Improving Uncertainty Estimation in Geophysical Inversion Modelling

A dissertation presented
by
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I can live with doubt, and uncertainty, and not knowing. I think it's much more interesting to live not knowing than to have answers which might be wrong. I have approximate answers, and possible beliefs, and different degrees of certainty about different things, but I'm not absolutely sure of anything.

– Richard P. Feynman

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ABSTRACT

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Numerical inversion modelling is an integral part of geophysical data interpretation. Growing computational resources are used to invert ever-growing data sets and higher dimensional data. However, models without meaningful uncertainty estimates are difficult to interpret reliably and limited attention has been paid to the advancement of model quality estimation techniques to keep up with the more sophisticated inversion schemes. The employment of meaningful uncertainty estimation methods is often hindered by the complicated implementation of those methods, and inadequate model quality estimators are frequently used. This project was aimed at the advancement of model uncertainty estimation, to enable a more common use.

Two different approaches were developed, approaching the problem from different directions:

Firstly, a bootstrap resampling approach for the qualitative estimation of model uncertainties is presented. The algorithm is characterised by an easy implementation and the fact that it can provide model quality estimation capabilities to existing inversion algorithms without requiring access to the inversion algorithm's source code. A given data set is repeatedly resampled to create multiple realisations of the data set. Each realisation is individually inverted and the variations between the generated models are analysed and visualised to generate interpretable uncertainty maps. The capabilities of the approach are demonstrated using the example of synthetic and real 2-D magnetotellurics data.

Secondly, the multi-objective joint optimisation algorithm MOJO is presented, which aims to remedy the common shortcomings of classical joint inversion approaches. Joint inversion modelling is a powerful tool to improve model results and reduce the effects of data noise and solution non-uniqueness. Nevertheless, the classic joint inversion approaches have a variety of shortcomings, such as a dependency on the choice of data weights, optimising only a single solution resulting in inadequate uncertainty estimates, and the risk of model artefacts being introduced by the accidental joint inversion of incompatible data. MOJO is based on the concept of Pareto-optimality and treats each data set as a separate objective, avoiding data-weighting. The algorithm generates solution ensembles, which are statistically analysed to provide model uncertainty estimates. The shapes and evolutions of the solutions ensemble's distribution in objective space is dependent on the level of compatibility between the data set. The solution distributions are compared against a theoretical solution distribution corresponding to perfectly compatible data to estimate the compatibility state of any given objective-pair, allowing to distinguish between compatible and incompatible data, as well as identify data sets that are neither mutually exclusive nor sensitive to common features. MOJO's effectiveness was demonstrated in extensive feasibility studies on synthetic data as well as real data. The algorithm is adaptive and can be expanded to incorporate a variety of different data types.

Additionally, ways were explored to make the communication of the modelling results and the model quality estimates as clear and concise as possible, to allow the user to make an informed decision and avoid misinterpretations.

Thesis Supervisors: Prof. Dr. Graham Heinson, Dr. Stephan Thiel

STATEMENT OF ORIGINALITY

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