Magnetotelluric modelling: towards a 4-D inversion

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SUMMARY

Recent work has shown the utility of magnetotellurics (MT) in monitoring dynamic processes, however current MT inversion schemes are not optimised for time-variant resistivity models. In this study we investigate if we can improve inversion results by introducing a time axis into the model space, creating time-lapse (4-D) models. We outline an inversion methodology which is altered from the existing Occam inversion to accommodate temporal changes. Our inversion incorporates only one spatial dimension, however the method is extensible to 2-D and 3-D spatial models. We assess the effectiveness of our method compared to existing time-invariant inversion by comparing inversions of synthetic MT data with the two techniques. Motivated by methods in other geoelectrical techniques, we also compare regularisation schemes and assess their suitability for use with MT data. Based on the results of the study, our work aims to help establish an inversion scheme for MT monitoring data.

Key words: magnetotellurics, monitoring, inversion, time-lapse

INTRODUCTION

Monitoring of dynamic hydrological processes is a growing application of the magnetotelluric method (MT), with case studies presented for diverse projects such as coal-seam gas extraction, hydraulic fracturing in shale gas plays (Rees et al., 2016) and hydraulic fracturing of geothermal prospects (Peacock et al., 2013). Most modelling tools for MT cannot incorporate the dynamic nature of these projects, and it has therefore been difficult to extract as much information as possible from the data. This work aims to provide a new tool for modelling dynamic systems.

Previous work on time-lapse MT data has been undertaken by Carbajal et al. (2012), which showed that improved modelling results could be obtained by modelling the systematic error in the time-lapse data and removing it from all datasets. The same work also showed that stochastic regularisation could be used in discrete inversions of time steps to improve the accuracy of the model update. Further work by Carbajal et al. (2015) investigated using probabilistic inversion for modelling time-lapse MT data, which can allow the modeller to impose further hydrological constraints.

This project aims to implement some of the techniques use in time-lapse modelling of other geophysical techniques, particularly the work of Kim et al. (2009), which incorporates a time axis into inversion. This allows the modeller to impose constraints on the time-continuity of the resistivity model and obtain as much information from the model as possible. This work will assess the suitability of time constrained inversion to dynamic MT modelling by testing it against synthetic datasets. The impact of different regularisation methods will also be investigated.

METHOD AND RESULTS

The inversion of MT data is a non-unique problem, with many models (**m**) fitting the data equally well. The Occam inversion (Constable et al) addresses this problem by penalising models for roughness (R), a measure of spatial variability. Roughness can be defined as the sum of the squares of either the first or second derivative of the model parameters in space. An objective function (U) is constructed from the roughness, model misfit (X) and desired misfit (X*) such that

$$U = R + \mu^{-1} (X - X^*),$$

where μ is a Lagrange multiplier. The objective function is minimised when the gradient of U with respect to **m** is zero. When the optimal value of μ is found then this leads to the smoothest possible model at the desired misfit X*.

This concept can be extended to models with a time-dimension by adding an additional roughness term. This regularisation can either be applied to penalise changes in resistivity through time, or to enforce the spatial smoothness of the changes themselves, as in Kim et al (2009). The weightings of time smoothness can incorporate *a priori* data, for example to allow large temporal changes at the start of a pump test.

A simple 1-D test scenario, shown in Figure 1, is constructed to assess the ability of different regularisation schemes in the inversion of time-lapse MT data. The scenario simulates a fluid injection, where a layer is continually injected with conductive fluid which then diffuses into adjacent layers. The MT response is calculated at each time step and then 5% Gaussian noise is applied to the resultant MT impedance data.

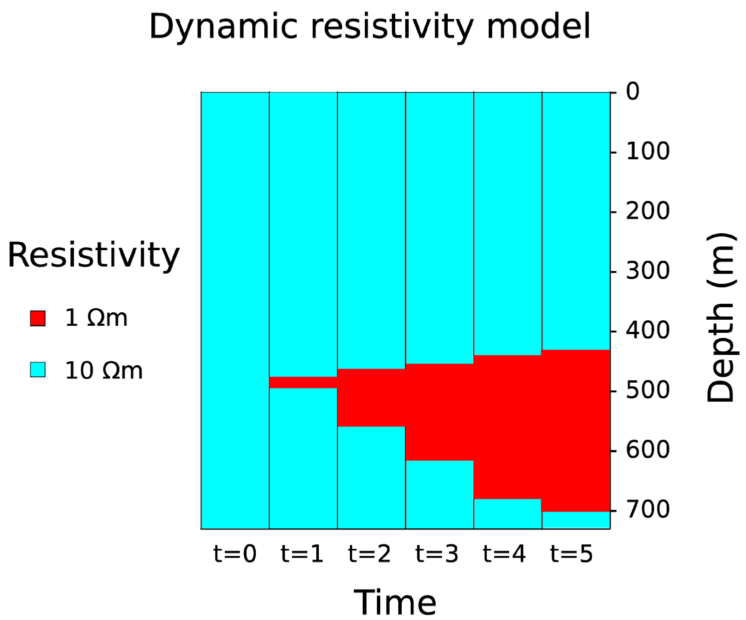

Figure 1: Resistivity model used to generate synthetic data.

The data is then inverted in a modified Occam's inversion program with the following inversion schemes:

1. Discrete 1-D inversion with spatial regularisation, models penalised by their distance from previous time steps
2. Time-lapse inversion with regularisation in both spatial and temporal domains
3. Time-lapse inversion with regularisation in spatial and temporal domains, and also the spatial distribution of the changes between time slices.

It is anticipated that the inversion accuracy of these three schemes will determine the value in using 4-D inversion for MT data.

CONCLUSIONS

Magnetotellurics has the potential to be a useful tool in the monitoring of dynamic processes, however new inversion methodologies are required in order to best extract information from 4-D MT data. This work looks towards incorporating strategies from other geoelectrical methods, and proposes adding a time-axis to the inversion model space. The effectiveness of this method is compared to existing inversion techniques through synthetic testing. Different regularisation schemes are also considered. The aim of this work is to compare the results of the inversion methods and to determine the value in using 4-D inversion for MT data.

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