2.5 marine CSEM modeling using COMSOL Multiphysics®

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Abstract

In this paper, we present the implementation of 2.5D models using the software COMSOL Multiphysics® to simulate the propagation of the electromagnetic field related to marine controlled source electromagnetic (mCSEM). To validate this approach we compare the amplitude and phase of electric field in-line E_x against two models. The first model is the 1D model, which is actually an approximation of a laterally extended 2.5D model to ensure variation only with depth, the results show satisfactory with the analytical solution, known in the literature and open code implementation, like DIPOLE1D.f90. The second model is a 2.5D, we compare our results with the MARE2D code and the results presents good agreement.

Introduction

Nowadays the marine controlled source electromagnetic (mCSEM) is a important technique in exploration and production of hydrocarbon. The method has been stablished since 2002 (Eidesmo. et al., 2002) and its forward modeling is well stablished, but we have account some characteristics to numerical modeling, like: numerical stability, mainly with derivatives, interactivity and facility with user interface and computational performance. The COMSOL Multiphysics® is a finite element analysis and solver software package for various physics and engineering applications, especially coupled phenomena, or multiphysics. In this paper we present the numerical modeling of mCSEM method using the COMSOL Multiphysics® , in this approach we decompose the three-dimensional problem in a spectral domain of wave-number - k_y and apply the theory of the digital filter (Kong, 2007; Li and Key, 2007) to achieve the solution on the space domain. We present results, comparing with 1D model, with own analytical solution Chave and Cox (1982) and with 2.5D model, through of MARE2D code Li and Key (2007).

The COMSOL Multiphysics®

COMSOL Multiphysics® is a finite element analysis and solver software package for various physics and engineering applications, especially coupled phenomena, or multiphysics. It includes a complete environment for modeling any physical phenomenon that can be described using ordinary or partial differential equations (PDEs). The main advantages of this software are the friendly interface and the implementation of optimized solvers for linear equations. There are many applications of COMSOL Multiphysics® in numerical modeling, which can be accessed on software webpage. We can mention examples in geosciences, such as ground water modeling Li et al. (2009) and also in applied geophysics forward modeling (Butler and Sinha, 2012). In recent years, COMSOL Multiphysics® has been used to forward modeling of electromagnetic problems in applied geophysics, for example Arif et al. (2010); Luz (2014); Lopes Leite and Tocantins (2015); Butler and Zhang (2016) implemented by the RF Module, which simulates electromagnetic fields in 3D, 2D, and 2D axisymmetric. The 3D formulation is based on the full-wave form of Maxwell's equations using vector edge elements, and includes material property relationships for modeling dielectric, metallic, dispersive, lossy, anisotropic, gyrotropic, and mixed media. Under the hood, the RF Module is based on the finite element method. Maxwell's equations are solved using the finite element method with numerically stable edge elements, also known as vector elements, in combination with state-of-the-art algorithms for preconditioning and iterative solutions of the resulting sparse equation systems. Both the iterative and direct solvers run in parallel on multicore computers. Cluster computing can be utilized by running frequency sweeps, which are distributed per frequency on multiple computers within a cluster for very fast computations or by solving large models with a direct solver using distributed memory (MPI).In this work the geometry of models is two-half dimensional (2.5D), the materials are isotropic and homogeneous by parts.

Building 2.5 models in COMSOL Multiphysics®

The study of the forward modeling of the mCSEM in the COMSOL software is evaluated in the frequency domain, which simplifies the problem efficiently, assuming that all the temporal variations of the signal occur in a sinusoidal manner. In this way, we obtain complex solutions that represent the phase and amplitude of the field, where the frequency is specified as a scalar input model, usually provided by the solver. The equation provided by the RF module that COMSOL Multiphysics solves by means of finite vector elements is given by:

$$\nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - k_0^2\left(\varepsilon_r - \frac{\sigma i}{\varepsilon_0 \omega}\right)\mathbf{E} = -i\omega\mu_0\mathbf{J} \qquad (1)$$

where $\mathbf{E}$ is the electric field in [V/m], σ is the conductivity of medium in [S/m]. The constitutive proprieties are defined as usual. $\varepsilon_r = \varepsilon/\varepsilon_0$ and $\varepsilon_0 = 8.854 \times 10^{-12}$ f/m

