Marlim R3D: A first approach with COMSOL Multiphysics

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Abstract

We present a simplified approach using the COMSOL Multiphysics software for modeling the Marlim R3D, a powerful numerical tool employed in Marine Controlled-Source Electromagnetic Method (MCSEM) studies. The Marlim R3D model enables the simulation and analysis of electromagnetic responses in marine environments. In this study, we demonstrate the effectiveness of our simplified approach by comparing the results obtained with the COMSOL Multiphysics model to previously known results. The comparison revealed a satisfactory agreement between our approach and the known results, thereby validating the effectiveness of our simplified modeling strategy. This approach provides a practical and efficient solution for conducting MCSEM simulations, facilitating accurate subsurface conductivity mapping in marine settings.

Introduction

The Marine Controlled-Source Electromagnetic Method (MCSEM) has garnered significant attention in recent years due to its ability to map subsurface electrical conductivity structures in marine environments. This geophysical technique involves deploying electromagnetic transmitters and receivers on a marine platform to measure the subsurface's response to controlled electromagnetic fields (Constable, 2006; Constable and Srnka, 2007). MCSEM is based on the principle of electromagnetic induction, where a time-varying electromagnetic field induces an electrical current in the subsurface. The measured electromagnetic fields are then analyzed to infer information about the subsurface's conductivity distribution. By varying the frequency of the transmitted field, MCSEM provides valuable insights into subsurface properties at different depths and resolutions (Um and Alumbaugh, 2007; Liu et al., 2013). Several case studies have demonstrated the effectiveness of MCSEM in various marine applications, including the exploration of hydrocarbon reservoirs beneath the seabed. By analyzing the electromagnetic response, MCSEM can identify variations in subsurface resistivity, enabling the detection of potential hydrocarbon-bearing formations. This information is crucial in guiding subsequent drilling operations and optimizing hydrocarbon extraction (Johansen et al., 2007; Mohr et al., 2008; Myer et al., 2012, 2015).

The Marlim R3D (MR3D) model is an open-source geoelectric model specifically developed for the deep-water turbidites reservoir system of the Brazilian continental margin, which is analogous to similar systems found in other parts of the world, such as the African continental margin. In phase 1, Carvalho and Menezes (2017b) outlined the workflow for building the model and made it freely accessible for research and commercial purposes. Phase 2 involved conducting a series of CSEM finite-difference 3D simulations using the MR3D resistivity model (Correa and Menezes, 2019). Recently, in phase 3, Correa and Menezes (2021) performed a forward-modeling exercise to generate a broadband marine magnetotelluric (MMT) data set at the same CSEM receivers used in phase 2. Werthmüller et al. (2021) introduced a coarser mesh discretization version.

Our objective is to conduct forward modeling using a simplified approach with the available dataset from the Marlim R3D field (Carvalho and Menezes, 2017b). We will utilize the COMSOL Multiphysics software to perform the modeling and compare the results obtained with those shown in Correa and Menezes (2019).

Marlim R3D

The Marlim field (Figure 1), located in the northeastern portion of the Campos Basin, between northern Rio de Janeiro and southern Espírito Santo, was discovered in 1985 and stands as a representative example of offshore fields in the Brazilian coast, showcasing unique geological and geomorphological characteristics. With reservoir rocks rich in Oligocene and Miocene sandstones and porosity above 30 percent, the Marlim field stands out in MCSEM studies due to its complexity and the challenges it poses for hydrocarbon exploration. The CSEM acquisition geometry superimposed on the bathymetric map of the MR3D area. The Marlim reservoir outline is shown in the white line. The yellow dots are the receiver locations distributed in a $1000\,\mathrm{m}$ spacing regular grid. The black lines are the source towlines evenly spaced at $1000\,\mathrm{m}$. Source locations are spaced every $100\,\mathrm{m}$ along each towline.

