Utilisation of stochastic MT inversion results to constrain gravity inversion

Introduction

The integration of geophysical techniques through joint or cooperative geophysical modelling has been gaining traction in recent years. The idea is not new and a number of techniques exploiting the complementarities between diverse datasets through joint inversion have been developed over the past two decades (see for instance Lelièvre and Farquharson (2016), Moorcamp et al. (2016) and references therein). One of the most widely used approach to joint geophysical modelling is to encourage structural similarity between the physical properties the different geophysical datasets modelled are sensitive to (Haber and Oldenburg, 1997, Gallardo and Meju, 2003). Another possibility is to constrain the statistics of the recovered model so that it resembles the petrophysical measurements’ (e.g., Lelièvre et al., 2012, Sun and Li, 2015, Giraud et al., 2017). While these approaches effectively exploit the complementarities between different geophysical datasets, running simultaneous joint inversions may be challenging computationally and often require expert knowledge.

In this abstract, we propose an alternative approach to joint inversion based on a cooperative strategy that does to rely on the constraints mentioned above. We develop a methodology leveraging separate domain, standalone inversions by taking advantage of the strengths of the different geophysical techniques used. Here, we pass information from one domain to another, making conservative assumptions about the structural and petrophysical correlations between the domains. The workflow we develop is applied to the inversion of gravity data and magnetotelluric (MT) data to better constrain the thickness of the sedimentary cover and potentially deeper structures. We exploit the complementarity between MT, which is mostly sensitive to vertical resistivity variations, and gravity data, which is sensitive to lateral property variations. Here, we perform 1D probabilistic inversion of MT data (Seillé and Visser, 2020) to several sites and use apply a Bayesian ensemble fusion method (Visser 2019) a posteriori to derive constraints on the distribution of different geological units within the subsurface. From these results, we first estimate the probability of occurrence of the different rock units. We then divide the studied area into domains where different rock units can be observed by application of a Boolean filter on the probabilities. Finally, we use these domains to define ranges of potential density values for gravity inversion using multiple-bound interval constraints (Ogarko et al. 2021) as implemented in the Tomofast-x open-source code (Giraud et al. 2021). This final stage of the workflow (Figure 1) discriminates between the different lithologies allowed by probabilistic 1D MT inversions.

In what follows, we present the proof-of-concept of the proposed joint modelling technique using a realistic synthetic dataset derived from a geological model of the Mansfield area (Victoria, Australia).

Methodology

Workflow

We perform a three-step workflow as indicated in Figure 1. The probabilistic 1D MT inversions are performed first (step 1), the 1D ensembles are fused together and the probabilities of occurrence \( \psi_{k=1,..,N} \in [0,1] \) of the \( N \) rock units modelled are calculated across the studied area, given the resistivities found in the area. The subsurface is then divided into domains, by application of a Boolean filter on the probabilities. Calculating \( [\psi_{k=1,..,N}] = \text{sign}(\psi_{k=1,..,N}) \) for each model cell of the subsurface determines which rock unit is allowed by MT, and which is not, thereby subdividing the mode area into domains with a specific combination of possible rock units (step 2). These domains are used to define multiple disjoint intervals bound constraints that are applied during gravity inversion. Such constraints, which can be assimilated to categorical clustering, restrict density values in the recovered model to the range corresponding to the rock units derived from the analysis of the MT ensembles found out to have \( \psi_{k=1,..,N} > 0 \).
Inversion algorithms

The 1D MT inversions are performed for each MT site separately using a 1D trans-dimensional Markov chain Monte Carlo sampler (Seillé and Visser, 2020), which has been designed to be robust to non-1D effects present in the data.

Gravity inversion is performed using the algorithm of Ogarko et al. (2021) as implemented in Tomofast-x (Giraud et al., 2021), which enforces multiple spatially varying, disjoint interval bounds. That is, density values are allowed to vary only within the intervals defined by rock units assumed to be present in the different parts of the model. Note that in such case, the intervals can be overlapping or disjoint.

