Absorbing boundary domain for CSEM 3D modelling

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Abstract: In the study, we present an efficient absorbing boundary domain technique whose main application is the 3D finite element (FE) modelling of the so-called controlled-source electromagnetic (CSEM) data, collected for the geophysical exploration. The developed technique is based on the real-value exponentially-stretched coordinates. We have implemented the developed technique using the user-defined PML tool available in COMSOL Multiphysics, RF module. In the article, we evaluate its performance through several examples of the marine CSEM data.

Keywords: marine CSEM; geophysical EM data; frequency domain; 3D FE modeling; absorbing boundary domain/condition; PML

1. Introduction

The controlled-source electromagnetic (CSEM) survey is a promising geophysical exploration technique in the offshore environment, often referred as marine CSEM or SeaBed Logging (SBL) [2]. The technique transmits and records the very-low frequency (e.g. 0.1 to 10 Hz) electromagnetic signal on the seafloor in order to detect high resistivity (hydrocarbon) target layers within the earth. To analyze the data, we use the so-called amplitude versus offset (AVO) and phase versus offset (PVO) curves. The offset range of interest is rather large, e.g. between 1 km to 10 (or 20) km. Since the CSEM data is highly attenuated through the subsurface propagation, the AVO curve is normally plotted in logarithmic scale (i.e. $\log_{10}$) with a dynamic range of e.g. 10^{-15} to 10^{-5} V/Am^2. The low frequency introduces extremely long skin-depth (e.g. order of 100km's or even infinity in the air-layer), which makes the 3D numerical modelling of CSEM data challenging (to perfectly remove reflection from finite-size model boundaries) during the CSEM data interpretation and inversion.

In the study, we have developed an efficient absorbing boundary domain technique and implemented using the user-defined PML tool built in COMSOL Multiphysics, RF module. The developed technique is based on the real-value exponentially-stretched coordinates. In the article, we present the absorbing boundary domain formulation and evaluate its performance (e.g. accuracy, meshing, size/location, i.e.) by solving several examples of the marine CSEM survey and comparing the results with an available reference solution.

2. Absorbing boundary domain (ABD)

We propose an efficient absorbing boundary domain technique that is based on the real-value and exponentially-stretched coordinates. The technique is not a very novel one, but just one type of the perfectly matched layer (PML) method among many others, e.g. [1,5,6]. A similar one can be found from an old soil-and-structure interaction code, called SASSI [4]. The technique requires a few input parameters, whose values can be decided almost arbitrarily (e.g. as in [1,5,6]), depending on the physics (e.g. attenuating or non-attenuating wave), the required accuracy, etc. In the current study, we propose a set of optimal values, which ensures the accuracy of the simulated marine CSEM data at the interface between the main computational domain and the absorbing boundary domain at around 1% relative error.

The coordinate stretching in the proposed technique is done by the following formula.

$$\xi = x_0 a^{x_0/h_0}$$

where ξ and x_0 are, respectively, the stretched and unstretched coordinates, both defined locally in the absorbing boundary domain; a is a base and its optimal range is $(1,3$ or $\pi]$, which is determined through extensive numerical test. The formula can be implemented into COMSOL Multiphysics, RF module, using the user-defined PML tool. An important condition to satisfy is that the size of the absorbing boundary domain ($\xi_{\max}$) should be no smaller than 10 times the skin-depth of the absorbing boundary domain (d_{ABD}), i.e. $\xi_{\max} \geq 10 d_{ABD}$. Note that the skin-depth depends on the frequency and the conductivity of the domain of interest. From our experience, $x_{0,\max}$ (the size of the absorbing boundary domain in unstretched coordinate) that satisfies hte condition of $\xi_{\max} \geq 10 d_{ABD}$ is normally 3 to 10 km, which is rather small in comparison to the wave-length or skin-depth in the air-layer. Finally, again through numerical test, the optimal number element-layers in the absorbing boundary domain is found to be around 15, which satisfies our accuracy goal of 1% relative error at the interface between the main computational and absorbing boundary domains.

3. Validation via numerical examples

We solve two numerical examples: one with the shallow water of 500 m depth and the other for infinitely deep water. It will be shown that the former example model requires much bigger size absorbing boundary domain, because the air-wave of extremely long wave-length or skin-depth is involved. For each example, we consider two different sizes for the main computation domain, i.e. 10 km and 5 km, in order to demonstrate that the absorbing boundary domain works well, almost independently of the computational domain size. The subsurface consists of four layers: layer 1 (from the top) is the overburden layer of 1 Ωm and 1000m thickness; layer 2 is a high resistivity target-layer of 100 Ωm and 100m thickness; layer 3 is the underburden layer of 1 Ωm and 400m thickness; and layer 4 is a homogeneous half-space of 10 Ωm. The subsurface profile is the same for both of the shallow and infinite water models. The inline electric transmitter (J_x) and the inline receiver line (E_x) are both located exactly on the seabed. The frequency of interest is 0.25 Hz.

