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To cite this article: Lindsey J. Heagy, Seogi Kang, Rowan Cockett & Douglas W. Oldenburg (2020) Open-source software for simulations and inversions of airborne electromagnetic data, *Exploration Geophysics*, 51:1, 38-44, DOI: [10.1080/08123985.2019.1583538](https://doi.org/10.1080/08123985.2019.1583538)

To link to this article: <https://doi.org/10.1080/08123985.2019.1583538>



Published online: 10 Jun 2019.



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Open-source software for simulations and inversions of airborne electromagnetic data

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ABSTRACT

Inversion of airborne electromagnetic data is often an iterative process, not only requiring that the researcher be able to explore the impact of changing components, such as the choice of regularisation functional or model parameterisation, but also often requiring that forward simulations be run and fields and fluxes visualised in order to build an understanding of the physical processes governing what we observe in the data. In the hope of facilitating this exploration and promoting the reproducibility of geophysical simulations and inversions, we have developed the open-source software package SimPEG. The software has been designed to be modular and extensible, with the goal of allowing researchers to interrogate all of the components and to facilitate the exploration of new inversion strategies. We present an overview of the software in its application to airborne electromagnetics and demonstrate its use for visualising fields and fluxes in a forward simulation, as well as its flexibility in formulating and solving the inverse problem. We invert a line of airborne time-domain electromagnetic data over a conductive vertical plate using a 1D voxel inversion, a 2D voxel inversion and a parametric inversion, where all of the forward modelling is done on a 3D grid. The results in this paper can be reproduced using the provided Jupyter notebooks. The Python software can also be modified to allow users to experiment with parameters and explore the physics of the electromagnetics and intricacies of inversion.

ARTICLE HISTORY

Received 1 October 2018
Accepted 25 January 2019

KEYWORDS

Airborne electromagnetics; electromagnetic geophysics; inversion; programming; 3D modelling

1. Introduction and motivation

Even for a simple model of a conductive vertical plate in a resistive half-space, it can be challenging to unravel the contributions of the diffusing “smoke-ring” currents that intersect the plate and vortex currents induced by the time-varying magnetic flux through the plate to the observed airborne electromagnetic signal. These challenges are exacerbated if the background has a significant structure or if other physical properties, such as magnetic permeability or chargeability, are significant. Dissecting and understanding the physical phenomena that produce the data that we observe in an airborne electromagnetic survey require that we have the ability to simulate Maxwell’s equations and visualise currents and magnetic fields through time or over a range of frequencies for a variety of models, which might be 1D, 2D or 3D in space.

Beyond building a fundamental understanding of the physics governing an airborne electromagnetic response, extracting meaningful geological information from airborne electromagnetic data requires that we have the ability to invert those data. Electromagnetic inversions are nonlinear; thus, the choice of regularisation and selection of tuning parameters can have a significant impact on the recovered model. To progress research into the extraction of more geological or hydrogeological information from airborne data in an

inversion, researchers require the flexibility to experiment with aspects of the inverse problem, including not only regularisation and tuning parameters but also such aspects as the dimensionality of the numerical simulation and the definition of the inversion model (e.g. voxel or a parametric model). Looking forward, we also want the ability to interface to other geophysical methods through joint or cooperative inversions.

The classic model of black-box proprietary software does not promote the collaboration or transparency necessary to achieve these goals. In the hope of facilitating collaboration and easing the overhead for researchers in going from a new idea to an implementation of that idea, we have been developing an open-source framework and software implementation for simulation and parameter estimation in geophysics, SimPEG (Cockett et al., 2015). SimPEG includes finite-volume simulations and inversion routines for a variety of geophysical applications, including potential fields, vadose zone flow, DC resistivity, and electromagnetics. Simulations may be performed on several different mesh types, including cylindrically symmetrical meshes, 3D tensor meshes and OcTree meshes. The fields and fluxes computed everywhere in the simulation domain are readily accessible, so that they can be easily visualised and explored, particularly when used in the interactive Jupyter computing environment (Perez

and Granger, 2015). Such simulations and visualisations have proved valuable in the context of geoscience education (Oldenburg, Heagy, and Kang, 2017) and can be a useful tool for understanding the physical processes that contribute to the data we observe.

