

Inversion of magnetotelluric sounding data based on Very Fast Simulated Annealing

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In this paper authors applied a nonlinear optimization method, based on Simulated Annealing to one- and two- dimensional inversion of magnetotelluric sounding data. Paper presents an attempt to apply faster approach, called Very Fast Simulated Annealing (VFSA). To test the algorithm we used both synthetic noise-free data and with random noise added, which imitated real 1D and 2D MT data. The efficiency of the VFSA method was tested on real data and the results were compared with those obtained from 1D Occam and 2D-SBI inversion. To make the algorithm more efficient the authors made some, simplified assumptions (preceded by tests) concerning the selection of cooling constants and 2D geometry of model.

Pragmatic 2D inversion of MT/MV data sets

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The recent progress of 2D inversion techniques is well seen in a fine convergence of partial and multi-component solutions for synthetic 2D data. However, a real data 2D inversion meets the influence of 3D distortions, which cause convergence difficulties and noticeable contradictions between solutions obtained for different data ensembles.

Several approaches are examined to overcome 3D distortions: the extension of data error bars depending on skew and strike parameters to outline 1D/2D data elements; the use of robust inversion estimators to resolve convergence contradictions; the static shift elimination/correction within the inversion, the robust averaging of models obtained for different data selection to outline the “mainstream” and estimate a scatter; (iv) the multi-component inversion starting from such average models.

The study was based on 3D simulation and real data. It was supported by the RFBR-DFG grant 03-05-04002.

2D inversion resolution in the EMTESZ-Pomerania project: data simulation approach

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Our general robust 2D inversion approach applied to the EMTESZ-Pomerania profile data resulted in models with a complicated superposition of sedimentary, crustal and upper mantle conductivity anomalies and a number of correlated fine details at two main profiles, namely, P2 and LT7. To better feel the resolution bounds of this approach we simulate multi-component 2D data ensembles for alternative “EMTESZ-style” models and analyze the variability of inversion solutions obtained with different selection of synthetic data components and other initial assumptions, imitating on this way the strategy of real data inversion.

For the obtained inversion results we discuss the rational misfit measures in the data and model spaces, undertake the sensitivity analysis and monitor the robust data weights. This analysis helps to compare the sensitivity and resolution issues related to different model areas, data components, periods and sites; brings better understanding of the capabilities of multi-component data interpretation routines in favorable 2D conditions and gives important hints how to improve the inversion of the EMTESZ-Pomerania data.

The study was supported by the RFBR-DFG grant 03-05-04002.

Magnetotelluric Inversion for Anisotropic Conductivities via Stochastic Sampling

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Magnetotelluric inversion for anisotropic conductivities in the Earth often suffers from excessive non-uniqueness with regard to the parameters that constitute the conductivity tensor. In such situations, global optimization techniques can be used with advantage both to map the parameter space in detail and to produce the inverse solution with properly specified uncertainties of the model parameters. We present a bayesian formulation of the inverse magnetotelluric problem for anisotropic conductivities in the Earth and use a standard Monte Carlo Gibbs sampling technique to approximate the posterior probability distribution of the model parameters conditioned on the observed data. We first test the performance of the stochastic inversion for both the parameter estimation and model appraisal on simple 1 D anisotropic models. Computationally very intensive 2D model sampling is made feasible by employing the Sherman-Morrison formula to accelerate repeated direct solutions for weakly perturbed conductivity structures. The 2D stochastic inverse results are compared with available modelling and inverse solutions for practical magnetotelluric data from the Variscean Ossa Morena Zone in southern Portugal.

Fast imaging techniques for marine Controlled Source Electromagnetic (CSEM) data with specific applications to hydrocarbon exploration.

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Marine Controlled Source ElectroMagnetic (CSEM) surveying is a powerful tool for mapping offshore electrical resistivity structure, including applications for hydrocarbon exploration. Geophysical forward and inversion modelling are currently the standard methods of CSEM data analysis, however these are computationally time consuming. We present a number of different fast imaging techniques that use a variety of approaches and parameters extracted directly from CSEM data. These allow for the lateral mapping of thin resistive layers buried in a conductive background. Normalized imaging uses the normalised response of the electric fields to some background model to map the extent of thin resistive layers in the subsurface. Apparent resistivity imaging fits a halfspace to each observed data point and plots this as a function of position.