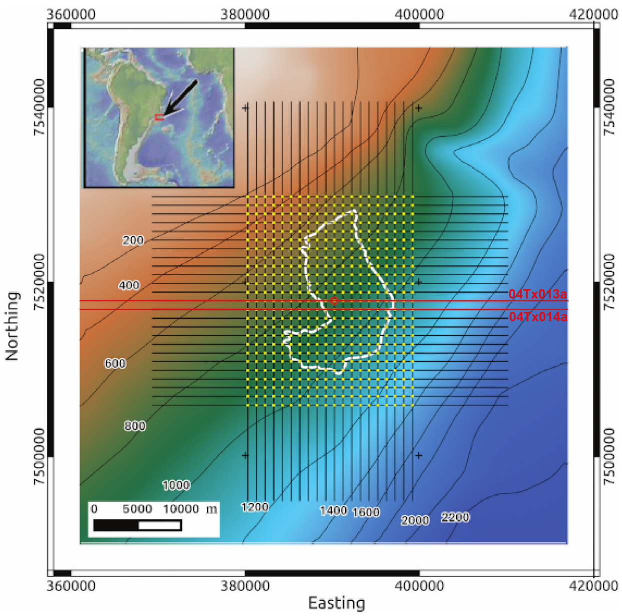

***Figure 1** – The Marlim field and the CSEM acquisition geometry superimposed on the bathymetric map of the MR3D area. Adapted from Correa and Menezes (2019).*

Although synthetic models are useful in the development of the MCSEM method, they often overly simplify the challenges faced in a production environment (Buonora et al., 2014; Tseng et al., 2015). In this context, Marlim R3D emerges as a realistic anisotropic geoelectric model (Figure 2), intended to serve as a reference for MCSEM studies of turbidite reservoirs (Carvalho and Menezes, 2017a).

Figure 2 depicts the reservoir MR3D. the vertical resistivity obtained from a horizon slice at the uppermost part of the reservoir. Within this slice, the Marlim reservoir facies, characterized by clean sandstones, is identifiable as a high-resistivity entity situated within a low-resistivity background consisting of marls and shales. The MR3D model exhibits a resistivity pattern that is more intricate than a single homogeneous body. Thus we propose a new approach using the software COMSOL Multiphysics.

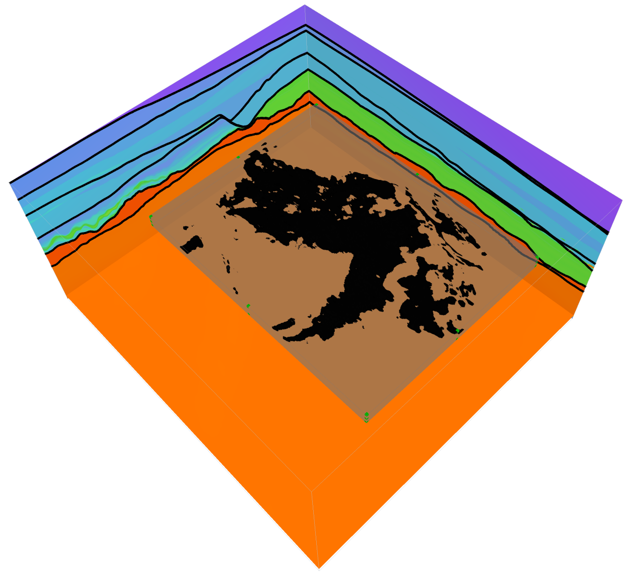

***Figure 2** – View of the reservoir Marlim R3D from horizons dataset, plotted in OpendTect.*

COMSOL Multiphysics

The software COMSOL is an interactive development platform designed for simulations using the Finite Element Method (FEM), a numerical technique used to provide approximate solutions for systems of partial differential equations, making problems of infinite dimensions more manageable. The software is versatile, allowing for the creation of simple to complex geometries, including interpolation of discrete data. Additionally, COMSOL offers the capability to incorporate physical properties of materials used and utilize meshes of various geometric shapes. An additional notable feature is its ability to function independently while also integrating with tools such as MATLAB and CAD software. In the context of our study, COMSOL will be used to model the stratigraphic layers of the Marlim R3D model. In the realm of geophysics, COMSOL Multiphysics software stands out for its user-friendly interface and the utilization of optimized solvers for solving linear equations. Within the geoscience field, notable applications include groundwater modeling (Li et al., 2009) and, more specifically, the applied modeling of electromagnetic methods (EM) Butler and Zhang (2016). When it comes to modeling the Marine Controlled-Source Electromagnetic Method (MCSEM) and Magnetotellurics (MT), several studies have made significant contributions. Miranda and Tocantins (2017), and Li and Butler (2021) have produced notable works in this domain, exploring the intricacies and advancements of these methods.

Methodology

The methodology consists of two essential steps: reservoir data pre-processing and geoelectric model construction. In the first step, the resistivity data obtained from the Marlim-R3D model, as provided by Correa and Menezes (2019), is carefully processed to ensure accuracy and reliability. This involves data validation, cleaning, and normalization to account for any inconsistencies or anomalies. In the second step, the pre-processed data is utilized to construct a detailed geoelectric model using the advanced capabilities of the COMSOL Multiphysics software. The software enables the integration of various geological and geophysical parameters, allowing for the creation of a realistic and accurate representation of the subsurface conductivity distribution.

