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# Modeling ground-wave propagation at MF band in hilly environments through FDTD method and interaction with GIS

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ABSTRACT

This paper shows the calculation of electric field levels at MF band (medium frequency: 300 kHz–3 MHz) at different distances from the transmitter in environments where there are: (a) conductivity changes of the soil and (b) altitude variations. To assess the influence of these factors, a 2D tool named MF-FDTD (MF finite-difference time-domain) is implemented and it is calibrated and validated with the Millington method for flat land, and the FEM-PE (Finite Element Method-Parabolic Equation) for the inclusion of typified mountains. Then, this tool is also applied to real environments where certain AM (Amplitude Modulation) transmitters are located, selecting several profiles via a Geographic Information System. In our case, oscillations up to 10 dB have been obtained when comparing the results of irregular versus flat terrains with frequencies around 1 MHz. Part of the computation has been made using the Lusitania supercomputer, parallelizing tasks on multiple cores.



## 1. Introduction

Medium frequency band waves (300 kHz–32 MHz) can travel long distances because its propagation is mainly via surface and ionospheric waves [1]. AM (Amplitude Modulation) transmitters, within this band, are widely used for broadcasting within areas of coverage which can reach several hundreds of kilometers via surface wave. In this sense, the surface wave propagation has been discussed since its inception, both from a theoretical and practical point of view [2–4]. However, new developments and applicability of computational techniques, although highly costly in resources, are making that more robust and accurate methods for calculating electric field levels can be used; they take into account all the peculiarities of the real environment, both conductivity changes and altitude variations. The combination of Geographic Information Systems (GIS) and the High Performance Computing (HPC) is making more and more that we can address more ambitious projects or studies. This is where our work is stated, trying to study the electric field oscillations in different profiles of land via the finite-difference time-domain method (FDTD).

But before starting to explain more deeply the implemented application, it is necessary to perform a historical overview of the main methods which have been developed regarding the ground wave. In the origins of the formulation, it is bound to mention the theory of propagation of space and surface wave by Zenneck and Sommerfeld [5,6], which was widely studied by Wait and many other authors. They obtained a solution for the attenuation of a short dipole located at the interface between an insulator and a conductor plane, considering flat, lossy Earth. Norton, Van der Pol and Bremmer's contribution included its applicability to spherical earth, proposing practical expressions for the calculation [6–9]. Later, Millington proposed a semi-empirical method to take into account the constants of the medium (conductivity and permitivity) [10–12]; we must highlight that ITU (International Telecommunications Union) provides a free application named GRWAVE for calculating the variations of the electric field with the distance, considering a certain frequency and soil conductivity, being possible to extrapolate its use with the Millington equations [13]. Based on integral equations, Hufford developed a method for calculating the field in smoothly varying, inhomogeneous terrain, albeit with great difficulty of calculation [14].

Recently, supported by HPC, other techniques have been applied to the calculation of electromagnetic propagation [15–17]. We can stress the finite-difference time domain (FDTD) introduced by Taflove [18] and used by himself [19,20] and Zhou in her works of LF (Low Frequency) [21,22], among others. The disadvantage of FDTD techniques [23] is the high degree of processing that they need, and hence these techniques are often limited to short distances in relation to the wavelength, but lately the trend is changing with the use of supercomputers and GPUs (Graphics Processing Units) and the parallelization of tasks [15]. Above all, we must emphasize that FDTD is being applied in many disciplines: to analyze acoustic

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waves or electromagnetic waves (for example to assess the levels inside the human body by carrying out simulations) [24–29].

Apart from FDTD techniques, we must also highlight the use of the Method of Moments (MoM), or the Split Step Fourier Parabolic Equation (SSPE) which have been deeply used by Apaydin to calculate electric field levels at rough terrains [30]. In addition to this, Finite Element Method (FEM) has also been applied to the development of software based on PE (Parabolic-Equation); specifically FEMIX [31], is based on FEM (Finite Element Method) applied to the prediction of surface waves, and it will be used to calibrate and validate the results when including typified mountains to check their influence on the oscillations of the field levels. The FEMIX software allows the calculation of levels when including hilly terrain. With regard to the implementation of FEMIX, it should be noted that it only considers one-way propagation, with forward propagation (not backward).

The present work implements a 2D-FDTD tool to be used for the calculation of electric field levels along a certain profile. Previously the model will be validated on the one hand and for flat land with a proprietary application (UexWAVE) which incorporates the Millington expressions and which makes use of the GRWAVE software, and on the other hand, for typified mountains, with the FEMIX software previously mentioned.

The goal is to compute how big the difference in levels is when considering an irregular terrain with respect to a flat land, and to analyze the behavior of the electric field strength [32] in these conditions.

The FDTD technique [33] is characterized by considering all propagation phenomena such as reflection, diffraction [34], surface wave, backscattering and forward propagation, thus providing a complete solution [35,36], although with extensive use of computational resources. This is the reason why we have made use of the Lusitania supercomputer in some parts of the work to parallelize certain tasks and shorten the execution times.