Heagy et al. (2017) provide a complete overview of the structure and implementation of electromagnetic simulations and inversion within SimPEG. In brief, SimPEG includes staggered-grid, finite-volume solutions to the quasistatic Maxwell's equations in both the time domain and the frequency domain on cylindrically symmetrical meshes, 3D tensor meshes and OcTree meshes. Variable electric conductivity and magnetic permeability may be considered. Kang and Oldenburg (2016) have recently extended the implementation to account for chargeable material.

We take a deterministic gradient-based approach to the inverse problem and consider a Tikhonov-style inversion, where the inversion minimises an objective function consisting of a data misfit and a regularisation functional. The inversion model is decoupled from the forward simulation mesh, allowing different model parameterisations to be employed. For example, a 2D inversion can be performed for a single line of airborne electromagnetic data while the forward simulation is conducted on a 3D mesh, or, similarly, a parametric model (e.g. a plate in a half-space earth) may be considered. SimPEG has been built in a flexible modular manner, to enable researchers to experiment with components, such as which norm is employed in the regularisation or which mesh is used in the forward simulation.

SimPEG is implemented in Python and is licensed under the permissive MIT license, which allows commercial and academic use and adaptation of the software (<https://simpeg.xyz>); we hope that this maximises the utility of the software itself and creates opportunities for new contributions.

In what follows, we will demonstrate the use of SimPEG for simulations and inversions of airborne electromagnetic data through three examples. In the first example, we will consider an airborne time-domain electromagnetic (TDEM) experiment over a vertical conductive plate, examine the behaviour of the channelled smoke-ring currents and induced vortex currents and discuss how each contribute to the measured data. From there, we will demonstrate a 1D inversion of TDEM data collected over the plate. Our final example will consist of two 2D inversions where the forward simulations are carried out in 3D; the first inversion is for a voxel-based model and the second is for a parametric model. We will conclude with a discussion on extensions of this example, including our vision of how to move forward as we look to address large 3D airborne electromagnetic inversions using the SimPEG framework.

In the examples that follow, we will use a model of a conductive vertical plate in a resistive half-space.

This is a problem of relevance in mineral exploration, brings to light a number of fundamental aspects of electromagnetics, and is a challenging inverse problem, particularly as 1D inversions cannot explain the 3D nature of the model. We will look at the behaviour of currents through time, demonstrate the multidimensional nature of the electromagnetic responses and then conduct 1D and 2D inversions of synthetic airborne TDEM data over the plate. The examples have purposefully been kept computationally lightweight so that they can be run in a moderate amount of time on a modern laptop. The source code for each of these examples is available as a Jupyter notebook at <https://github.com/simpeg-research/heagy-2018-AEM> (Heagy et al., 2018).

1.1. Airborne TDEM response over a conductive plate

The model and simulation mesh we consider is shown in Figure 1. A 100 m thick conductive plate (0.1 S/m) is embedded 50 m below the surface. The plate is 400 m tall and extends 850 m along the x -axis. The background conductivity is 10^{-3} S/m. One line of airborne TDEM data is computed along $y=0$ m; the source waveform is a step-off waveform, and vertical db/dt data are collected at 21 time channels between 0.05 and 2.5 ms. The simulation is performed in 3D on a tensor mesh.

The synthetic data generated in this simulation are shown in Figure 2; each profile line indicates db_z/dt at a given time channel. At early times, we see a single peak anomaly over the plate; as time progresses, a double-peak character emerges. To understand the responses, we plot the currents in the subsurface through time in Figure 3 and the magnetic flux density in Figure 4. The transmitter location is shown by the green dot.