Reservoir Model Pre-Processing

In the pre-processing stage, as depicted in Figure 3, resistivity data is collected from the SEG-Y file and filtered to isolate the region of interest within the reservoir. A custom algorithm is then utilized to convert this data from a data cube format into a point cloud. Subsequently, the point cloud is further filtered to encompass the resistivity range specific to the reservoir, as shown in Figure 4.

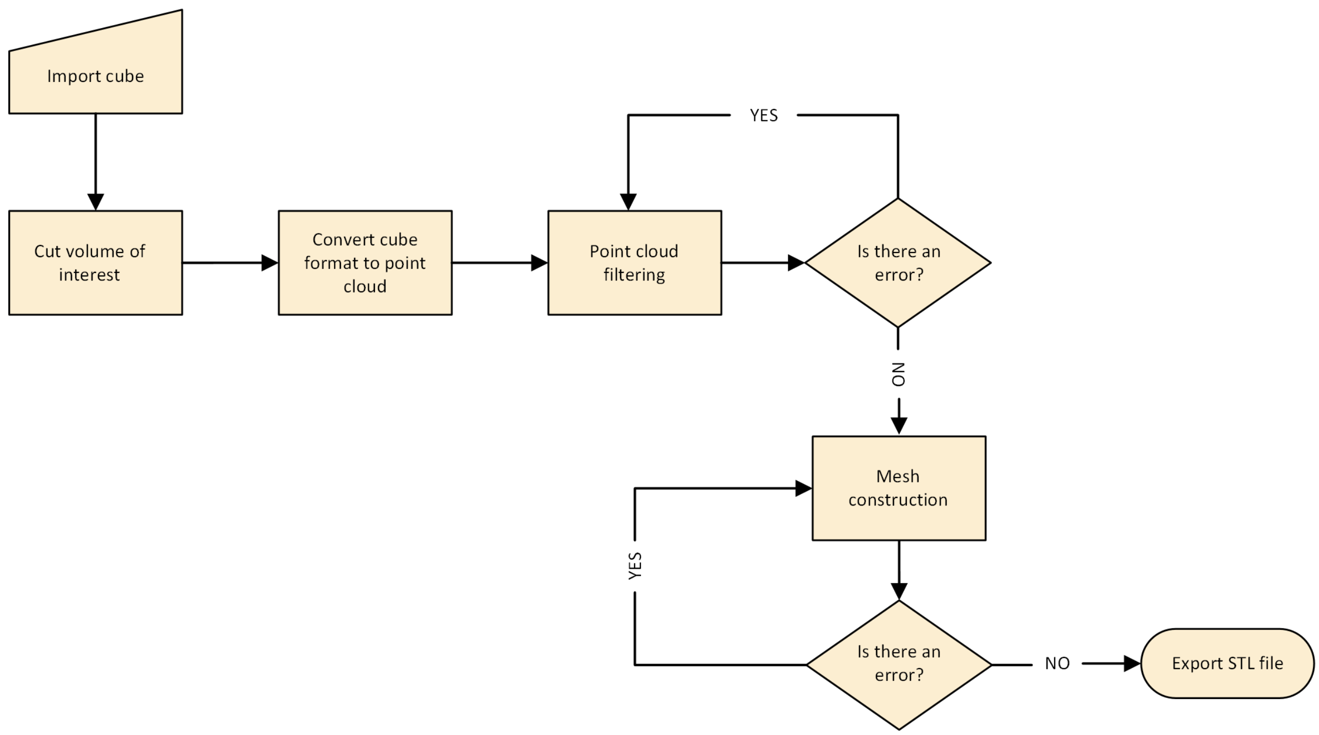

Figure 3 *– Flowchart of the reservoir mesh creation process.*

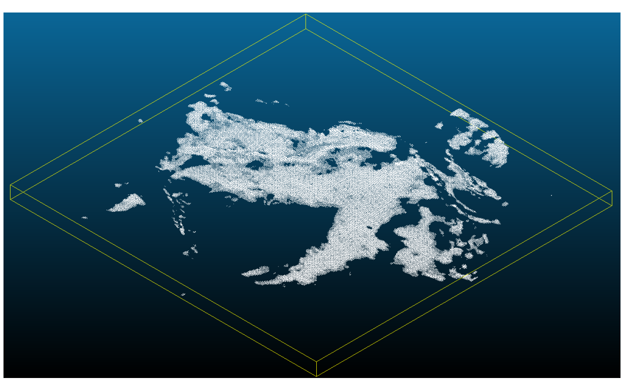

Figure 4 *– Representation of the point cloud that corresponds to the conductivity distribution of the reservoir.*