are respectively the relative and free-space electric's permittivity. $\mu_r = \mu/\mu_0$ and $\mu_0 = 4\pi \times 10^{-7}$ are respectively the relative and vacuum magnetic's permeability. The $\omega = 2\pi f$ is the angular frequency in radians per second. The term $k_0 = \sqrt{k_0^2}$ represents the wave number of free space. The source term $-i\omega\mu_0\mathbf{J}$ represents the density of current generated by an horizontal electric dipole in x direction.
The equation (1) is a complex vector equation, the electric vector solution $\mathbf{E}$ has three-components E_x, E_y, E_z. To take advantage of the 2D structure of the configuration (Figure 1),, we introduce the 1D spatial Fourier transform and its inverse with respect to the y-coordinate axis:

$$\tilde{u} = \mathscr{F}\left[u(x,y,z)\right] = \int_{y=-\infty}^{\infty} u(x,y,z)e^{-ik_y y}dy \qquad (2a)$$

$$u = \mathscr{F}^{-1}\left[\tilde{u}(x,k_y,z)\right] = \frac{1}{2\pi}\int_{k_y=-\infty}^{\infty} \tilde{u}(x,k_y,z)e^{ik_y y}dk_y \qquad (2b)$$

We apply this Fourier transform, equation (2a) to equation (1) to obtain

$$\tilde{\nabla} \times \mu_r^{-1}\left(\tilde{\nabla} \times \tilde{\mathbf{E}}\right) - k_0^2\left(\varepsilon_r - \frac{\sigma i}{\varepsilon_0 \omega}\right)\tilde{\mathbf{E}} = -i\omega\mu_0\tilde{\mathbf{J}}, \qquad (3)$$

where $\tilde{\nabla} = \left(\partial_x, k_y, \partial_z\right)$.

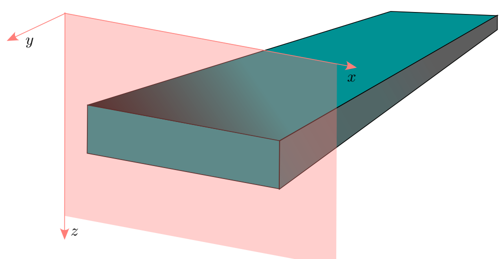


Figure 1. 2D geometry for the geo-electric structures.

After solving the partial differential equation (3), the electric field, can be obtained appling the equation (2b) in $\tilde{\mathbf{E}}$. The inverse fourier transform is performed by application of digital filters (Li and Key, 2007; Kong, 2007).

Results

In order to validate the methodology employed in this work we first compare the 1D model reproduced in COMSOL with the DIPOLE1D code implemented in FORTRAN 90 based on Key (2009). The 1D model is illustrated by Figure 2, it consists of a horizontal stratified structure composed by five layers representing the air, the sea, the host sediment and the reservoir, whose resistivities and thickness are equivalent to ($10^{12}\Omega$m $-$ 10km), (0.33Ωm $-$ 1km), (1Ωm $-$ 1km), (100Ωm $-$ 100m). The substract layer has 1Ωm with breadth of 7900m. One of several advantages of the run forward modeling in the COMSOL Multiphysics® software is that it allows us to obtain the solutions for primary field (without reservoir) and for the secondary field (with reservoir) with only one model using a variable type parametric sweep. The parametric sweep allows us to change the parameter values (in this case the parameters are the layers material) through a specified range, so to get both fields in only one model we need to specify the reservoir layer resistivity values (which is located in the model in depth from 1000m to 1100m). For the value of 1Ωm, we will have exactly the same material as the sediment layer. In this case it is like we had only one sediment layer for the whole model, so COMSOL will generate one of its results - the primary field; for the value of 100Ωm we will have exactly the reservoir layer generating in this case the second result corresponding to the secondary field (the range in this case is 99). For the simulation of this model we use as an electromagnetic source an horizontal electric dipole (HED) at 50m above from the ocean floor with frequencies of 0.25Hz, 0.5Hz and 1Hz. The point of the source is $(0,0,950)$m, that corresponds to the center of the model. In Figure 2 we have the illustration of this first model. The mesh generator of the COMSOL Multiphysics® is automatic and follows the parameters of qualities to the shape of the finite elements, you can refine determined regions of interest from the current model or where are made the measurements of the electromagnetics fields. The Figure 3 exemplifies the mesh for the approaching model 1D.