Example 1: shallow water

Fig. 1 shows the finite element (FE) model with the 500 m deep water. Note that the sizes of absorbing boundary domains are 10 km in all the directions, which is because we have the air-layer on the top and a rather high (10 Ωm) resistivity half-space at the bottom.

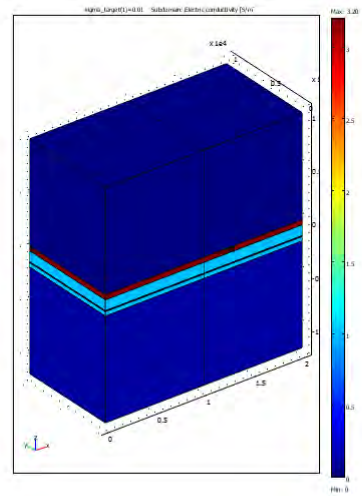

Fig. 1. Example model 1 with 500m deep water: note that only one quarter of the full 3D space is simulated by specifying the symmetric conditions at x=0 and y=0 planes.

Figs. 2 and 3 present the AVO and PVO curves for the 10 km size computational domain in comparison to those obtained by means of an in-house analytical solution (called EMSEA1D, [3]). It is shown that the absorbing boundary domain proposed in the study work very well.

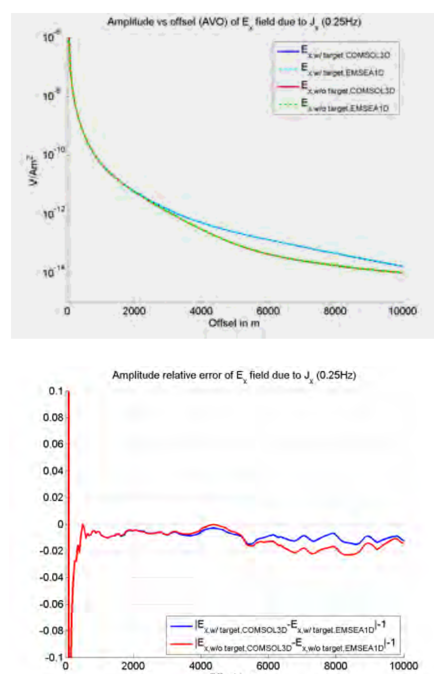

Fig. 2. AVO for example model 1, with 10 km main computational domain

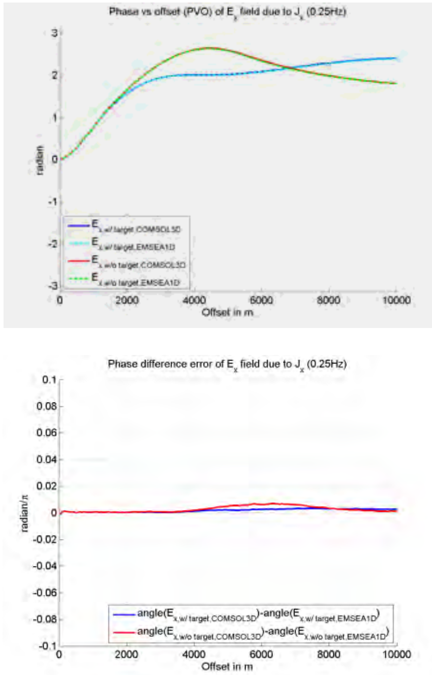

Fig. 3. PVO for example model 1, with 10 km main computational domain

Figs. 4 and 5 present the AVO and PVO curves for the 5 km size computational domain. It is shown that the absorbing boundary domain proposed in the study works very well for the smaller size computation domain as well.