The points are processed to eliminate those that are in close proximity to each other and statistical outliers, using criteria based on proximity analysis and statistical distribution. The resulting point cloud is divided into two groups, representing the top and base of the reservoir. Normal orientations are subsequently calculated for each point.

The mesh is generated from the point cloud using the Ball Pivoting algorithm (Bernardini et al., 1999). This algorithm creates a surface mesh that conforms to the point cloud. The mesh then undergoes refinement and correction processes to eliminate duplicate vertices and faces. The final product is exported in the STL format, which is compatible with importation into COMSOL, as is showed in Figure 5.

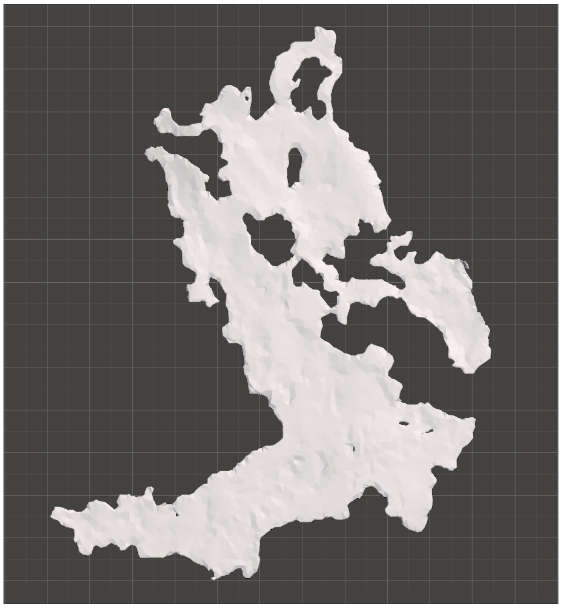

Figure 5 *– The reservoir surface after point cloud filtering and mesh generation algorithm application. This geometry will be imported into the COMSOL software.*

Constructing the Geo-electric Model in COMSOL

The geometry of the geo-electric model is defined in COMSOL using the mesh data and lithology information from the Marlim-R3D reservoir model. The geometry includes the source and receivers, which are positioned in two configurations: inline and broadside. The material properties are assigned to each layer of the model, considering anisotropy where relevant. Next, boundary conditions are defined, and the domain is discretized into a finite element mesh, wich is refined in areas of interest and where the domain is fine, while it is kept coarser in less relevant areas for the study. This methodology enables the creation of a detailed and accurate geo-electric model from public resistivity data, paving the way for simulations and analyses of physical phenomena in geosciences and engineering. The use of advanced software, such as COMSOL Multiphysics, allows for precise and efficient modeling, contributing to a better understanding of reservoir processes and characteristics. The model discretization was performed using a finite element mesh. Figure 6 illustrates the construction of the model mesh carried out by the COMSOL software, highlighting variations in mesh density across different layers. This strategy was adopted to optimize processing time without compromising the accuracy of the results. Table 1 provides insight into the resistivity values utilized in the COMSOL simulations. These values represent the average resistivities observed horizontally and vertically.

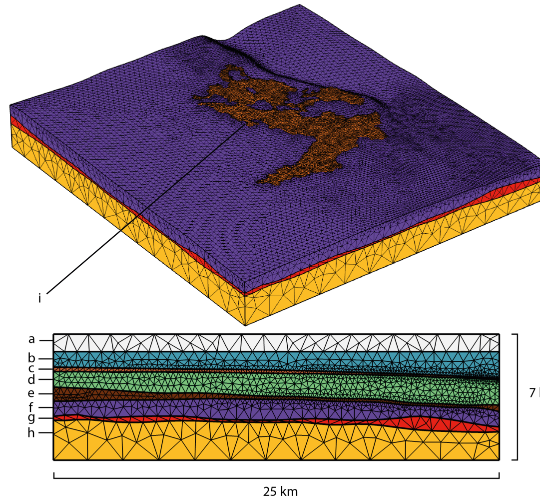

Figure 6 *– (a) Air, (b) Air - Sea, (c) Sea - Miocene, (d) Miocene - Oligocene, (e) Oligocene - Blue mark, (f) Blue mark - Salt top, (g) Salt top - Salt base, (h) Pre-salt, and (i) Reservoir.*