Numerical simulation of electromagnetic wave propagation using vector finite elements

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Computation of time-harmonic solutions to Maxwell's equations is a central task for a number of geophysical applications. We present an approach to spatially approximate the electric field using vector finite elements. The numerical response obtained by the finite element algorithm has been tested against known closed-form solutions. It can be shown that accuracy of the numerical results benefits from using piecewise polynomial approximations of higher order. We further illustrate that the vector wave equation leads to numerical instabilities at low frequencies because of the large nullspace of the curl operator involved. Stability can be recovered by solving a mixed boundary value problem instead of the vector wave equation only.

Solving the 2D dc resistivity inverse problem using evolution strategies and artificial neural networks

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Evolution Strategies (ES) represent a population-based random-search procedure. They belong to the class of Evolutionary Algorithms (EA) and their functionality is inspired by the natural process of evolution. ES are often used to solve different optimization tasks in a discrete, mono- or multiobjective way. Through the application of the genetic operations mutation, recombination, and selection, ES find a set of so called pareto-optimal solutions (fittest individuals) with respect to a vector valued objective function. ES and particularly two special implementations of them, the Multiobjective Elitist Evolution Strategy (MEES) and the Evolution Strategy with Probabilistic Mutation (ESP) have proved to be superior to other algorithms of the EA family in multiobjective optimization test problems. They were finally used to solve the inverse direct current resistivity problem in two dimensions. To speed up the solution time and to save computational costs ES have been combined with especially trained artificial neural networks generating rapid approximations of the forward response.

Blocky models in minimum-structure inversions

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Minimum-structure inversions, in which a measure of model structure is minimized in conjunction with data misfit, and in which the parameters being sought are the physical properties in cells in an otherwise fixed mesh, are generally robust, reliable, and produce models with few, if any, artifacts. However, the sum-of-squares measure that is typically used results in fuzzy, smeared-out models. Recently, there has been interest in inversion procedures which generate models comprising uniform regions separated by sharp interfaces. The work presented here incorporates L1-type measures (including diagonal differences) into the traditional minimum-structure inversion approach. This enables piecewise-constant, blocky models to be constructed while retaining the reliability of the minimum-structure approach. Examples are given for 2-D MT inversion.

A Modular System for Electromagnetic Inverse Problems

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We are developing a modular system for inversion of electromagnetic (EM) induction data, using an object oriented approach to maintain a clean division between model parameter, data, and EM solution objects. The idea is to represent the objects (e.g., data or model parameter vectors; EM model solutions) that would appear in an abstract discussion of geophysical inverse methods as abstract data types, without reference to instance specific implementation details. Inversion algorithms that manipulate these objects can then be generic, and extension to treat new cases or approaches is greatly simplified. For example, the modular system simplifies development, testing and comparison of inversion algorithms, and is thus an ideal test bed for developing new methods. The system also simplifies extension to new data types (e.g., allowing interstation transfer functions in MT), or to modified model parameter definitions. Ultimately, a modular EM system will also simplify development of methods for joint inversion of EM and other geophysical datasets. We are developing the modular code in F95, focusing initially on components required for implementing a broad range of previously proposed (and new) 2D MT inversion schemes. However, many components (e.g., data space modules, high level inversion modules) are generic enough to be used for 3D MT or other EM problems.

Efficiency of Inversions: GN-Type or CG and NLCG?

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Efficiency (in terms of speed) of EM inversion methods is determined primarily by the number of forward solutions required for sensitivity calculations. For data from N_s stations, Gauss-Newton-type inversion schemes (including Occam) calculation of the full sensitivity matrix requires N_s forward model solutions per frequency, for every iteration. By avoiding direct computation of the sensitivity matrix, conjugate gradient (CG) and non-linear CG (NLCG) inversions require only a few forward solutions per frequency on each iteration. These numbers seem to be promising, and have led to numerous developments of MT inversion based on CG and NLCG methods. However, many fewer iterations are required by a GN scheme such as Occam, so it is not clear that the total number of forward solutions required for convergence of CG or NLCG are actually fewer. Here we compare the total number of forward solutions required by a range of popular approaches to 2D MT inversion, using synthetic data examples. In general CG type approaches require as many or more forward solutions than Occam. We therefore conclude that CG and NLCG-type inversions are not superior (and even are inferior in some cases) to GN-type methods in term of CPU time. The CG approaches still have advantages with regard to memory.