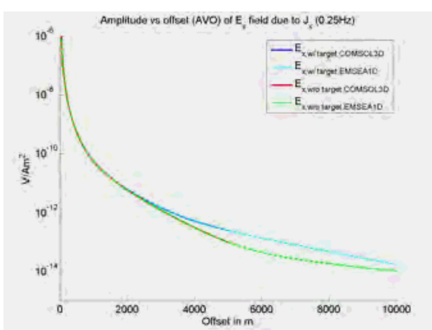

Fig. 4. AVO for example model 1, with 5 km main computational domain

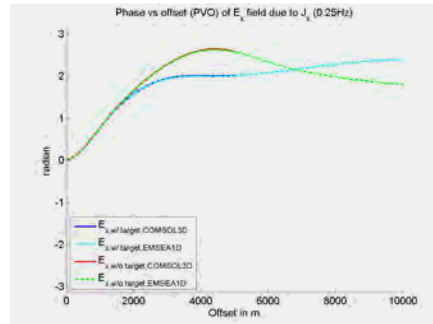

Fig. 5. PVO for example model 1, with 5 km main computational domain

Example 2: infinite water

Fig. 6 shows the finite element (FE) model with the infinite deep water. Note that the sizes of absorbing boundary domains are 3 km for the upward and lateral directions; and again 10 km for the downward direction.

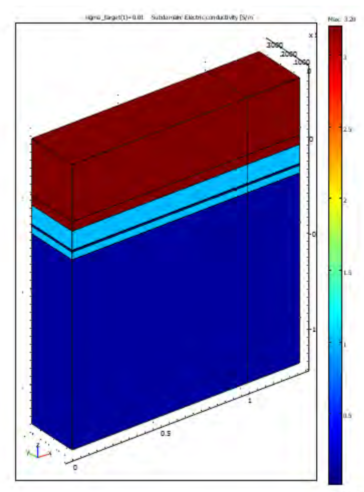

Fig. 6. Example model 2 with infinite deep water: note that only one quarter of the full 3D space is simulated by specifying the symmetric conditions at x=0 and y=0 planes.

Figs. 7 and 8 present the AVO and PVO curves for the 10 km size computational domain. It is shown that the absorbing boundary domain proposed in the study work very well for the infinite deep water.

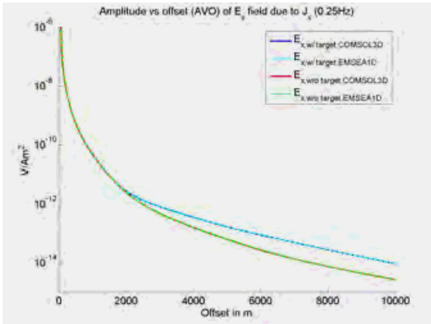

Fig. 7. AVO for example model 2, with 10 km main computational domain

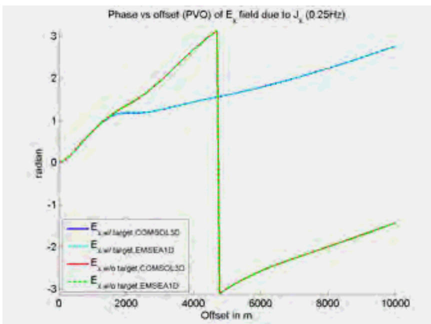

Fig. 8. PVO for example model 2, with 10 km main computational domain

Figs. 9 and 10 present the AVO and PVO curves for the 5 km size computational domain. It is shown that the absorbing boundary domain proposed in the study works very well for the smaller size computation domain as well.

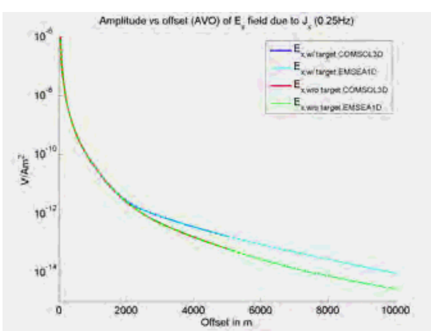

Fig. 9. AVO for example model 2, with 5 km main computational domain

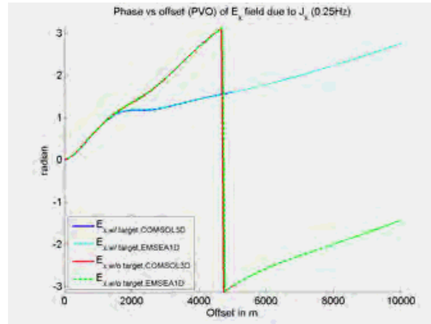

Fig. 10. PVO for example model 2, with 5 km main computational domain

4. Summary

In this study, we have developed an efficient absorbing boundary domain technique and implemented it using the user-defined PML tool in COMSOL Multiphysics, RF module. The developed technique is based on the real-value exponentially-stretched coordinates. We have also evaluated its performance (e.g. accuracy, meshing, size/location, i.e.) through several examples of the marine CSEM survey and compared it with an available reference solution.

5. Acknowledgements

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6. References

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