Dominio	Iso	Ani	$Res_H (\Omega\,\text{m})$	$Res_V\ (\Omega\,\text{m})$
a	✓		1×10^8	1×10^8
b	✓		0.31	0.31
c		✓	0.5	2.00
d		✓	1.40	2.85
e		✓	1.40	2.85
f		✓	2.00	4.00
g	✓		1×10^3	1×10^3
h		✓	35.71	71.42
i		✓	71.42	140.84

Table 1 *– Layer Resistivity Values for COMSOL model.*

Results

The Figures 7 – 12 we present the results obtained using the COMSOL model compared to those from Correa and Menezes (2019) study.

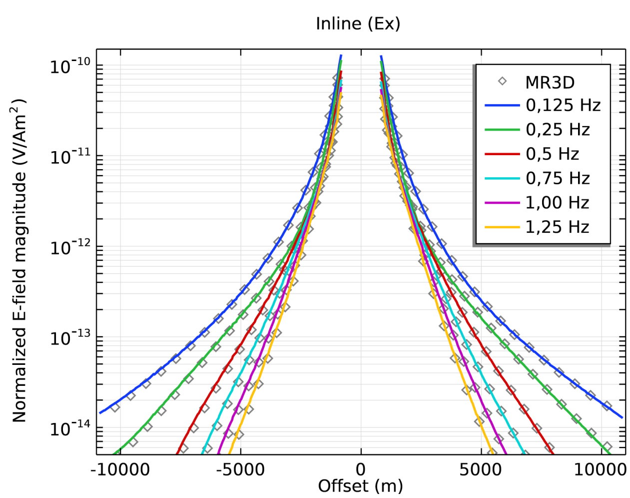

Figure 7 *– MR3D 04Tx013a, 04Rx251a.* $(0.125, 0.25, 0.50, 0.75, 1.00$ *and* $1.25)$ Hz.

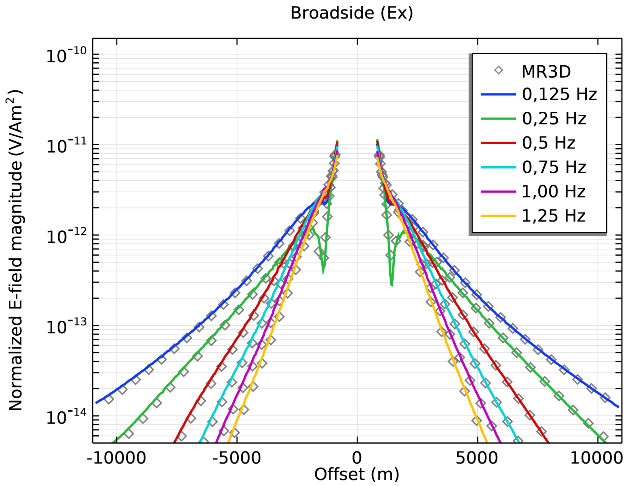

Figure 8 *– MR3D 04Tx014a, 04Rx251a.* (0.125, 0.25, 0.50, 0.75, 1.00 *and* 1.25) Hz.

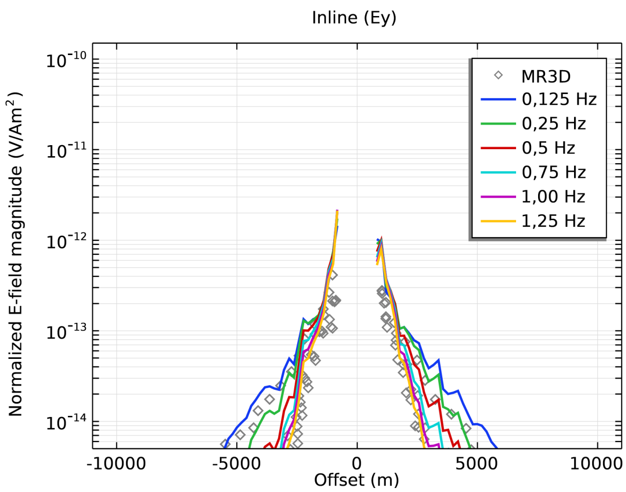

Figure 9 *– MR3D 04Tx013a, 04Rx251a.* (0.125, 0.25, 0.50, 0.75, 1.00 *and* 1.25) Hz.