Phase tensor analysis on conductivity structures of the crust and mantle in Iceland

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3 major conductivity structures dominate magnetotelluric (MT) observations in Iceland: A mid crustal good conducting zone spreads beneath almost all the island, the mid Atlantic ridge crosses Iceland from the south west to the north, and the highly conducting sea water of the Atlantic Ocean. A 3D model study compares their influence on the rotational invariants of the phase tensor giving clear evidence for 1D, 2D and 3D features varying with location and period. The phase tensor representation of MT data at 163 sites (10 – 1000 seconds) reveals a highly resolved transient change of the crustal conductivity in SW Iceland, whereas the analysis of MT data at 4 long period sites (10 – 10000 seconds) gives evidence for the location of the Ridge beneath Iceland.

2D inversion for plane wave EM methods using an adaptive unstructured grid finite element forward operator

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We present a 2D damped least-squares inversion approach for plane wave EM methods (MT and VLF) using an adaptive unstructured grid finite element forward operator. The forward operator is able to do efficient discretisation of arbitrary 2D model geometries and hence also allows to model arbitrary topographic variation. The inversion model is parameterised on a coarser grid, for which the sensitivities are determined. A modified sensitivity equation system obtained from the derivative of the finite element equations with respect to the model parameters is used for sensitivity calculation. The parameterised region is further discretised in unstructured triangular meshes using adaptive refinement to perform forward modelling. We show that the inversion process converges and gives reasonable results. Concluding, we obtain a two-grid technique which has proved to be numerically efficient.

Three-dimensional finite-element simulation of electromagnetic fields using unstructured grids

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The interpretation of an increasing number of three-dimensional data sets requires the simulation of the electromagnetic fields in three directions in space. The formulation of the equation of induction using vector and scalar potentials reduces the number of unknowns to four per grid node. Applying a secondary potential approach allows for the implementation of simple homogeneous Dirichlet boundary conditions. To expand the classic Magnetotelluric (MT) frequency range to lower periods used by the Radio and Audio MT method for studying shallow conductivity structures displacement currents need consideration. Beside the electric conductivity and permittivity, the presented finite-element algorithm incorporates the magnetic permeability as model parameter that can be advantageous e.g. in the case of ore exploration and for studies of the earth's crust where basaltic rocks occur.

Three-dimensional topographic responses in MT modeled using the vector finite element method combined with divergence corrections based on the electric field (VFEE++)

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A new algorithm (VFEE++) by integrating three-dimensional vector/edge finite element method (VFEE) combined with divergence corrections based on the electric field was developed to compute the magnetotelluric responses of 3-D conductivity structures. The new VFEE++ algorithm was verified by comparison with the results of integral equation method, staggered-grid finite difference method, and COMMEMI project for two 3-D models. The 3-D topographic responses for different rugged surfaces such as hill, valley were computed. The numerical results show that the apparent resistivities R_{xx} , R_{xy} , R_{yx} and R_{yy} are both heavily distorted by the three-dimensional topographic terrain, which is quite different from those of two-dimensional cases. This result implies that the VFEE++ algorithm could be another powerful way of numerical modeling of 3-D topographic effects and could be applied for 3-D MT inverse problems of field data incorporating with rugged terrain.

A comparison of one- two- and three-dimensional modelling of audiomagnetotelluric data collected at the world's richest uranium mine, Saskatchewan, Canada.

