3D inversion of an integrated TEM survey

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SUMMARY

Recent instrument advancements in the field of the transient electromagnetic (TEM) method enable applications adapted to different environments. To invert integrated datasets from ground-based and waterborne TEM surveys under one model domain, the complexity increases for two factors: i) significant multi-dimensionality effects from settings with strong conductivity contrasts such as a coastline. ii) sensitivity footprints vary depending on the systems. We address these challenges by utilizing a previously developed 3D octree-based inversion scheme, where the decoupling between forward and inversion mesh allows local meshes for individual soundings, and a commonly shared model for the inversion domain. We demonstrate the framework environments through synthetic and field case studies. These experiments show that: i) for such surveys, the 3D inversion outperforms the 1D inversion in terms of a lower data misfit and more accurate predicted model; ii) a careful forward mesh refinement is required to effectively explain the data collected at the settings with thin and highly conductive top layers.

Keywords: Time-domain electromagnetic, 3D, Inversion, Borehole

INTRODUCTION

The transient electromagnetic method is an efficient and non-invasive geophysical tool for characterizing the resistivity distribution of the subsurface. Nowadays, many TEM systems are developed for improved maneuverability and acquisition, allowing for measurements in a variety of environments – e.g. airborne, ground-based, or waterborne surveys. An integrated survey, which consists of a mix of several TEM systems, can be a helpful solution in some circumstances, since different systems may offer superior resolution by concentrating at different sensitivity depths or surveying different types of land/sea. Following TEM measurements, a 1D inversion is routinely applied, assuming the subsurface is quasi-1D. However, it is difficult to resolve the subsurface structures with little ambiguity if major 2D or 3D effects are present (Rabinovich, 1995; Bauer-Gottwein et al., 2010), such as salinity-related anomalies, even if there is a strong agreement between predicted and measured data. Furthermore, the inevitable mix of system configurations result in varied sensitivity footprints horizontally and vertically, necessitating individually tailored meshing for 3D modeling.

The outlined challenges are especially prominent in coastal surveys. First, both ground-based and waterborne (or airborne) TEM systems are used to image the resistivity distribution below land and seawater. Second, the strong conductivity contrast between seawater and/or lithologies affected by high salinity and freshwater lithologies results in significant 2D and 3D effects in the data. As a result, a standard 1D inversion framework is unable to appropriately resolve subsurface structures correctly, which could be crucial for effectively conceptualizing seawater intrusion problems. To address the issues, we use a developed 3D multi-mesh inversion scheme (Xiao et al., 2022): i) 3D octree-based forward modeling is employed to describe the multi-dimensional environment and simulate the electromagnetic field diffusion. ii) a decoupling between the forward and the inversion mesh is utilized to provide the flexibility of modeling each sounding separately to minimize computational costs while accounting for differences in configuration and sensitivity. The mesh decoupling further allows for a continuation of the model-domain across the land-sea interface during inversion, in comparison to an approach that uses independent model domains for the land-based and waterborne sub-surveys. We investigate the problem on a synthetic example and demonstrate our solution on a field dataset collected from a coastal area, where borehole data is available to verify the result.

METHODS

TEM Modeling and inversion

Assuming that the media is isotropic, non-magnetizable and that electrical properties are independent of time, the time-domain forward problem is formulated as a diffusion equation in terms of the electrical field $\mathbf{e}(\mathbf{x},t)$:

$$\nabla \times \nabla \times \mathbf{e}(\mathbf{x},t) + \mu\sigma(\mathbf{x})\frac{\partial \mathbf{e}(\mathbf{x},t)}{\partial t} = -\frac{\partial \mathbf{j}_s(t)}{\partial t} \qquad (1)$$

where the electric field $\mathbf{e}(\mathbf{x},t)$, is a function of space, $\mathbf{x}(\mathbf{x}\in\Omega)$, and time, $t \in (0,T)$; μ is the magnetic permeability of free space, σ denotes the electric conductivity, and $\mathbf{j}_s$ denotes the current source. The modeling and inversion used a previously developed octree-based scheme (Xiao et al., 2022). In particular, the multi-mesh approach (Zhang et al., 2021) is employed in the scheme, which is beneficial in this dual-system ground-based and waterborne TEM inversion. In the inversion, one regular mesh is used for the full-scale model update. The forward modeling and Jacobian calculation, however, are performed on sounding-based, with a local mesh description for the different systems.

