3D modelling of controlled-source electromagnetic fields in applied geophysics

Proposers:

- Thomas Kalscheuer, Geophysics, Department of Earth Sciences, Uppsala University, thomas.kalscheuer@geo.uu.se.
- Maya Neytcheva, Sci. Computing, Department of Information Technology, Uppsala University, maya.neytcheva@it.uu.se.

Controlled-source electromagnetic (CSEM) methods are routinely applied in geophysical field measurements that are related to tectonic studies (e.g. to determine locations of potential earthquakes), energy-related geothermal and CO$_2$ sequestration studies, investigations of groundwater aquifers to identify contamination with fertilisers or saltwater intrusion, delineation of mineral deposits, etc. There has been substantial progress in development of airborne, ground-based and marine CSEM instruments and time-series processing codes during the last few decades. Nevertheless, forward and inverse modelling of such data is mostly restricted to 1D and 2D models. Thus, the inversion algorithms fail to account for 3D geological or hydrological structures resulting in serious misinterpretation and significantly increased expenditure in associated drilling programs. At present, the only few 3D CSEM modelling codes that exist are either owned by industry or not disclosed. Hence, development of a flexible research code for 3D inverse modelling of CSEM data is highly desirable.

Modelling of CSEM data consists of two basic building blocks: (1) forward modelling, i.e. the simulation of electric and magnetic fields for a given source-receiver setup and model of the material parameter electric resistivity $\rho$ (dielectric permittivity $\varepsilon$ and magnetic permeability $\mu$ may be further relevant parameters) using finite-element or finite-difference methods, appropriate boundary conditions and efficient iterative and direct matrix inversion algorithms and (2) inverse modelling, i.e. the computation of a model of the material parameters (most often resistivity) from a given set of electric and magnetic field measurements using numerical optimisation methods such as Gauss-Newton methods (Grayver et al., 2014), quasi-Newton methods (e.g. Haber et al., 2007) and non-linear conjugate gradient methods.

CSEM methods can be divided into two categories: (1) frequency-domain methods where the transmitter on board an aircraft, on land or on board a ship sequentially generates sinusoidal signals of a series of predetermined frequencies and subsequent forward and inverse modelling is applied in the complex-valued frequency domain and (2) time-domain methods where the sudden shut-off of a constant transmitter current generates broad-band transient electromagnetic signals and subsequent forward and inverse modelling relies most often on implicit time-stepping algorithms. For frequency-domain methods, modelling has mostly been pursued using a decomposition into primary and secondary fields, where the primary fields for a layered background model are computed using semi-analytical solutions and the secondary fields owing to 2D or 3D anomalies are computed using finite-element or finite-difference methods (Streich, 2009; Grayver et al., 2014). In time-domain methods, a total-field approach is typically used where the sum of primary and secondary fields is solved for using
finite-element or finite-difference methods (e.g. Haber et al., 2007). An appropriate modelling approach would discretize the curl-curl equation of the electric field \( \mathbf{E} \)

\[
\nabla \times \left( \frac{1}{\mu} \nabla \times \mathbf{E} \right) + \sigma \frac{\partial \mathbf{E}}{\partial t} + \epsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} = -j_s
\]

(1)

using staggered finite-difference grids or finite elements with Nedelec curl-conforming edge-based shape functions. The curl-curl equation shown here is for the time domain, \( \nabla \times \) is the curl operator, \( \frac{\partial}{\partial t} \) is the temporal derivative, \( \sigma = \frac{1}{\rho} \) is electrical conductivity, and \( j_s \) denotes the source current distribution. Alternatively, partial differential equations for the magnetic field or vector potentials of the electric and magnetic fields could be considered.

Our project may include but is not limited to the following methodological development for frequency- and/or time-domain CSEM:

- Development of a 3D finite-element or finite-difference forward modelling routine.
- Inclusion of appropriate boundary conditions to reduce the size of the computational domain and speed up simulations.
- Investigation of iterative and direct matrix-inversion methods in the forward and inverse modelling processes.
- Investigation of different implicit time-stepping schemes for time-domain CSEM methods. Study and develop suitable preconditioned iterative solution methods to be used for solving the algebraic system arising when implicit time stepping methods are applied, aiming at achieving robustness with respect to problem, discretization and method parameters, (nearly) optimal computational complexity and suitability for parallel computations.
- Inclusion of the thus developed forward modelling routines in an already existing object-oriented inversion code (Kalscheuer et al., 2010, 2015; Zbinden, 2015), that is written in FORTRAN 2008 and contains Gauss-Newton and non-linear conjugate gradient inversion algorithms.

The forward-modelling routines may be proto-typed in MATLAB.

The successful candidate will be given ample opportunity to develop skills in electromagnetic field theory, numerical methods such as finite-element and finite-difference methods, numerical linear algebra and gradient-based inversion techniques (e.g. non-linear conjugate gradient methods or quasi-Newton methods), parallel programming, acquisition and processing of electromagnetic field data and interpretation of multi-dimensional resistivity models inverted from electromagnetic data.

The applicant should have a university degree at MSc level in geophysics, computer sciences, applied mathematics, physics or similar. A solid basis in mathematics and physics and adequate knowledge of programming languages (e.g. MATLAB, C++ or modern FORTRAN) are requirements. Experience with parallel computations will be an advantage. Knowledge of geologic and tectonic processes will be considered an advantage. Further, it is an advantage to have a valid driver’s licence (class B or higher).
References


