Study of a hybrid Finite Volume method to simulate RCS from buried objects illuminated by a plane wave

L.-M. Mazzolo and X. Ferrieres
DEMR, ONERA, F-13661 Salon cedex Air, France
ONERA/DEMR, Université de Toulouse, F-31055 Toulouse, France

Email: lisa-marie.mazzolo@onera.fr, xavier.ferrieres@onera.f

***Abstract*—This paper introduces a hybrid finite-volume method developed for efficient resolution of the time-domain Maxwell's equations, aimed at evaluating Radar Cross Section (RCS) values of buried objects illuminated by a plane wave. First, we present the principle of the hybrid finite-volume method Subsequently, we provide several examples, comparing our resuls with existing literature or analytical solutions to highlight the method's advantages by considering meshes with Cartesian part and non-structured parts.** [1]

I. Introduction

The detection of buried objects using radar remains an important part of electromagnetic studies, with a particular emphasis on airborne Synthetic Aperture Radar (SAR) detection among the current measurement devices. In this context, our focus is on conducting effective simulations of scenes involving both buried and non-buried objects in lossy ground. Several studies in the literature have proposed solutions based on finite difference and finite volume schemes, in which models to account for plane waves and calculate far fields have been introduced. This paper is dedicated to presenting a numerical method aimed at enhancing existing approaches. Specifically, we introduce a hybrid finite-volume approach that combines Cartesian mesh zones with local refinements and unstructured mesh zones.

In this paper, we first outline the principle of the proposed method, followed by demonstrating its efficacy through various examples. Our goal is to highlight the advantages of this hybrid approach in simulating complex scenarios involving buried objects.

II. Mathematic formulation of the problem

The problem under consideration requires the evaluation of electric and magnetic fields within an environment consisting of two distinct media: free space and a lossy ground. Subsequently, by considering these fields and employing a Near- to Far-field formulation, we can compute the RCS of the buried objects [1].

The mathematical formulation of our problem involves solving Maxwell's equations in terms of scattered fields (E_s, H_s):

$$\begin{cases} \varepsilon_0\varepsilon_r\partial_t E_s + \sigma E_s = \nabla \times H_s \\ \qquad\qquad -\varepsilon_0(\varepsilon_r - \varepsilon_g)\partial_t E^{3D}_{inc} - (\sigma - \sigma_g)E^{3D}_{inc} \\ \mu_0\partial_t H_s = -\nabla \times E_s \end{cases} \quad (1)$$

[1]This work is supported by the Agence de l'Innovation de Défense (AID) and the Office National d'Etudes et de Recherches Aérospatiales (ONERA)

with ε_0 and μ_0 the electric permittivity and magnetic permeability of free space, ε_g and σ_g the relative permittivity and the conductivity of the ground respectively. The incident electric fieldE^{3D}_{inc} is obtain through the numerical solution of a 1D problem [2].

III. Principle of the Hybrid Finite-volume method

This section oulines the numerical method to solve our problem. To accomodate curved geometries and local refinements in the mesh, we opt to adress our problem by employing the Finite Volume Time Domain (FVTD) method. To improve efficiency, we use a hybrid mesh consisting of two parts: one with Cartesian cells and the other with unstructured cells. The numerical scheme used in each part can be not the same, but ensuring the stability of the overall hybrid numerical scheme is imperative. To achieve this stability, we employ two FVTD approaches adapted to each part of the mesh. In the section, we begin by presenting the general principe of the finite volume scheme. Subsequently, we delve into the adaptations of this scheme for both Cartesian and unstructured parts.

A. General principle of the FVTD scheme used for our application

Let Ω be a domain and τ a partition of it. Consider K as a cell of this partition. The FVTD scheme [3] involves evaluating $U_K = (E_K, U_K)$ in each K by solving:

$$\partial_t U_K = \frac{1}{V_K} \sum_{l=1,ms_K} S_l F_l(U^*) \quad (2)$$

where V_K represents the volume of the cell K, ms_K denotes the number of faces bounding K. S_l is the surface and $F_l(U^*) = (\frac{n\times H^*}{\varepsilon}, -\frac{n\times E^*}{\mu})$ the flux for a boundary face l. U^* corresponds to the value of U on this face and n the outer normal of it.

B. FVTD-ST scheme fo the Cartesian part of the mesh

By using the FVTD general formulation, the FVTD-ST scheme applied within the Cartesian part, consists in evaluating the fluxes by a Godounov strategy [4] and referencing elements with three indices (i, j, k). These choices significantly enhance the performance of the scheme.

C. FVTD-UNST scheme for the unstructured part of the mesh

For the unstructured part of the mesh, the FVTD-UNST scheme employs a MUSCL approach [4] to compute gradients for flux evaluation. A local time-stepping (refer to Figure (1)) and a local order (0 or 1) are introduced into the scheme, resulting in a significant reduction in CPU time.