Immediately after the source current has been shut off, smoke-ring currents are induced in the earth. These horizontal circular currents produce a magnetic field similar to that of a vertical magnetic dipole, as seen in Figure 4(a). When we are directly over the plate, which is 100 m wide, the greater conductivity of the plate results in larger currents and thus a larger magnetic field. This is what gives us the single peak at early times in Figure 2. The conductivity and thickness of the plate will control the time constant of the decay of these horizontal circular currents.

At larger offsets, the plate still contributes to a larger signal as the smoke-ring currents are channelled into the plate, as can be seen at $t=0.01$ ms and $t=0.1$ ms in Figure 3. The excessive currents are more like an electric dipole along the top of the plate, and this gives a magnetic field that is also pointing up at the receiver location; the resultant magnetic field can be seen in Figure 4(b), where the rotational magnetic fields at

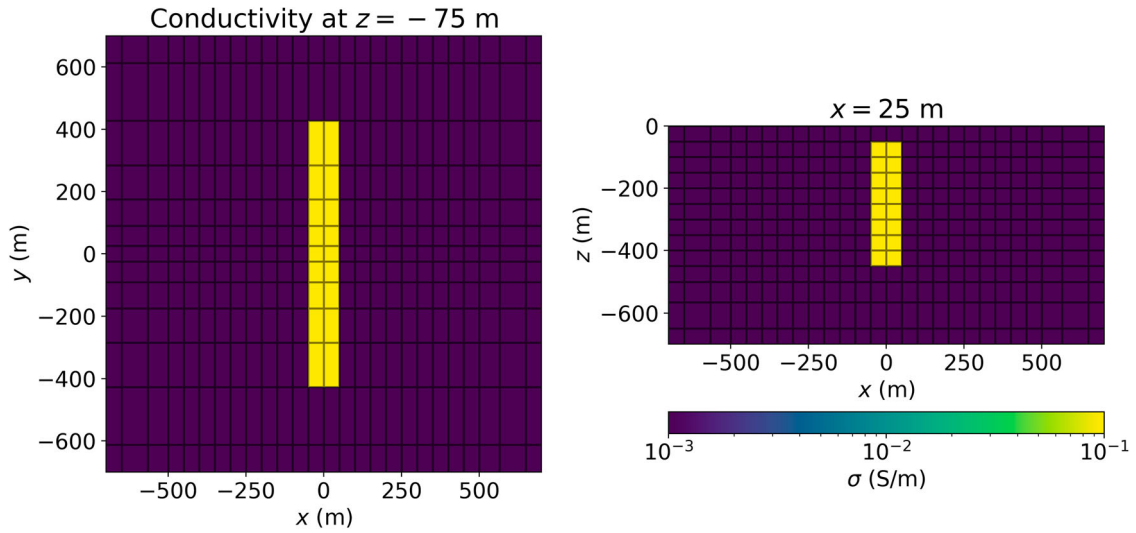


Figure 1. Depth slice (left) and cross-section (right) through model of conductive plate (0.1 S/m) in resistive half-space (10^{-3} S/m).

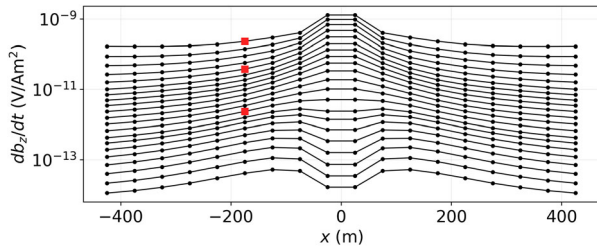


Figure 2. Vertical db/dt data over the conductive plate. The red dots correspond to the times and source locations shown in Figure 3.

the top of the plate are generated by the channelled currents.