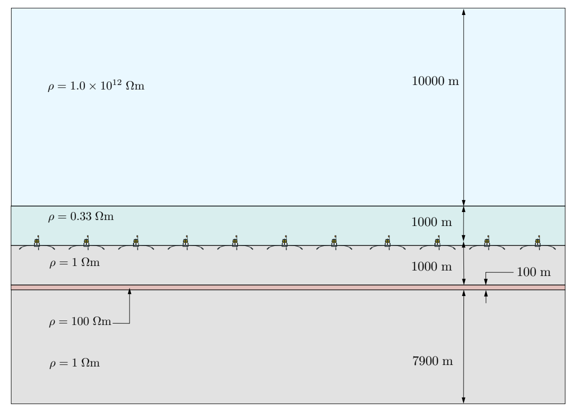


Figure 2. Unidimensional model. The air has $10^{12}\Omega$m, the sea has, 0.33Ωm, with thickness of 1km. The layer of hydrocarbon is deep in 2km with 100Ωm of resistivity and 100m of thickness, embedded in sediment half-space of 1Ωm.

The mesh generator of the COMSOL Multiphysics® is automatic and follows the parameters of qualities to the shape of the finite elements, you can refine determined regions of interest from the current model or where are made the measurements of the electromagnetics fields. The Figure 3 exemplifies the mesh for the approaching model 1D.

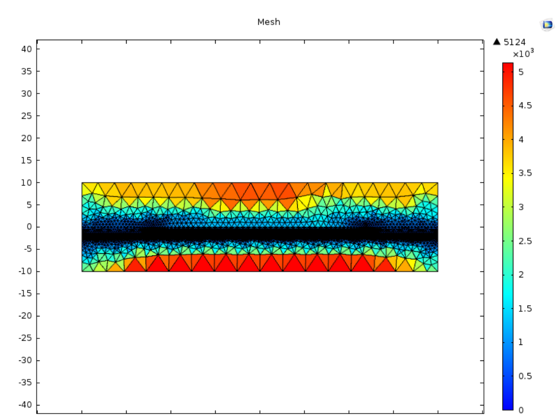
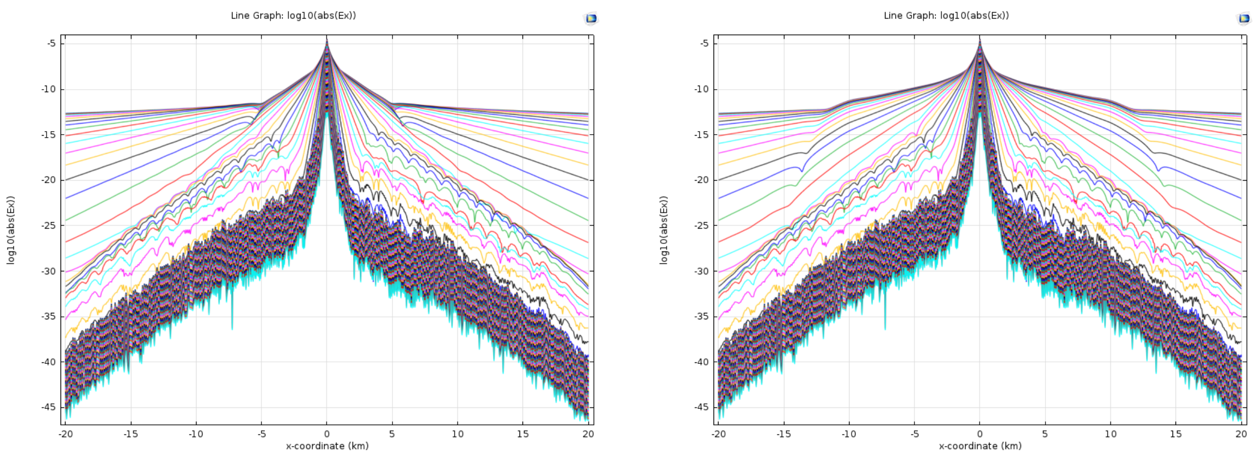


Figure 3. Mesh for the approaching model 1D. illustrated in Figure 2.

The responses of COMSOL Multiphysics® is function of the wave number k_y. The values of k_y is determined from the user, that should have in mind, consistent values of k_y to perform the inverse Fourier transform. The COMSOL Multiphysics® does the numerical modeling to all k_y, afterwards we sum the weighing responses to obtain the solution. Due the symmetry of the E_x field (in-line component), we choose the filter of 81 points to cosine filter to calculate the inverse Fourier transform. The Figures 4a and 4b show the amplitudes of E_x.