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Innovative 3-D modeling algorithms are becoming increasingly popular and useful for MT exploration. This study facilitates the comparison of multiple modelling algorithms by assembling the results of independent modelling studies on a grid of audiomagnetotelluric data collected in northern Saskatchewan, Canada. The survey area was directly over the world's richest uranium deposit (190 000 tons of U grading 23

2-D Niblett-Bostick magnetotelluric inversion

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A simple and robust imaging technique for two-dimensional interpretations is developed following the well known Niblett-Bostick transformation for one-dimensional profiles. The algorithm processes series and parallel magnetotelluric impedances and their analytical influence functions using a regularized Hopfield artificial neural network. The adaptive, weighted average approximation preserves part of the nonlinearity of the original problem, yet no initial model in the usual sense is required for the recovery of the model. Rather, the build-in relationship between model and data considers automatically, all at the same time, many half spaces whose electrical conductivities vary according to the data. The use of series and parallel impedances, a self-contained pair of invariants of the impedance tensor, avoids the need to decide on best angles of rotation for identifying TE and TM modes. Field data from a given profile can thus be fed directly into the algorithm without much processing. The solutions offered by the regularized Hopfield neural network correspond to spatial averages computed through rectangular windows that can be chosen at will. Applications of the algorithm to simple synthetic models and to the standard COPROD2 data set illustrate the performance of the approximation.

3D TEM inversion scheme using adjoint green's function approach in time domain

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Although the direct and inverse problem for many applied geophysical methods are solved in 3D now, the interpretation of TEM data sets are commonly done with 1D models. Among other things, this is due to relatively high computation cost which arises for the simulation of 3D diffusive EM processes. To create an effective 3D inverse solution with reduced computational effort, we use a fast Krylov solver within a first order conjugated gradient scheme, which we'd like to present. Although the explicit calculation of sensitivities can be avoided, we use an approximated adjoint green's function approach to calculate them direct in time domain at each iteration step. The Sensitivities inhere the resolution properties and can be used for the interpretation and discussion of model ambiguities during the inverse process.

Does a low in Apparent Resistivity Curve always indicate the presence of Conductor?

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The apparent resistivity ($\tilde{\rho}_a$) versus frequency curve forms one of the major parameter for interpretation of subterranean conductivity structure in electromagnetic induction studies. The lows and highs in the curve are usually considered as indicators of conductive and resistive formation respectively. However, it is seen on the basis of numerical experiment that for some situations, significant low in $\tilde{\rho}_a$ -curve occurs even over highly resistive formations. These quantitative simulations clearly show the extent of distortions that the resistivity sounding curves could undergo in the vicinity of a laterally heterogeneous conductive structure. This calls for a cautious approach in interpretation of the deep e.m. probing and/or MT data; particularly in those areas where the conducting layer may be hidden beneath a relatively resistive cover. The quantitative effect is demonstrated by solving synthetic forward and inverse models. The errors that are likely to creep in the interpretation for possible parametric ranges of field situations have been simulated. One of the interesting results is the role of underlying conductor as a major sink of the currents generated, in the earth, close to the lateral heterogeneity. It is found from the numerical study that for realistic conductivity contrasts (1:500), the measured apparent resistivity would be less by a factor of two, than its actual value, even at 10 km distance away from the discontinuity. Implication of these findings on deep electrical probing of the areas like Himalayas, Ganga basin and Saurashtra peninsula are discussed.

Fundamental models construction operated by neural network (FM-NN)