At intermediate times (0.1 ms), the background field has set up strong vortex currents within the plate. By the time the vortex currents are fully engaged, the galvanic currents are decaying, so at later times (0.5 ms) the vortex currents dominate. The vortex currents effectively generate a horizontal magnetic dipole, which has a positive vertical field at the receiver, as can be seen in Figure 4(c). It is this horizontal-dipole contribution that leads to the double peak observed in the late-time data in Figure 2.

1.2. Stitched 1D inversion of airborne electromagnetic data

When inverting airborne electromagnetic data, 1D inversions are commonplace. They have the benefit that each sounding is a relatively inexpensive computation and that the inversion can be readily parallelised over soundings. A basic 1D inversion will treat each sounding independently; more advanced 1D inversions may include lateral or spatial constraints in the regularisation to promote smooth variation in the model between stations (Viezzoli et al., 2008; Viezzoli, Auken, and Munday, 2009). For this example, we adopt the

basic approach, inverting and regularising each sounding independently. The extension to laterally or spatially constrained regularisation can be considered within the SimPEG framework.

For each of the 1D inversions, the forward simulation is conducted on a cylindrically symmetrical mesh. We perform a Tikhonov-style inversion (Tikhonov and Arsenin, 1977), which states the inverse problem as an optimisation problem in which we minimise an objective function composed of a data misfit term, ϕ_d , and a regularisation functional, ϕ_m .

$$\begin{aligned} \underset{\mathbf{m}}{\text{minimise}} \quad & \phi(\mathbf{m}) = \phi_d(\mathbf{m}) + \beta\phi_m(\mathbf{m}) \\ \text{such that} \quad & \phi_d \leq \phi_d^* \end{aligned} \quad (1)$$

The parameter \mathbf{m} denotes the inversion model, which is the set of parameters sought in the inversion; β is a trade-off parameter, which weights the relative contribution of the data misfit and the regularisation in the inversion. The mathematical description of the data misfit and regularisation follow a standard ℓ_2 formulation and are described in Cockett et al. (2015).

For the 1D inversions, the data were assigned 5% uncertainties and no noise floor was used. The trade-off parameter, β , was set at a fixed value of 20. The starting and reference model were set to be equal to the background conductivity of 10^{-3} S/m. The inversions were terminated either when the target misfit was reached or when 10 iterations were completed.

The recovered model and associated predicted data are shown in Figure 5. Most of the soundings terminate at the maximum number of iterations without reaching the target misfit. The recovered conductivity model is typical of 2D effects in a 1D inversion: a resistor is imaged beneath conductive ‘‘pant-legs’’, which are centred above the vertical conductor. The 1D assumption is inadequate for imaging the 3D structure, as the horizontal-dipole behaviour observed in Figure 4(c)