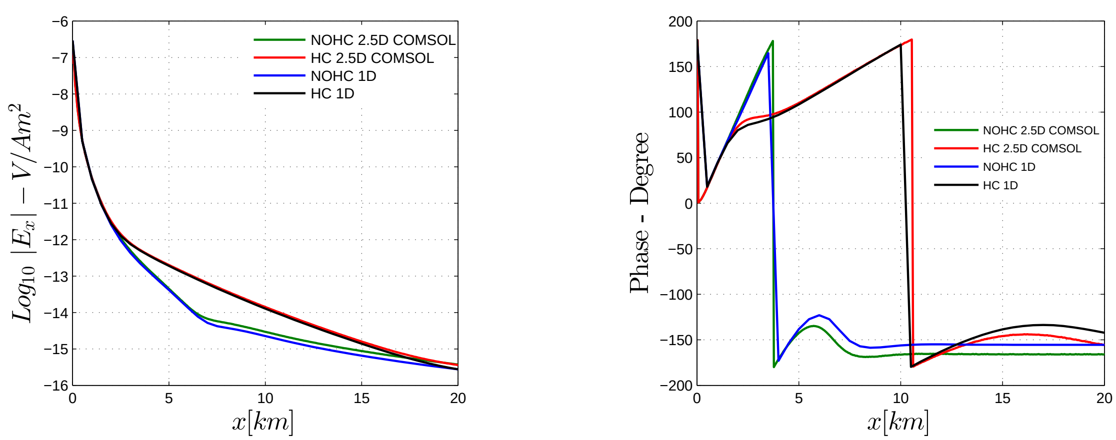


(a) Amplitudes of E_x to model without reservoir.

(b) Amplitudes of E_x to model with reservoir.

Figure 4. Amplitudes of E_x to 81 values of k_y.

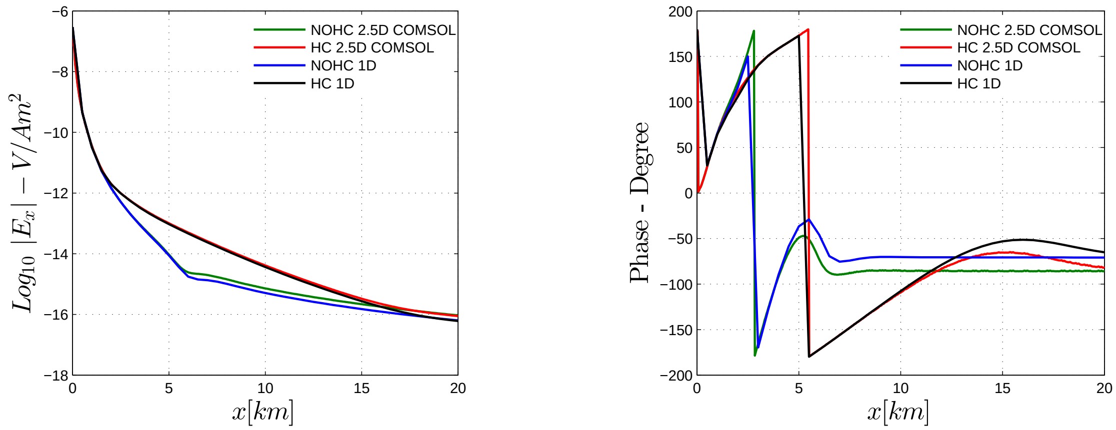
The curves of the amplitude and phase versus off-set receiver-transmitter to electric field in-line E_x are presented for three frequencies. 0.25Hz in Figure 5, 0.5Hz in Figure 6 and 1Hz in Figure 7. All the results are compared with responses from the code DIPOLE1D (Key, 2009). The three figures show that both model with hydrocarbon reservoir (HC 2.5D COMSOL) and without hydrocarbon reservoir (NOHC 2.5D COMSOL) are very similar with the curves obtained from DIPOLE1D. This evince the robustness of this approach with COMSOL Multiphysics® . We emphasize that DIPOLE1D is a solution of analytical expression, add the solution from COMSOL is numeric with imposition of boundary condition at limited domain, besides the COMSOL implements a approximation to calculate the inverse Fourier transform by digital filter application.



(a) Amplitudes of E_x.