## 2. Formulation

### 2.1. FDTD Equations

#### 2.1.1. Expression in 2D

MF-FDTD tool is designed for the calculation of electric field levels in two dimensions, assuming that this 2D structure is infinitely extended in the direction (or axis) which is not considered; in our case all physical and electromagnetic parameters are only function of the coordinates $x$ and $y$ [18]. Maxwell's equations [37] can be decomposed into two sets of equations, the TE mode (transverse electric) and TM mode (transverse magnetic) [38]. In our case, as Fig. 1 shows, the electric field is perpendicular to the $z$ axis, with the working components $H_z$, $E_x$, and $E_y$, and can be named: the TE$_z$ mode (Fig. 1). Actually, considering a 2D space is a simplification of a 3D real environment where reflections which occur in other objects

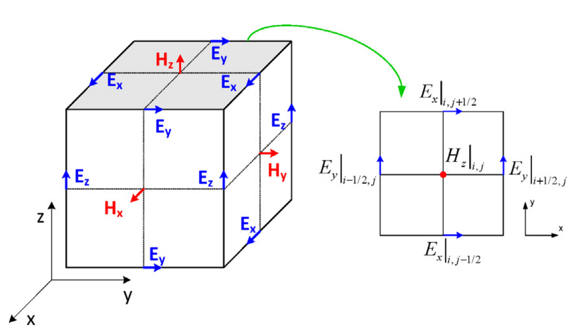


**Fig. 1.** Scheme of the FDTD cell in 3D, standing out the 2D plane which applies in this work.

which are not in our 'plane of study' may affect the results, nevertheless it serves to obtain a first approximation for calculating the fluctuations of levels, without excessive computational resources.

The equations which govern the MF-FDTD tool are shown in Eqs. (1)–(3), where $\varepsilon$ (F/m), $\mu$ (H/m), $\sigma$ (S/m) and $\sigma^*$ ($\Omega$/m) are the permittivity, permeability, conductivity and equivalent magnetic losses respectively (the latter considered 0 in this paper). Meanwhile the index $i$, $j$ are the number of cell in the $x$ and $y$ direction respectively and $n$ refers to the time instants. The magnetic component is calculated at discrete times $\Delta t$, $2\Delta t$, $3\Delta t, \ldots, n\Delta t$, and the electrical components are calculated at $\Delta t/2$, $3\Delta t/2, \ldots, (n+1/2)\Delta t$.

When we want to fill the cells with a type of land, of specific conductivity and permittivity, these are inserted into the appropriate section of land; at the same time, the air above the land is filled with cells according to the refractive index [39]. The objects, hills or irregularities, are shaped via an interpolation of the object's surface, being the resolution the cell size (the grid).

$$E_x\Big|_{i,j+1/2}^{n+1/2} = \left( \frac{1 - \frac{\sigma_{i,j+1./2}\Delta t}{2\varepsilon_{i,j+1/2}}}{1 + \frac{\sigma_{i,j+1./2}\Delta t}{2\varepsilon_{i,j+1/2}}} \right) E_x\Big|_{i,j+1/2}^{n-1/2} + \left( \frac{\frac{\Delta t}{\varepsilon_{i,j+1/2}}}{1 + \frac{\sigma_{i,j+1./2}\Delta t}{2\varepsilon_{i,j+1/2}}} \right) \times \left( \frac{H_z\Big|_{i,j+1}^{n} - H_z\Big|_{i,j}^{n}}{\Delta y} \right) \tag{1}$$

$$E_y\Big|_{i-1/2,j+1}^{n+1/2} = \left( \frac{1 - \frac{\sigma_{i-1/2,j+1}\Delta t}{2\varepsilon_{i-1/2,j+1}}}{1 + \frac{\sigma_{i-1/2,j+1}\Delta t}{2\varepsilon_{i-1/2,j+1}}} \right) E_y\Big|_{i-1/2,j+1}^{n-1/2} + \left( \frac{\frac{\Delta t}{\varepsilon_{i-1/2,j+1}}}{1 + \frac{\sigma_{i-1/2,j+1}\Delta t}{2\varepsilon_{i-1/2,j+1}}} \right) \times \left( - \frac{H_z\Big|_{i,j+1}^{n} - H_z\Big|_{i-1,j+1}^{n}}{\Delta x} \right) \tag{2}$$

$$H_z\Big|_{i,j+1}^{n+1} = \left( \frac{1 - \frac{\sigma^*_{i,j+1}\Delta t}{2\mu_{i,j+1}}}{1 + \frac{\sigma^*_{i,j+1}\Delta t}{2\mu_{i,j+1}}} \right) H_z\Big|_{i,j+1}^{n} + \left( \frac{\frac{\Delta t}{\mu_{i,j+1}}}{1 + \frac{\sigma^*_{i,j+1}\Delta t}{2\mu_{i,j+1}}} \right) \times \left( \frac{E_x\Big|_{i,j+3/2}^{n+1/2} - E_x\Big|_{i,j+1/2}^{n+1/2}}{\Delta x} - \frac{E_y\Big|_{i+1/2,j+1}^{n+1/2} - E_y\Big|_{i-1/2,j+1}^{n+1/2}}{\Delta x} \right) \tag{3}$$

### 2.2. PML layers

With respect to the boundary conditions [40], they require special treatment. This is needed to prevent or reduce the wave reflection from the artificial limits which are the computational domain, and thus we avoid the reflected signal (forward to backward). For this purpose we filled with layers of type "Perfectly Matched Layer" (PML) the top and sides of the simulation domain, being not necessary the bottom because of the large attenuation of the soil [18,35,36], see Fig. 2.

Therefore, to truncate an FDTD lattice having very low reflections, PML layers are used. Implementing PML as a single step-discontinuity, this would lead to significant spurious wave reflection at the PML surface. To reduce this error, Berenger proposed that the PML losses along the direction normal to the interface gradually rise from zero. If we consider a plane wave impinging at angle $\theta$ upon a PEC-backed PML slab of thickness $d$,