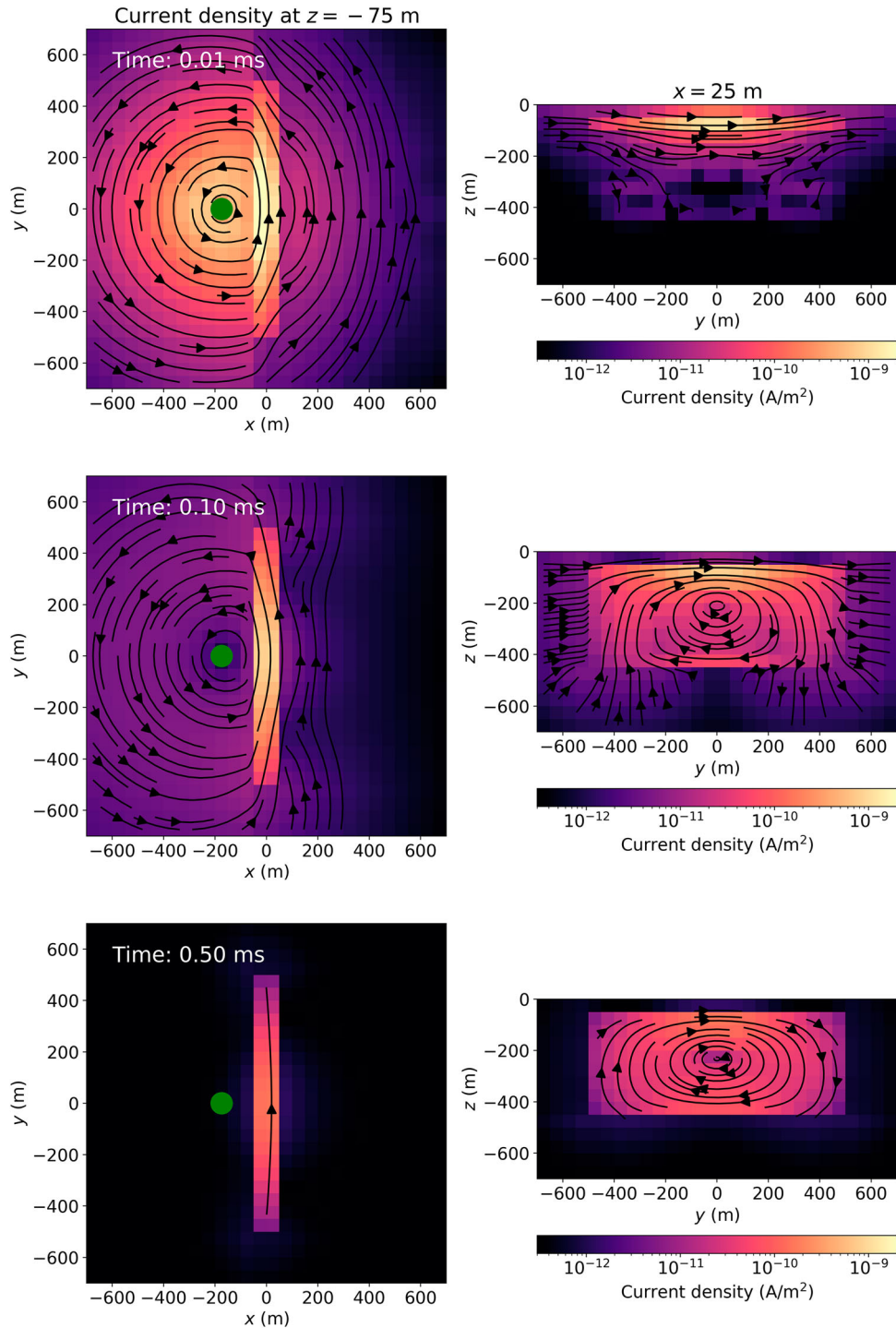


Figure 3. Depth slices (left) and cross-sections (right) showing the current density in the subsurface at 0.01 ms, 0.1 ms and 0.5 ms after shut-off. The source location is shown by the green dot.

cannot be explained by a 1D conductivity structure. In the next section, we will increase the dimensionality of the inversion and examine two approaches for a 2D inversion of these data.

1.3. 2D inversions of airborne electromagnetic data

In both of the following inversions, the forward modelling is conducted on a 3D tensor mesh, while the inversion model we consider is 2D. To populate the 3D

space with physical properties, the 2D slice is simply surjected along the y -axis; within SimPEG, this is handled by the Maps class. Kang et al. (2015) further discusses the Maps class and how it appropriately modifies the sensitivity.