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Fundamental model (FundMod or FM) is a sub-space M of models (of real geoelectrical structures), which produce approximately the same (in the limits of reasonable selected uncertainty) response function (RF) behavior at the Earth's surface and this FundMod can be distinguished from any other FM by means of RF behavior analysis (Rokityansky, 1988, Geophysical Journal, v.10, 3, 21-28 (in Russian)). RF in geoelectromagnetic studies usually include impedance tensor (8 numbers), tipper (4 numbers), and we strongly recommend also the normalized anomalous field in horizontal magnetic components obtained from synchronous records (8 numbers). All this quantities are displayed temporary (in frequency or period domain) and spatially (in separate sites, or in profile(s), or in 2D array). For ideal data, the inverse problem can have unique solution. For real data, the inverse problem is always non-unique. To gain the complete solution of an inverse problem for given data set, one should find sub-space M of models satisfying the data, i.e. FundMod. In such formulation, FM depends of volume and quality of data, i.e. of observed RF. To minimize this disadvantage and infer an objectivity in FundMods construction, we select "the best data" available for given epoch. "The best data" can be simulated by direct problem solving, they can have any broad temporary and spatial coverage and prescribed error inherent for the best modern instruments and processing technique. For FundMods construction, the direct problem calculation for great number of models should be made. Cardinal problem in this procedure is adequate parameterization of models. The parameters spacing must be neither too small, to avoid excessive growth of the number of models, not very great, to provide satisfactory approximation of any real structure. The constructed body of Fundamental models can be used for interpretation. It can be done by Monte-Carlo procedure or better by neural network (NN). Use of neural network is based on Kolmogorov-Arnold theorem (1957) on the presentation of a continuous function of many variables by means of superposition of continuous functions of one variable. Hecht-Nielsen (1987) applied this result to neural network. He proved that function of n variables (parameters of a model) can be presented by three layers neural network: input layer with n neurons, internal or hidden layer with $(2n+1)$ neurons and output layer with m neurons (RFs). The interlayer neuron synaptic connections provide possibility of NN training by finding a set of weights that minimizes an error function. NN, being educated and trained by sufficiently complete set of FM, can solve the inverse problem very fast, practically in real time, without limiting assumption about linearity and can yield complete solution for an observed data set. The FundMod approach opens a perspective for relatively compact description of complete space of geoelectrical

structures. Of course, it is long lasting study, the problem for international cooperation. Resulting knowledge of FM-space (together with counterpart in RF-space for every model) will form base for better understanding of the real 3D geoelectromagnetics.

3D effects in the central part of the Polish Basin

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MT measurements carried out in Polish Pomerania in 2001-2006 were concentrated mainly along two regional profiles, P2 and LT7, crossing quasi-2D deep crustal conductor(s) associated with the Trans-European Suture Zone (TESZ). However, the TESZ is overlapped by sediments of the Polish Basin with a distinct 3D structure. The North German sedimentary basin, located to the northwest, is also causing 3D distortions of the EM data in Pomerania. The simplified volume conductivity model of Pomerania and surrounding structures was constructed. The results of forward 3D modeling gave valuable estimates of 3D influence of sedimentary structures and provided synthetic data for the verification of 2D inversion approaches in the presence of 3D distortions.

Violation of dispersion relationship in seafloor TE-impedance

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It is known that the dispersion relation between modulus and phase is violated at the seafloor within the continental slope for the impedance component parallel to the coastline (in TE mode). The generalized 2D coast effect model was constructed to analyze this phenomenon. Calculated response has shown anomalies, most prominent in TE-phase. Short-period (up to 30 000 s) branches of some phase curves exceed the bounds of native quadrant $[-90,0]$. It was ascertained that this anomalous effect is mainly coming from magnetic components. Relationship between the intensity of this anomaly and the bathymetry was investigated. The influence of the outlined phase excursion in the course of 2D inversion of simulated bottom observations was finally studied.

Far East subduction zone 3D-conductivity structure modeling (case study)

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Numerical modeling was performed to understand main peculiarities of EM field behavior in typical marginal sea settings and to study the resolution of EM field to deep conductors. A number of idealized conductivity structure models of Japan sea, Japanese Island Arc and subduction zone of different complexity were constructed. MT-response sensitivity to conductive asthenosphere beneath marginal sea and conductive zone beneath volcanic arc was estimated. Conductive asthenosphere causes essential distinctions in resulting response, so it can be confidently resolved. Except of sensitivity case study, some 3D-effects analysis was performed. A number of 3D vs 2D and vs 1D residuals of various MT-transfer functions were evaluated.

ON THE STRUCTURE ELECTROMAGNETIC INVERSE PROBLEM

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The electric and magnetic fields are now used quite effectively in geophysical prospecting. However, the interpretation theory of these data has been inadequately developed: the research carried out has been devoted, as a rule, to solution of direct problems or inverse problems for narrow model classes. The inverse problem in a general case is reduced to an operator equation of the first kind with an implicitly stipulated operator. The programmed application of the algorithm for solving such an equation requires considerable expenditures of computer time. We have derived the new integral and integrodifferential equations of the structure electromagnetic inverse problem. An original numerical algorithm is written for their solving in a case of arbitrary boundary relief. We have constructed a special algorithm for ice-water boundary determining on the basis electromagnetic data measurements.