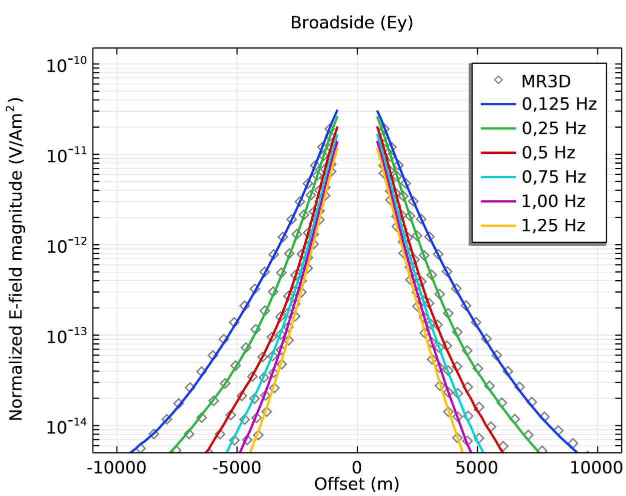

Figure 10 *– MR3D 04Tx014a, 04Rx251a.* (0.125, 0.25, 0.50, 0.75, 1.00 *and* 1.25) Hz.

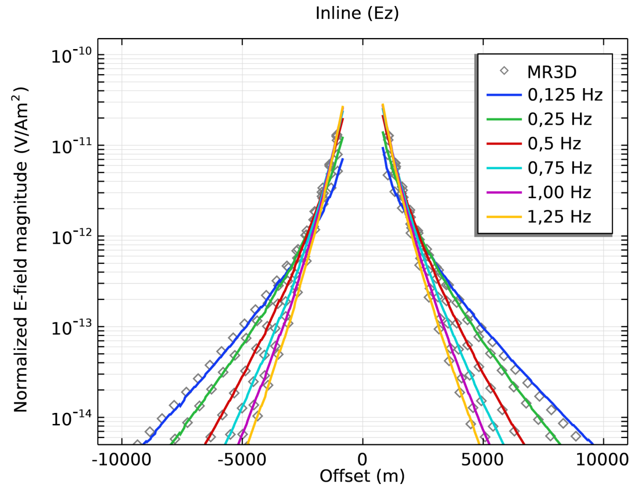

Figure 11 *– MR3D 04Tx013a, 04Rx251a.* (0.125, 0.25, 0.50, 0.75, 1.00 *and* 1.25) Hz.

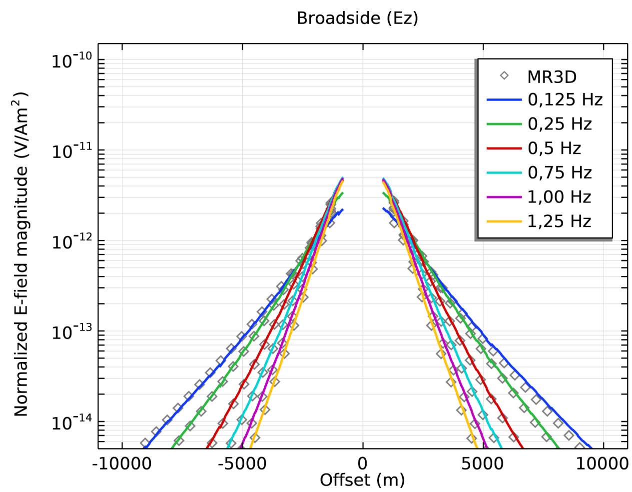

Figure 12 *– MR3D 04Tx014a, 04Rx251a.* (0.125, 0.25, 0.50, 0.75, 1.00 *and* 1.25) Hz.

Final Remarks

The utilization of the COMSOL software in conjunction with the MR3D model has proven to be a highly effective approach for numerical modeling of the Marine Controlled-Source Electromagnetic Method (MCSEM). The results obtained using this approach have demonstrated excellent agreement with those reported in the literature, highlighting its accuracy and reliability. Furthermore, the computational effort required for implementing the MR3D model through COMSOL was significantly reduced compared to traditional methods that rely on high-performance computing resources. This efficiency makes the MR3D model accessible to a broader range of researchers and practitioners, facilitating its widespread adoption in marine geophysical studies. The successful application of the COMSOL-based approach and the promising results obtained with the MR3D model pave the way for further advancements in MCSEM and contribute to enhancing our understanding of subsurface conductivity structures in marine environments.

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