ModEM: developing 3D EM inversion for the masses

Gary Egbert[1], Anna Kelbert[1] and Naser Meqbel[2]
[1]College of Earth, Oceanic, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA
[2]GFZ German Research Centre for Geosciences, Potsdam, Germany

SUMMARY

ModEM is a prototype modular system for inversion of EM geophysical data, which has been developed over the past years at Oregon State University, and applied to 2D and 3D magnetotellurics (MT), global induction studies, and in test applications, to controlled source EM problems. For several years ModEM has been made available to collaborators at other institutions, in some cases leading to extension and refinements to the code. More recently we have provided the 3D MT inversion code on an "as is, users beware" basis, and are now in the early stages of an NSF funded project to extend, "harden", maintain and more fully support broad use of ModEM. Our primary initial focus is on support of the 3D MT capabilities, although we also are working to build on the more general capabilities of ModEM to support inversion of CSEM data, and joint inversion of multiple EM (and ultimately other) data types. In addition to development and maintenance of software, we will offer training in 3D MT inversion, and maintain a web presence where the community of ModEM users can discuss with us and each other problems and solutions as they arise, and develop and provide short courses on 3D MT inversion and interpretation.

Keywords: inversion, electromagnetic geophysics, magnetotellurics, software, CSEM

INTRODUCTION

Interpretation of MT (and other EM) data underwent a revolution in the late 1980's, when computer codes for two-dimensional (2-D) inversion first became widely available. Over the next decade or so the EM induction community learned how to use these new tools and to make scientifically defensible interpretations of MT profile data in quasi-2-D. The impact of MT as a tool for addressing broader Earth science questions was greatly enhanced by the widespread adoption by the EM community of 2-D data acquisition and interpretation methods). We now sit on the verge of a potentially more profound revolution, with the transition to larger and denser datasets and fully 3-D inversion and interpretation. The revolution is being driven by development of cheaper (and easier to use) digital instruments, improved data acquisition strategies and increasingly powerful computers that have finally made 3-D inversion and interpretation practical. Here we address another key component of the "3-D EM revolution": supporting and further developing the software, and the community expertise in using this software, that will make 3-D inversion and interpretation truly routine.

"ModEM" is a prototype modular system for inversion of EM geophysical data, developed over the past few years at Oregon State University (Egbert and Kelbert, 2012; Egbert et al., 2013). ModEM was initially developed for, and applied to 2-D and 3-D MT, but we have also adapted the system for global induction studies (with a spherical forward code), and have done initial work on developing CSEM capabilities. Over the past several years we have made the code available to collaborators, who are in some instances developing extensions and refinements to ModEM. More recently, we have offered the code for free use on an "as is, users beware" basis for non-commercial applications. We are now in the early stages of project to extend, "harden", maintain and support use of ModEM by a broader community of Earth science researchers. Our primary initial focus in this project is on support of the 3-D MT capabilities, although we are also continuing to build on the more general possibilities for ModEM to support inversion of CSEM data, and joint inversion of multiple EM (and ultimately other) data types. In addition to development and maintenance of software, we have plans to develop and offer training in 3-D MT inversion, and to maintain a web presence where the community of ModEM users can discuss problems and solutions.

ModEM

The mathematical development of Egbert and Kelbert (2012) provides the framework for implementation of ModEM as a general modular system for inversion of frequency-domain EM data. ModEM is written in Fortran 95 following an object oriented programming philosophy, and consists of interchangeable modules which in principal can support different inversion algorithms, forward modelling codes, data functionals, model parameterization and regularization, etc., to allow relatively painless implementation of applications for inversion of a broad range of EM geophysical data types. A coarse-grained parallelization (over forward/adjoint problems, using MPI) has been incorporated following the approach described by Meqbel (2009). The parallelization is essentially independent of the specifics of the forward solver, and to some degree the inversion search algorithm. A schematic overview of key system components is given in Figure 1.

ModEM is loosely partitioned into three layers: Numerical Discretization, which is specific to a numerical implementation of the forward problem; (parallel) Generic Inversion, which is applicable to most inverse problems; and the Interface layer which defines data functionals, and forward problem details (e.g., number and type of sources) and hides problem and implementation specific details from the general inversion modules.