The first approach we take to invert the data is a conventional voxel-based inversion. The data are assigned 5% uncertainties and a noise floor of 10^{-14} V/Am². A Tikhonov regularisation is used and a beta-cooling schedule, which reduces the value of the trade-off parameter, β , by a factor of five every three iterations

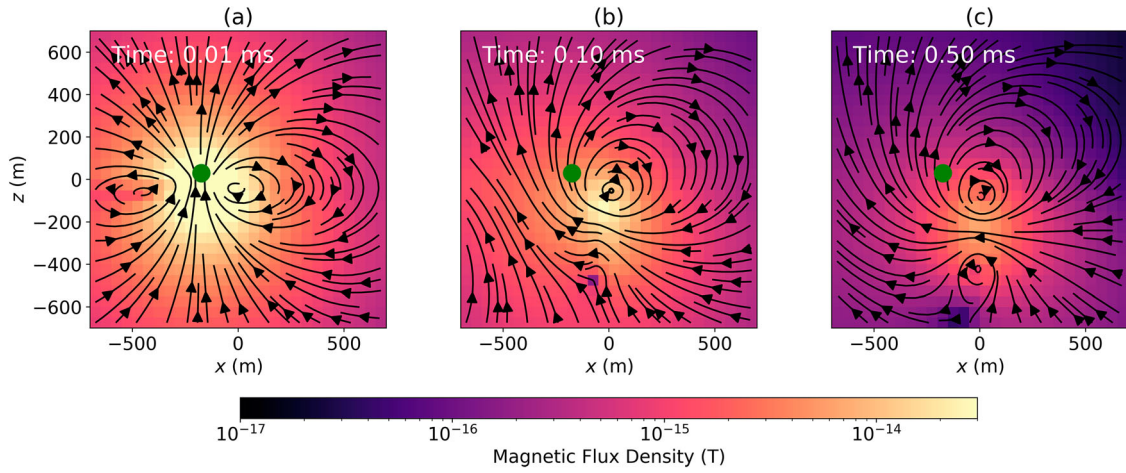


Figure 4. Magnetic flux density along the $y = 0$ m cross-section. The location of the source and receiver is shown by the green dot.

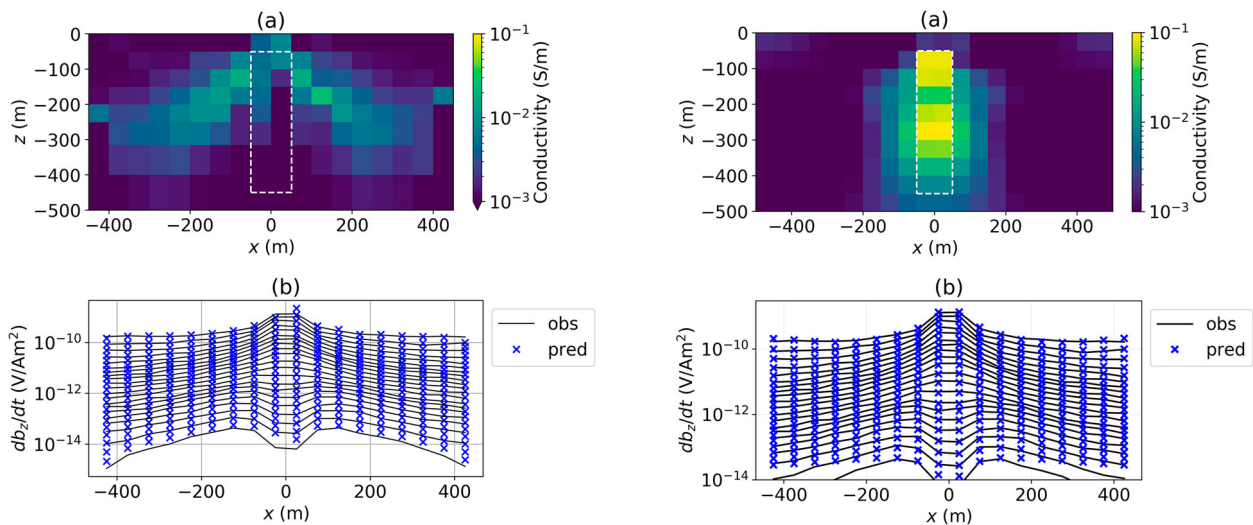


Figure 5. (top) Inverted 1D conductivity. (bottom) Predicted and observed data.