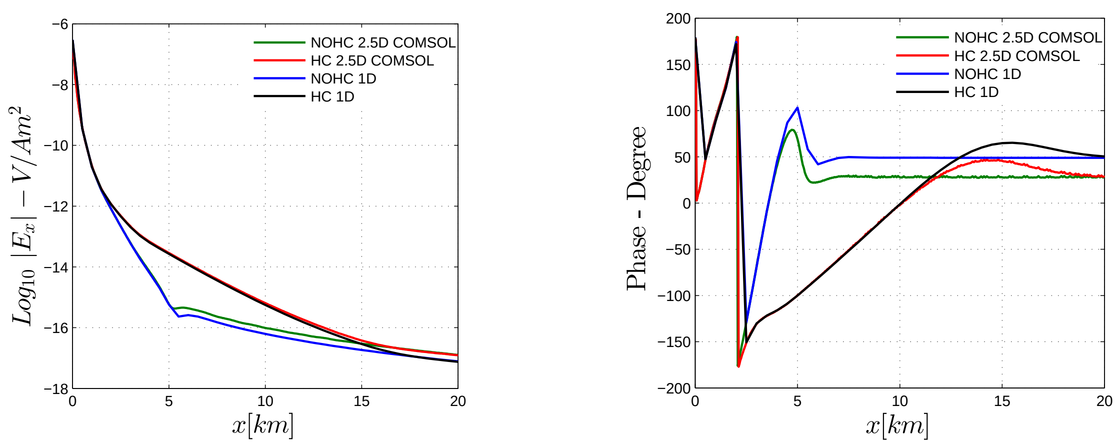
(b) Phases of E_x.

Figure 5. Amplitudes and phases of E_x to COMSOL and DIPOLE1D, the frequency of the transmitter is $f = 0.25$Hz.



(a) Amplitudes of E_x. **(b)** Phases of E_x.

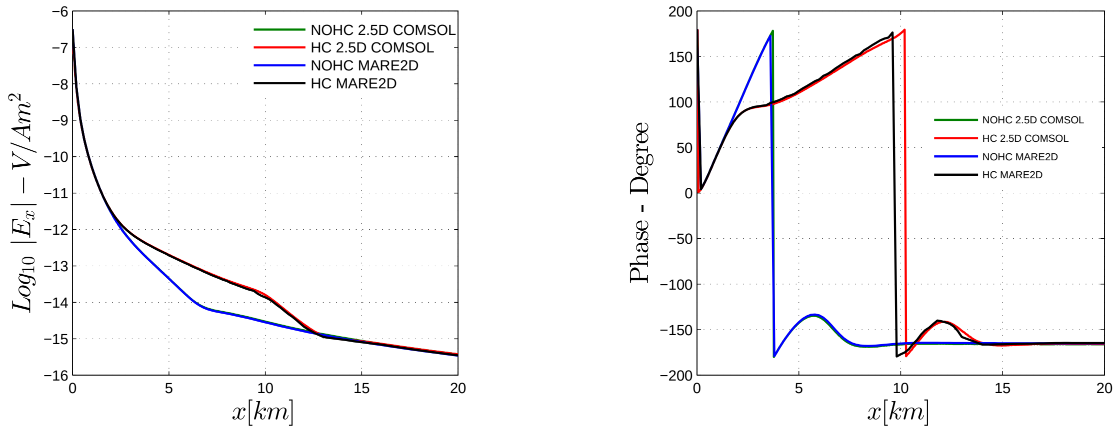
Figure 6. Amplitudes and phases of E_x to COMSOL and DIPOLE1D, the frequency of the transmitter is $f = 0.5$Hz.



(a) Amplitudes of E_x. **(b)** Phases of E_x.

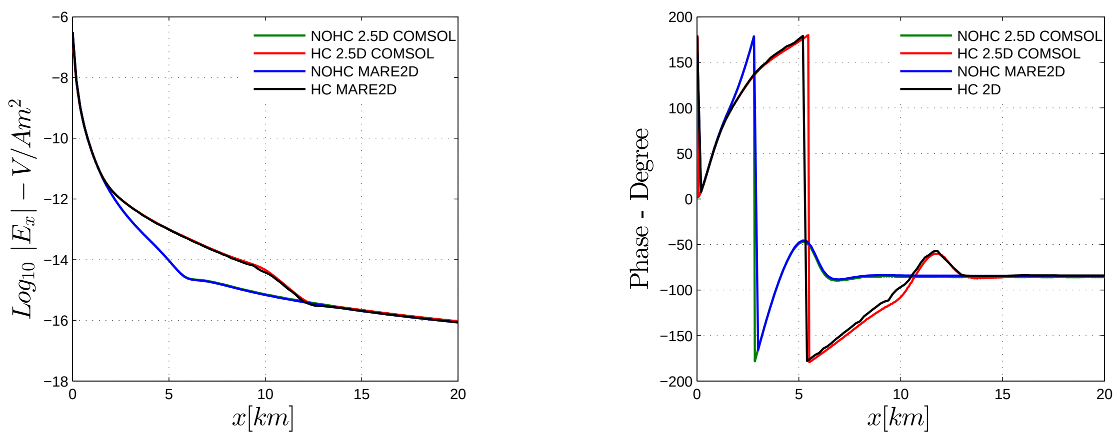
Figure 7. Amplitudes and phases of E_x to COMSOL and DIPOLE1D, the frequency of the transmitter is $f = 1$Hz.