Proof-of-concept

Survey setup and objectives

In our investigations, we generate realistic synthetic data using a 3D geological structural framework of the Mansfield area (Victoria, Australia) (Pakyuz-Charrer 2018), using the synthetic density model of Giraud et al. (2018). In this study, we focus on a 2D profile crossing this 3D model in its middle at the same geographic location as Giraud et al. (2017). The ModEM 3D MT forward modelling code (Kelbert et. al., 2014) was used to simulate MT responses at 16 locations along the profile (see resistivity values shown in Figure 2a). The frequency range spans from 10 KHz to 0.01 Hz, with 6 frequencies per decades; 5% magnitude Gaussian noise was added to the data before running the 1D inversions. For gravity, we model the Bouguer anomaly using one measurement point per cell at surface level to simulate a ground survey. Gravity data is generated along a 2D profile for the densities shown in Figure 2a. The design of this study highlights how this cooperative workflow has the potential to be beneficial to imaging and to mitigate some of the inherent limitations of each methodology. In our example, an ambiguity exists in terms of resistivity between the basement and the intrusion: these two units are highly resistive and this weak contrast in resistivity makes it hard to detect using MT. On the other hand these two formations present different densities. Then, the parts of the model where most geological units are nearly horizontal (left-hand side of model) are known to be particularly challenging for gravity inversion and can benefit from the constraints derived from the domaining of the MT data.

The 1D MT probabilistic inversions constitute ensembles of 1D models for each site, each model satisfying the data within its uncertainty. The distribution of resistivities across all 1D ensembles is used to derive resistivity intervals corresponding to different rock units. Given these intervals and prior assumptions on spatial lateral continuity, we fuse the 1D ensembles along the 2D line and estimate the probability of occurrence of the different rock units (part 1 of workflow in Figure 1) along the gravity profile. The MT results are thus used to define domain where specific rock units have a non-null probability of occurrence (step 1 of the workflow in Figure 1) as shown in Figure 2b.

Inversion results
In Figure 2c and 2d we compare the results of gravity inversion without and with the utilisation of domains derived from probabilistic MT inversions, respectively. Overall, the sediments are much better recovered and the imaging of the basement is improved when MT domaining is used to constrain gravity inversion.

Visual inspection of Figure 2b and 2d reveals that the footprint of the domains from MT is visible on the left-hand side of the recovered densities, which is expected given the poor resolution of the gravity for this type of horizontal structures and the good definition of the domains from MT. On the other hand, on the right hand side of the model, where more ambiguity/uncertainty is present in the MT models (represented by a domain allowing all types of lithologies) the constrained gravity inversion is more similar to the unconstrained inversion. We note that the data misfit for gravity inversion is similar in the two cases shown here.

![Figure 1](image.png)

**Figure 1** 2D line of interest: true model (a), domains derived from MT modelling (b), gravity inversion without MT information (c) and gravity inversion with MT information (d).

Our results reveal that gravity inversion constrained in this fashion provides models that present a lower model misfit and are geologically closer to the causative model than without MT-derived prior information. This is particularly true in areas poorly constrained by gravity data such as the basement. Importantly, in this example, the basement is better imaged by the combination of both gravity and MT data than by the separate techniques. The same applies, to a lesser extent, to dipping geological structures closer to surface. In the case of the Mansfield area, the synthetic modelling investigation we performed shows the potential of the workflow introduced here. We conclude that it can be confidently applied to real world data. Compared to a joint inversion approach, based on either structural or petrophysical relationships, this approach does not apply hard constraints on the gravity inversion and similarity with a particular model from another method is not required. This has the advantage that a subjective weighting of one methodology over the other is not needed. Moreover, this workflow being relatively flexible, and the assumptions made during the Bayesian ensemble fusion to derive the domains can be adjusted if knowledge about geology or petrophysics is available, without having to re-run the MT inversions. Furthermore, the benefits of the presented workflow come at no additional computational cost compared to running the separate MT and gravity inversions completely independently.
Conclusion and discussion

We have introduced a workflow for the integration of MT inversion with gravity data by passing information between domains. This approach leverages the complementarities between the two methods in terms of sensitivity of the respective methods to physical parameters. While the usage of separately run inversion remains simple, it is capable of reducing interpretation ambiguity without incurring additional computational cost. As we have demonstrated in this proof-of-concept study, the proposed multi-physics integration workflow holds the potential to improve undercover imaging. The application to field data is the subject of ongoing investigations. Future work includes the development of a way to ensure that the structural model recovered by gravity inversion does not violate the observed MT data.

Acknowledgements

JG, ML and MJ are supported, by Loop – Enabling Stochastic 3D Geological Modelling (LP170100985) and the Mineral Exploration Cooperative Research Centre whose activities are funded by the Australian Government's Cooperative Research Centre Program. This is MinEx CRC Document 2020/18. ML is supported by ARC DECRA DE190100431. HS and GV are supported by the CSIRO Deep Earth Imaging Future Science Platform. We acknowledge the developers of ModEM for making it available.

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