is employed. The starting model is a half-space of 10^{-3} S/m. The inversion is run for 20 iterations and reaches a root-mean-square misfit of 1.8. This is a reasonably good misfit, considering that we are fitting a 3D plate with a 2D model. The observed and predicted data are shown in Figure 6(b). We note how much better fit the two-peak portion of the data are, compared with the fit obtained in 1D. The recovered model is shown in Figure 6. As is typical of smooth inversions, we recover a diffuse conductive feature. This arises because we are penalising gradients and using a fairly coarse mesh. By changing the norm used in the regularisation, which can easily be done in SimPEG, sharper, more localised, models can be obtained. Notwithstanding this, we note that the maximum amplitude of the recovered conductivity model closely reflects the true amplitude of the plate, and the horizontal location of the plate agrees well with the true model.

An alternative approach to the inverse problem is to consider a parametric inversion. There are a number of motivations for doing this. First, we see from

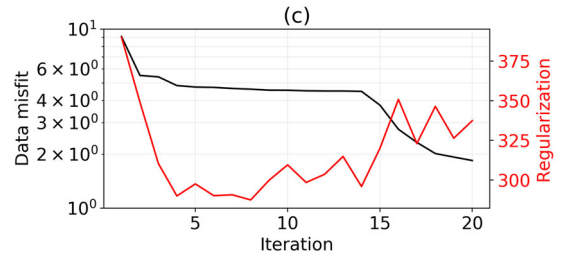


Figure 6. (a) Recovered conductivity model from the 2D time-domain electromagnetic inversion. (b) Observed and predicted data. (c) Data misfit and regularisation over the course of the inversion.

the data misfit curve in Figure 6(c) that this is been a challenging problem for the voxel inversion; between iterations 5 and 14, little progress is made in reducing the misfit. This may be related to some of the challenges observed by McMillan et al. (2015), where the circular nature of the sensitivity of an airborne electromagnetic survey tends to promote “ringing” artefacts in the inversion. The authors overcame this problem by introducing a parametric inversion. Another motivating factor for working in a parametric domain is that it may conform with a-priori knowledge about the earth.

