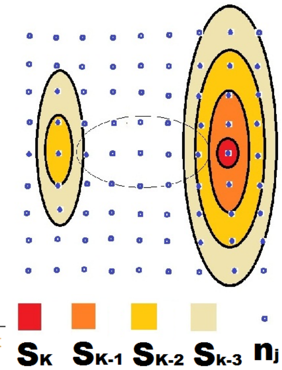

Fig. 2. Electric field regions

For each time step, the electrical energy is calculated within a hexahedral region P of the free space that does not contain the array of dipoles. The electric field intensity is computed at $22 \times 32 \times 28$ nodes $(n_j)_{j \in J}$ of a homogeneous grid on P.

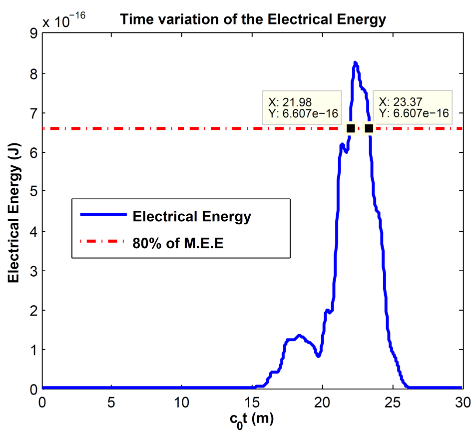

Fig. 3. Time variation of the electrical energy in P when using 49 dipoles.

IV. Localization Method

Then, only the set T of time steps $(t_i)_{i \in I}$ for which the electrical energy is superior to 80% of the Maximum Electrical Energy (MEE) is considered (Fig. 3). For each time step $(t_i)_{\in I}$, the set of points $(n_j)_{j \in J}$ on P is classified into K subsets $(S_1^i, S_2^i, ..., S_K^i)$, according to their electric field intensities (E_j^i) (Fig. 2). For any k, $1 \leq k \leq K$:

$$\forall j \in J \quad n_j^i \in S_k^i \Leftrightarrow E_j^i \in]\frac{k-1}{K} E_{max}^i, \frac{k}{K} E_{max}^i]. \quad (2)$$

In this paper $K = 6$ is chosen, so a contrast of 16.67% of the maximum electric fields (E_{max}^i) (registered every time step) is chosen to separate electric field intensity regions. Let N_k^i be the number of nodes at the time step t_i into the set S_k^i. We define the set T_K of time steps t_{i_K}such that $t_{i_K} = argmin_{t \in T}(N_K^i)$. If there is a unique solution t_{i_K}, the focusing time is $t_f = t_{i_K}$. Otherwise, for $p \geq 1$, we recursively define T_{K-p} the set of time steps $t_{i_{K-p}}$such that

$$t_{i_{K-p}} = argmin_{t_i \in T_{K-p+1}}(N_{K-p}^i), \quad (3)$$

until the solution $t_{i_{K-p}}$ is unique, then $t_f = t_{i_{K-p}}$.

Table I

Results for several distribution densities of dipoles

Nb of dipoles in Φ	4	9	16	25	36	49
M.E.E ($J .10^{-17}$)	0.06	0.9	9	17	38	83
$min_{i \in I}(N_K^i)$	1	2	2	2	1	1
$card(T_K)$	8	8	6	4	1	1
$card(T_{K-1})$	3	5	5	2	-	-
$card(T_{K-2})$	1	1	1	1	-	-
$c_0 t_f (m)$	22.33	23.11	22.95	22.95	22.95	22.98
Localization	No	No	Yes	Yes	Yes	Yes

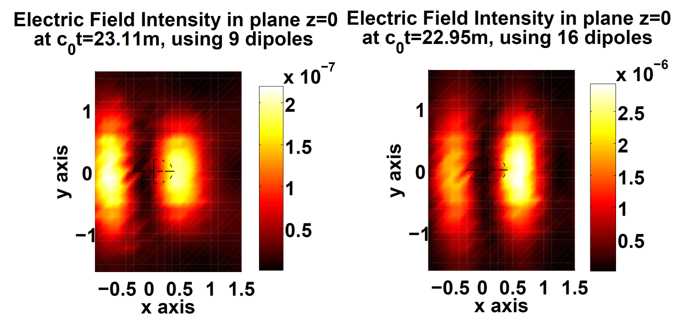

Fig. 4. Electric field intensity (V/m) at the focusing time t_f.

V. Discussion and comments

It can be noted that, for a density less than 16 dipoles in Φ (Tab. I), the scatterer cannot be localized by the method described above. Indeed, when using for example 9 dipoles in Φ, the focal spot is not situated near the side of the virtual scatterer which is exposed directly to the source in the direct problem (Fig. 4). It is also remarked that for densities up to 25 dipoles in Φ, the algorithm finds a unique focusing time by taking into consideration only the maximum electric field region S_K^i (Tab. I). It is obvious that the maximal distance between the dipoles -for having a TR focusing wave onto the target- depends upon the time shape of the signal pulse used to illuminate the scene. It also depends upon the size of the dipole array and its distance from the scatterer.

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