Uyeshima and Schultz (2000). The NLCG algorithm, in turn, can be replaced by alternative optimization schemes — e.g., the data space conjugate gradients (DCG) algorithm of Siripunvaraporn and Egbert (2007) and the hybrid DCG/Occam scheme of Egbert (2012) have been implemented (but not fully tested on real problems) as alternative inversion modules, built using identical sensitivity components. We have also developed a simple CSEM inversion (Vachieratenchai et al., 2011), by modifying solver and data functional modules in the interface layer, to allow for differences in sources (which for CSEM require a secondary field formulation) and receivers (direct observation of field components, instead of transfer functions). Novel observational configurations or data types can be readily accommodated through modifications to the data functional module. For example, inter-station transfer functions and phase tensor data types have recently been added. A range of model parameterization and regularizations can be realized

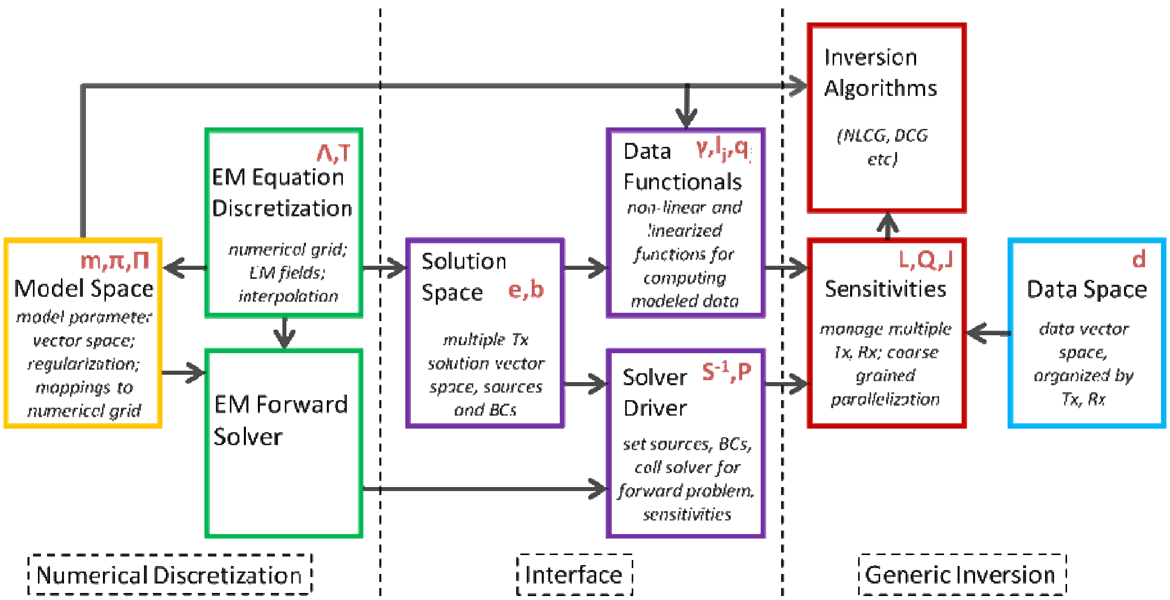

Figure 1: Schematic overview of the Modular Electromagnetic Inversion (ModEM) system. Boxes represent modules (or groups of modules, in actual implementation), with dependencies defined by arrows. Tx, Rx denote transmitter and receiver, respectively. The red letters indicate the functionality that each of the modules provide, following the notation of Egbert and Kelbert (2012). Briefly, m and d are the model and data vectors, respectively; π and Π are the non-linear and linearized mappings from the model parameter to the grid; Λ and T are interpolation operators used for evaluation of electric and magnetic field components; e and b are the solution vector and the source vector, respectively; γ, l and q are the non-linear and linearised data functionals; S-1 is the forward solver; P gives the sensitivity of the PDE coefficients to model parameters. L and Q are linearized data kernels, which, together with S-1 and P constitute the Jacobian J = L S-1 P + Q.