The second model is a 2.5D model. The geometry of this model is similar to the 1D model showed in Figure 2. The difference between them is that the reservoir width of the 2.5D model is 20km, extend symmetricly from -10km to 10km, while to 1D model the width extend until the frontiers. The Figure 8, 9 and 10, display the response in amplitude and phase for the same three frequencies showed previously. The curves of the amplitude and phase versus off-set receiver-transmitter to electric field in-line E_x are presented for three frequencies. 0.25Hz in Figure 8, 0.5Hz in Figure 9 and 1Hz in Figure 10. All the results are compared with responses from the MARE2D code Li and Key (2007). The three figures show that both model with hydrocarbon reservoir (HC 2.5D COMSOL) and without hydrocarbon reservoir (NOHC 2.5D COMSOL) are quite similar with the curves obtained from MARE2D. This evince the robustness of this approach with COMSOL Multiphysics® . We emphasize the COMSOL implements a approximation to calculate the inverse Fourier transform by digital filter application.



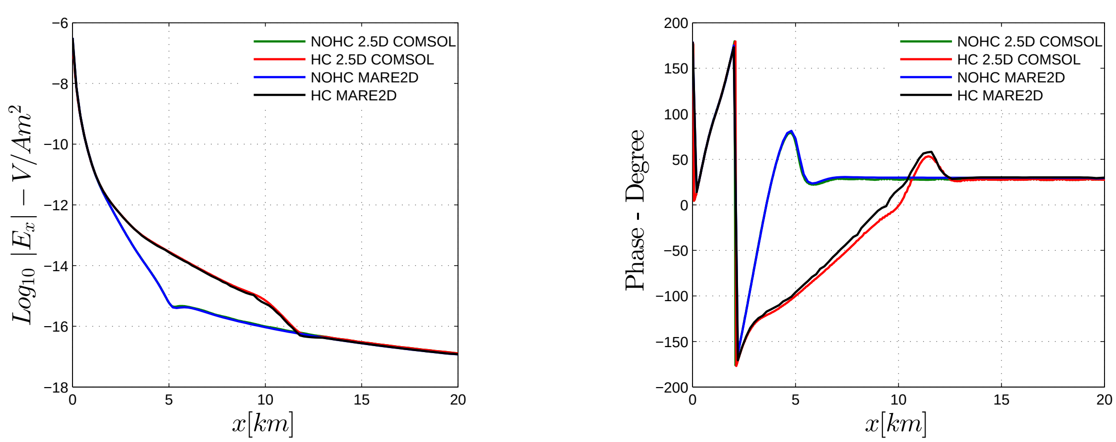
(a) Amplitudes of E_x. **(b)** Phases of E_x.

Figure 8. Amplitudes and phases of E_x to COMSOL and MARE2D, the frequency of the transmitter is $f = 0.25$Hz.



(a) Amplitudes of E_x. **(b)** Phases of E_x.

Figure 9. Amplitudes and phases of E_x to COMSOL and MARE2D, the frequency of the transmitter is $f = 0.5$Hz.



(a) Amplitudes of E_x. **(b)** Phases of E_x.

Figure 10. Amplitudes and phases of E_x to COMSOL and MARE2D, the frequency of the transmitter is $f = 1$Hz.

Conclusions

The methodology used in this work to implement 2.5D models uses the software COMSOL Multiphysics® to simulate the propagation of the electromagnetic field related to marine controlled source electromagnetic (mCSEM). To valid the results we compare with other models of the specialized literature and codes development in Fortran 90. Models proposed in this work showed that the use of COMSOL software represents a tool suitable in the construction of 2.5D geo-electric structures with complex geometries. The COMSOL Multiphysics® presents precision responses with a lower computational cost, providing quick studies of feasibility studies, fast inversions, besides presenting friendly interfaces and optimized solvers in the solution of linear systems.

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