D. Hybrization method

To hybridize the two finite-volume schemes in the Cartesian and unstrucrured parts of the mesh, we designate specific time appointments during which the two schemes exchange data (refer to Figure (1). In this process, the time step is chosen as the minimum between the time step of the FVTD-ST scheme and the maximum time step among all the time classes of the FVTD-UNST scheme.

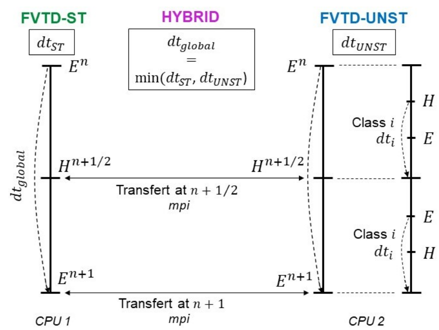

Figure 1. Hybridization process.

IV. Numerical examples

This section is dedicated to studying different examples to validate and highlight the advantages of our hybrid finite-volume approach. The first example involves evaluating the RCS of a Perfect Electric Conductor (PEC) sphere illumated with a plane wave and located in a free-space. The goal of this example is to show the advantage of accurately considering the curved geometry of the sphere in the simulation. The next example allows us to validate the ground and the far-field models introduced in the FVTD-UNST scheme, emphasizing the benefits of using mesh refinement for the ground to account for the lower speed of waves in the ground compared to free space. In a first subsection, we present the process proposed to obtain a Cartesian/unstructured mesh with local refinement.

A. Mesh process

To generate Cartesian meshes with local refinements and unstructured parts, we create a global Cartesian mesh whith introduced holes. Within these holes, local refinement or unstructured meshes are placed. The interfaces between them and the global grid are defined by faces belonging to both the global and the hole meshes.

B. RCS of a PEC sphere in free-space

The example considered in this subsection involves evaluating the RCS of a PEC sphere in free-space with a radius $R = 0.5$m. Figure (3) presents a comparison between our hybrid finite-volume approach and Yee's scheme, using a similar spatial step size. The Figure illustrates the advantage of accurately considering the geometry of the object.

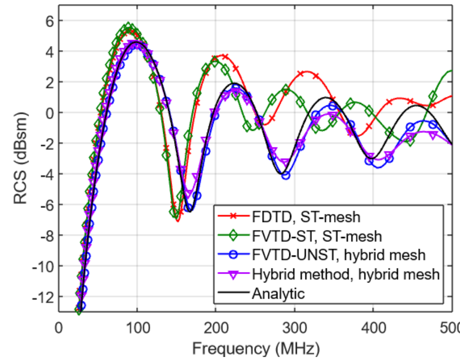

Figure 2. Sphere RCS comparisons.

C. Scattered far-fields by a dielectric box.

The example considered here involves evaluating far-fields around a dielectric box buried in a lossy ground. The goal is to show the CPU time improvement achieved by implementing refinement in the ground (cells approximately 3 times smaller than in free space). Figure (3) shows the configuration and a comparison of results. The results are similar with and without ground refinement; however, in the latter case, there is a time-saving factor of approximately 1.5.

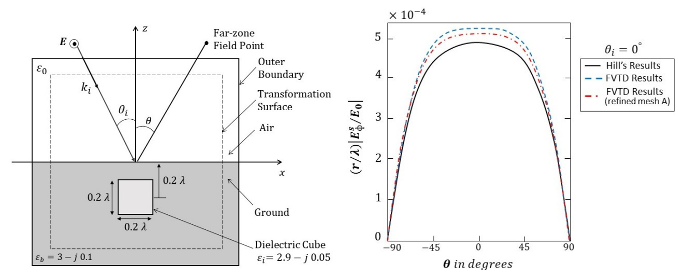

Figure 3. Scattered far-fields from a dielectric box buried in a lossy ground.

V. Conclusion

In this paper, we have presented a hybrid finite-volume method and show its effectiveness through two examples related to the problem of buried objects. This work is currently being improved to simulate RCS of buried objects in the ground.

References

[1] T. Martin and L. Pettersson, "FDTD Time Domain Near- to Far-Zone Transformation Above a Lossy Dielectric Half-space", The Applied Computational Electromagnetics Society Journal, vol. 16, no. 1, pp. 45-52, 2001

[2] I. Capoglu and G Smith, "A Total-Field/Scattered-Field Plane-Wave Source for the FDTD Analysis of Layered Media", IEEE Transactions on Antennas and Propagation, vol. 56, pp. 158-169, 2008, doi: 10.1109/TAP.2007.913088

[3] P. Bonnet, X. Ferrieres, F. Issac, F. Paladian, J. Grando, J. C. Alliot and J. Fontaine, "Numerical modeling of scattering problem using a time domain finite volume method", Journal of Electromagnetic Waves and Applications, vol. 11, no. 8, pp. 1165–1189, 1997 doi: 10.1163/156939397X01070

[4] B. Van Leer, "Towards the Ultimate Conservative Difference Scheme V. A Second-order Sequel to Godunov's Method", Journal of Computational Physics, vol. 32, pp. 101-136, 1979, doi: 10.1016/0021-9991(79)90145-1