Influence of a resistivity frequency dispersion and sloping boundary inclination on the TEM response

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The aim goal of this study is to make a comparison of TEM response above the sloping boundary inclination and the geoelectric cross-section with resistivity frequency dispersion. The urgency of this problem is determined by very complex diagnostics of field TEM data distortion. Which kind of the geoelectric environment features can cause TEM data distortion? It is unequivocal determed induced polarization effects only in a case of using the loop-in-loop configuration. In many other cases definition of the distortions reason is very complicated because the similar effects can caused by both rocks polarization and lateral inhomogeneity of the geoelectric cross-section. In this study the qualitative attribute (with using apparent conductivity curves) is offered. This attribute is allowed to determine which kind of model (1D or 2D-,3D) can be used for interpretation of the field TEM-data. Examples of qualitative changes of synthetic apparent conductivity curves and experimental apparent conductivity is presented and confirmed that the offered qualitative attribute allows to define is the electromagnetic response 1D or high dimensionality.

Evaluating data misfit in time domain EM inversion

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The data misfit functional plays a crucial role in solving time domain EM inverse problems. The assigned errors for inversion represent both modelling error as well as observational and field errors. In reality, especially in problems where there is large dynamic range in the data, there are questions as to how best to describe the errors. We discuss some aspects of what constitutes a 'good data-fit' for time domain EM data. We also note that for inversion of time domain EM data, certain components of data error may have a multiplicative rather than an additive nature. This means that log-normal distributions of data error may be present in the data which we intend to invert. We discuss the use of the hyperbolic arcsine in a data misfit functional for the inversion of time domain EM data. We believe this formulation can address both, these types of error, and our practical notions about quality of data-fit.

Influence of rocks porosity on TEM sounding data

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The distributions of electrical properties in a geological cross-section are the usual result of TEM data interpretation. However distribution of resistivity is not enough for geologists. They forced to find empirical connections between rocks resistivity and other rocks properties like porosity, material constitution, mineralogical composition. We tried to study correlation between laboratory physical measurements of rocks samples and geoelectric cross-sections parameters. Two spectra of rocks samples were choosen (from a collection of about 50 samples) with the most different porosity values for qualitative estimate of rocks porosity influence on the TEM response. On the next step the Cole-Cole model parameters have been picked up for these spectra, which were used for the electromagnetic response modelling above halfspace and three-layer geoelectric model. Our research have shown, that rocks porosity influences on TEM signal level. It allows to determine rocks porosity using TEM sounding data.

Three-dimensional electromagnetic modelling using Trefftz method

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Trefftz method for numerical solving boundary value problems for differential equations was investigated for 3-D electromagnetic problems. The approximate description of 3-D medium by homogeneous rectangular blocks was used. The electromagnetic field is represented as a linear combination of plane waves diffusing in three orthogonal directions inside blocks. This expansion in a block is the exact solution of Maxwell's equations. Coefficients of the combination are computed from continuity conditions of tangential field components on sides of blocks. For solving the corresponding very sparse system, the modified Kaczmarz iterative method was investigated. Some results for models from the COMMEMI project are presented.

New open source tools for 2D Marine EM modeling: MARE2DCSEM and MARE2DMT

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We present two new finite element (FE) formulations for marine electromagnetic exploration that are part of the MARE2D open source modeling package (Modeling with Adaptively Refined Elements). We use unstructured triangular FE grids, which easily accommodate arbitrarily complex 2D structures. Starting with a coarse grid, we use adaptive grid refinement based on a recently developed goal-oriented a posteriori error indicator to automatically refine the FE grid until any desired level of solution accuracy is obtained. This robust formulation allows for all levels of users (from novice to expert) to easily obtain accurate CSEM and MT responses for 2D models. We will demonstrate the MATLAB model construction graphical user interface Triangle.m and present several test cases that illustrate the utility of MARE2D for complex offshore modeling problems.