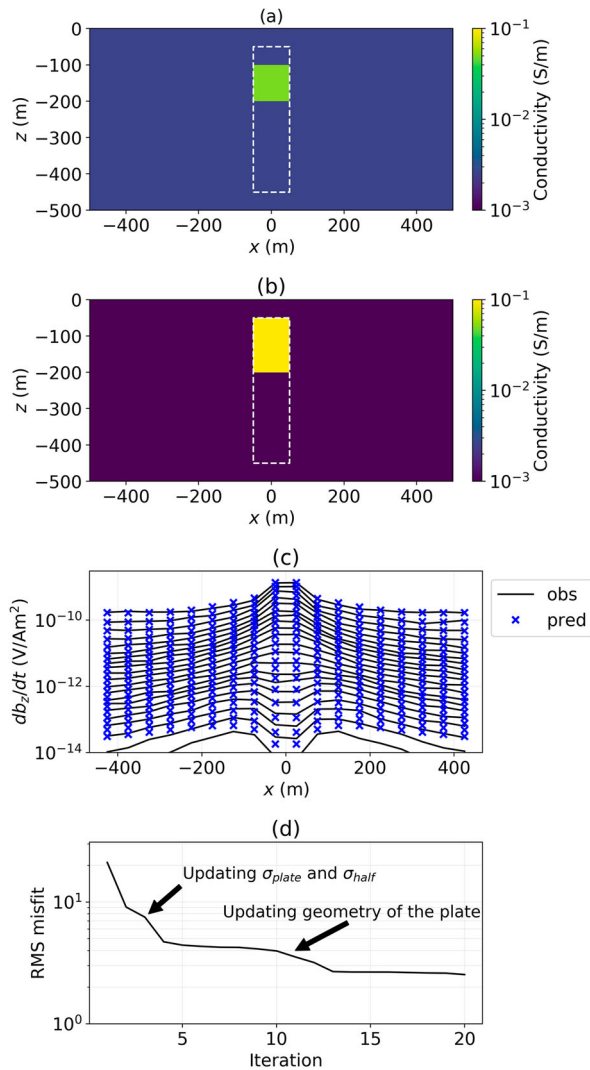


Figure 7. (a) Starting model for parametric inversion. (b) Conductivity model recovered in a parametric inversion for a 2D plate. (c) Resultant predicted and observed data. (d) Data root-mean-square misfit over the course of the inversion.

For these reasons, we now consider a parametric approach to the inverse problem. This, too, can be straightforwardly implemented in SimPEG. We describe the inversion model with six parameters: the conductivity of the background, the conductivity of the plate, the x and z locations of the centre of the plate and its width in the x and z dimensions. The same data uncertainties as in the previous inversion are applied. No regularisation is included, and the starting model used for the inversion is shown in Figure 7; the background conductivity is 5×10^{-3} S/m and the conductivity of the plate is 0.05 S/m. It is important to seed the parametric inversion with different background and plate conductivities; if the same conductivity is used for both, ambiguity is introduced, as the geometric parameters have no influence on the observed data if there is no conductivity contrast. The inversion is run for 20 iterations and the resultant model and data fit are shown in Figure 7. The root-mean-square misfit of this inversion is 2.5.

The inversion accurately recovers the conductivities of the background and plate, the width of the plate and the location of the top of the plate. The depth extent is not resolved; we lose sensitivity with depth and, again, the late-time data are poorly fit. This indicates that more progress might be made if we consider a 3D inversion. It is also interesting to examine the nature of the data misfit as a function of iteration and explore which parameters are updated at each iteration. In the first few iterations, the inversion updates the conductivity of the background and the plate. Once it has made sufficient progress on these parameters, it then proceeds to update the geometric properties. The order and magnitude of the updates at each step provide some indication of the sensitivity of the inversion to each parameter; this can be useful in a feasibility study to assess how well we might expect the inversion to resolve a geological feature of interest. A similar root-mean-square misfit is reached in both inversions, and the data are fitted quite well, with the exception of the last two time channels. This is likely due to the 3D nature of the target. Further improvements to the data fit could be explored with 3D voxel or parametric inversions within the SimPEG framework.

2. Outlook

Using an example of a conductive, vertical plate in a resistive half-space, we demonstrated the use of SimPEG for (a) building up an understanding of the observed data by visualising the behaviour of electromagnetic fields and fluxes and (b) exploring approaches for the challenging inverse problem for a compact conductive target in airborne electromagnetic data. The scripts used to generate the figures shown in this abstract are freely available so that they can be reproduced and further explored. In developing SimPEG as an open-source project, we aim to create opportunities for collaboration and the integration of expertise from a diverse group of researchers. As we move forward with the electromagnetics module, we plan to scale to larger 3D inversion by implementing domain decomposition similar to that provided by Yang, Oldenburg, and Haber (2014). Owing to the modular nature of SimPEG, this extension will be applicable for tensor, Octree and cylindrical meshes. We welcome new contributions and hope that these efforts promote greater reproducibility and transparency in geophysical simulations and inversions.

Acknowledgments

The authors thank the SimPEG community, including Dom Fournier, Gudni Rosenkjaer, Thibaut Astic, Michael Mitchell, Joseph Capriotti and David Marchant for their contributions, which have improved the quality of the software and extended its capabilities. Thanks also to Dr Eldad Haber for his guidance and instruction on finite-volume techniques and

the implementation of the electromagnetic problem. We are grateful to Dr Niels Christensen and the two anonymous reviewers for their constructive feedback on the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

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