Modeling mesh design

TEM techniques are highly sensitive to conductors. When doing a survey in saline water, the eddy currents diffuse horizontally in the water for a long time rather than moving downwards, resulting in a shallow vertical resolution. For such cases where conductive structures are present in the top subsurface, additional mesh refinement is required to attain acceptable numerical accuracy. First, the mesh elements in the seawater layer must be refined to depict rapid field variations near the TEM system. At the same time, the refinement must cover vast horizontal footprints to account for the lateral extension of the eddy currents with time.

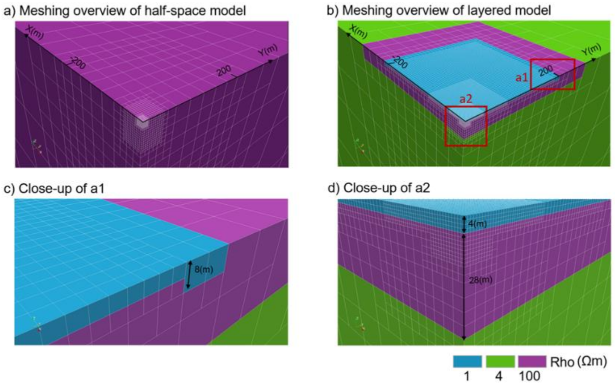

Figure 1. Illustration of the octree mesh refinement for a three-layered (1/4/100 Ωm) model. a) shows a normal half-space meshing while b) shows a refined mesh for a highly conductive and thin top layer. c) shows a close-up of the mesh in b) at the end of the fine mesh (a1), laterally, and d) shows a similar close-up just below the transmitter (a2).

RESULTS

Synthetic example

To replicate a coastal environment (Figure 2-b) similar to the field case scenario, we created a three-layer 3D synthetic model. The measurement for the synthetic example (Figure 2-c) uses tTEM (Auken et al., 2019) and FloaTEM (Maurya et al., 2021) systems to cover an area of 140mx70m with a 10 m sounding distance. We selected a profile perpendicular to the driving direction consisting of 6 tTEM soundings and 7 FloaTEM soundings. We compared the relative difference between the 1D response from AarhusInv (Auken et al., 2015) and the 3D response from the forward solution (Xiao et al., 2022).

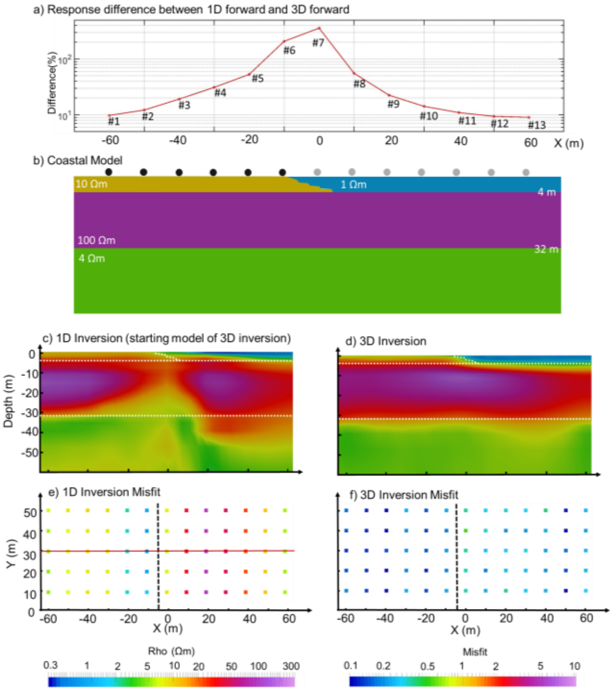

Figure 2. The 1D/3D forward and inversion result on a coastal model: a) Forward response difference; b) Coastal model illustration, where the tTEM and FloaTEM soundings are symbolized by black and grey dots, respectively; c) 1D inversion section (starting model of 3D inversion); d) 3D inversion section; e) 1D inversion misfit map; f) 3D inversion misfit map. The dotted white lines outline the structures of the true model. The dotted black lines symbolize the coastline. The solid red line indicates the section location of inversion results in subfigure (c) and (d).