An example of the flexibility of ModEM is provided in Figure 1: Egbert and Kelbert (2012) who illustrate use of the same set of generic inversion modules (implementing a parallelized non-linear conjugate gradients (NLCG) algorithm for penalty functional minimization) for 2-D and 3-D MT inversion, as well as for a global induction inversion problem based on the spherical forward code of through modifications to appropriate modules.

So far our principal application of ModEM has been to 3-D inversion of MT data. For most of this work the NLCG scheme has been the workhorse for inversion, with a 3-D finite difference staggered grid electric field solver similar to that of Siripunvaraporn et al., (2005) used for the forward code. All of the standard MT transfer functions (including inter-station transfer functions) are supported. A simple model parameterization has been used, with each cell in the numerical grid treated as an independent parameter, and the inversion has been regularized by penalizing deviations from a prior, with smoothness enforced using a model covariance, as in Siripunvaraporn and Egbert (2000). In our current implementation, the covariance allows parts of the model space to be "frozen", specification of discontinuities across flat or sloping interfaces, and spatially variable covariance length scales.

FURTHER DEVELOPMENTS

ModEM is already quite capable, and freely available, distributed using our dedicated Subversion (SVN) server. Registered users are given password-protected accounts, which they can use to download any updates or new releases. Our current focus is on code maintenance, development of improved documentation, and user training.

In particular, short courses to help potential users from the EM and broader geosciences communities get started using ModEM for 3-D MT inversion are under development. Several different levels of presentation are being pursued, from lower level introductions to MT inversion for non-EM specialists, to more advanced presentations for users already experienced using the code. Presentations are planned as both web-based and in-person short courses at national and international meetings. One goal of lower-level courses is to improve understanding of the strengths and limitations of MT inversion by seismologists and other geophysicists, facilitating inter-disciplinary collaboration.

We are also working to make inversion with ModEM faster and more efficient, robust, and capable, and to clean up and harden the code. Progress on several specific efforts in this direction will be discussed. These include:

1) Finite difference forward solvers are being modified to make use of PETSc (Portable, Extensible Toolkit for Scientific Computing; Balay et al., 2011), allowing multiple cores to be used for solving each forward problem, while still maintaining portability. Because PETSc is a well-supported general purpose computational toolkit, we can anticipate that future advances in computing hardware will be supported.

2) More flexible multi-resolution structured numerical grids are being implemented. A variant on the octree grid (Haber and Heldmann (2007)), with a subset of cells in a coarser grid subdivided in half in the x, y directions, may be particularly useful for 3-D EM modeling and inversion, where enhanced resolution is required in the near-surface layers, due both to the smaller induction length scales associated with higher frequencies, and the need for sufficient resolution to model small scale near-surface features.

3) Improved boundary conditions for the forward problem. We have already implemented simple "nesting" schemes that allow EM fields derived from a larger scale model to be used to provide boundary data for the inversion, and are now simplify the user interface, to make this more practical for a broader group of users. Alternative boundary conditions, such as those based on the zero normal gradient of tangential electric fields, are being developed as an alternative to the specified tangential fields now supported.

4) ModEM allows rapid development of a variety of inversion algorithms. We have so far implemented and tested NLCG and DCG schemes, and are now refining and testing the hybrid Occam schemes of Egbert (2012). Other approaches such as the quasi-Newton scheme used by Avdeev and Avdeeva (2009) will also be explored.

5) As part of our new project we intend to explore ways to transition support of ModEM to the US Computational Infrastructure for Geodynamics organization (CIG; http://geodynamics.org/), with the objective of developing a sustainable approach for long-term support of EM geophysical inversion software for a broad community of users.

CONCLUSIONS

It is our hope that the wide and free availability of advanced 3D inversion codes will facilitate expansion of the community of experienced 3-D EM inversion users, as well as the rapid development within this community of knowledge about appropriate use (and limitations) of these now novel interpretation methods. We will contribute further to this growth in the community of experienced and knowledgeable users through educational activities, and through support of community forums for information exchange. EM methods of course have important applications in industry and in environmental sciences, and our efforts will help develop capacity for such applied activities, as well as for basic science.

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