The modeling test has revealed a significant difference between a 1D and a 3D response, in the instance of strong 2D effects from a coastline (Figure 2-a). As a result, it has illustrated the importance of using multi-dimensional simulation instead of 1D modeling in such an area. To compare the inversion performance of different dimensions, we performed both 3D (Xiao et al., 2022) and 1D inversions (Christensen et al. ,2017) using the same model space, i.e. a voxel mesh with the same spatial discretization. Although we started the inversion with correct parameters, the seawater layer in 1D inversion result is too shallow compared to the true model; also, a conductive pant leg is reaching into the high-resistivity layer. The 3D inversion starting model (i.e.,1D inversion result), on the other hand, did not include a layer to represent the proper water table, but it recovered the true model substantially. This includes a more reasonable resistivity model without the pant leg.

Field case

Himmark Beach is a contaminated area in southern Denmark due to the deposition of chemical waste. The local government aims to characterize the pollution pathways to the sea using the TEM method and make a removal strategy for the environmental problem. We use a small subset from the TEM campaign to illustrate our solution to the inversion problem, due to the large computational complexity and the access to existing borehole information. The presented dataset (Figure 3) consists of 18 tTEM soundings and 41 FloaTEM soundings. In general, the distance between acquisition lines is around 20 m and the distance between soundings is 5 m.

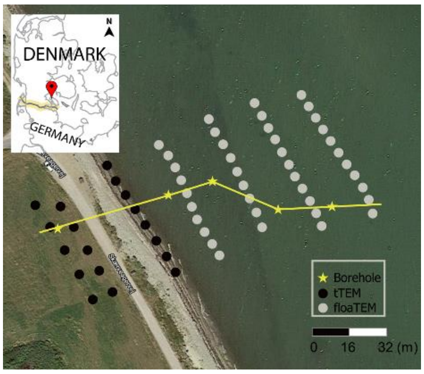

Figure 3. Survey map. The solid yellow line represents a profile along the existing boreholes.

In 1D inversion result (Figure 4-a), what appears to be a 2D pant leg effect, similar to the one seen in the synthetic example inversion. For the 3D result (Figure 4-d), the top resistive till layer (~20 Ωm) is only aligned with the borehole reported sand-clay interface. We further calculate the formation factor of the 1D/3D inversion models within the depth range of the saline-water-saturated sand layer observed in the boreholes. Following Archie's law (Archie, 1942), we find that the 1D result yields a formation factor of 20, whereas the 3D inversion predicts a value of ~4-5. Based on published lab measurements of saline sand formation properties (Frings et al., 2011; Kadhim et al., 2013), we learn that the 3D result gives a more reasonable estimation of the resistivity in the sand layer.

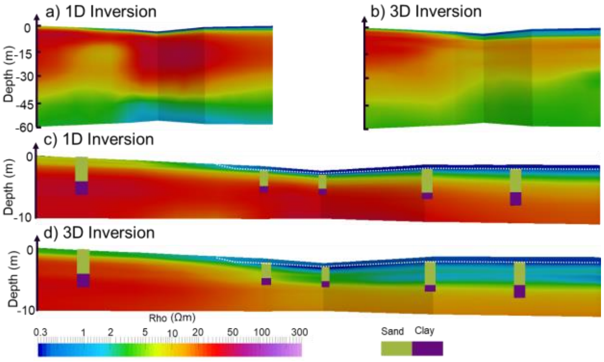

Figure 4. The result from inversions. The white dashed line represents the bathymetry based on measurements at the borehole locations.

CONCLUSIONS

In this study, we investigated the 3D effects present in integrated TEM surveys at coastal sites by applying a previously developed 3D inversion scheme, both with synthetic and field examples. In the synthetic coastal model, we analyzed both forward responses and inversion results using a 1D and a 3D forward code. The forward response difference increases significantly when the soundings are closer to the coastline, which was up to 400% on a sounding basis. As for the inversion, the 1D result did not recover the water depth properly. Furthermore, a clear pant leg effect appeared in the onshore survey area. The 3D inversion, however, reproduced the model fairly accurately with no particular artifacts and a low data misfit. In the inversions of the field data, many results from the synthetic study reappear. Existing borehole data verified that the 3D inversion provided accurate characterization of a particular interface between sand and clay, which was the primary target of the investigation.

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