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To cite this version:

François Bretaudeau, Sebastien Penz, Nicolas Coppo, Pierre Wawrzyniak, Mathieu Darnet. 3D land CSEM inversion in noisy environment with a single transmiter: inversion approach and application for geothermal water prospection. International Symposium in Three-Dimensional Electromagnetics (3DEM), Gerald W Hohmann Memorial Trust, Mar 2017, Berkeley, United States. hal-01458151

HAL Id: hal-01458151
https://hal-brgm.archives-ouvertes.fr/hal-01458151

Submitted on 6 Feb 2017

6th International Symposium on Three-Dimensional Electromagnetics
Berkeley, California, March 28–30, 2017

3D land CSEM inversion in noisy environment with a single transmiter: inversion approach and application for geothermal water prospection

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SUMMARY

Anthropogenic noise, cost and logistical constrains generaly limit to the use of land CSEM to a few transmiter positions for the deep imaging of the electrical conductivity. The 3D inversion of CSEM data in the near field using a single transmiter position suffers from critical sensitivity singularities. We proposed a robust inversion framework adapted to this ill-conditioned inversion problem. The framework relies specificaly on a robust Gauss-Newton solver, model parameter transformations to compensate the heterogeneous sensitivies, and on the reformulation of the near field CSEM data under the form of a pseudo-MT tensor. We describe the approach used for modeling and inversion implemented in our code POLYEM3D and show the advantages of pseudo-MT tensor formulation. The strategy have been tested on a pathologic synthetic case inspired from grayver et al (2013), and then was successfully applied to a real CSEM dataset acquired in the context of thermal water prospection in a noisy environnement.

Keywords: 3D inversion, land CSEM, noisy environment, single transmiter, sensitivity singularities, thermal water prospection.

INTRODUCTION

EM prospection is a method of choice for many applications such as deep water or geothermal prospection. However, the investigated areas are usually urbanised so high level of cultural noise prevents from the use of MT. Land CSEM is an alternative. But cost and logistical constrains generaly limits to the use of a small number of transmiter positions, most of the time only one. The inversion of CSEM data in the near field using a single transmiter position suffers from critical sensitivity singularities due to the unsymmetric illumination. To overcome this problem we proposed an inversion framework adapted to this ill-conditioned inversion problem. The framework relies specificaly on a robust Gauss-Newton solver, on model parameter transformations and data reformulation under the form of pseudo-MT tensors. We describe here the approach implemented in our code POLYEM3D and investigate the effect of the pseudo-MT tensor formulation. We illustrate its application on a pathologic synthetic case inspired from (Grayver, Streich, & Ritter, 2013) and then show the application of the process to a real CSEM dataset acquired for thermal water prospection at a few kilometer from a nuclear power plant in France.

METHOD AND/OR THEORY

The POLYEM3D code used in this study relies on an hybrid semi-analytical/finite-volume modeling on irregular cartesian grid (Streich, 2009). The FV formulation provides a linear system:

$$\mathbf{A}(\rho,\omega)\,\mathbf{E} = \mathbf{b}. \tag{1}$$

where $\mathbf{A}$ is the finite-volume operator matrix, ρ a 3D resistivity distribution, $\mathbf{E}$ the 3D electric field and $\mathbf{b}$ the source term.
The computed data $d^c_{s,r}$ (component c of the electric and/or magnetic field at each receiver r generated by the source s) can be expressed as:

$$d^c_{s,r} = \wp^c_r\,\mathbf{E_s} \tag{2}$$

where $\wp^c_r$ is a restriction operator that extract the value of the component of the field from the 3D electric field computed on the whole grid. It contains interpolation operators and curl operator for magnetic field.

Inversion of EM fields is achieved by minimising the misfit function:

$$\Phi \;=\; \delta\mathbf{d}^\dagger\mathbf{W_d}^\dagger\mathbf{W_d}\delta\mathbf{d} \tag{3}$$

with $\delta\mathbf{d} = \mathbf{d_{obs}} - \mathbf{d_{cal}}$ the data residual vector.

In CSEM inversion the data vectors usually contains each component of the electric and/or magnetic fields for each station, source and frequencies. However, other kind of observables can be used to build the data vector. In the framework of local linear inversion, we want at each iteration to determine the model update $\delta\mathbf{m}$ solution of the Gauss-Newton equation:

$$\Re(\mathbf{J}^\dagger\mathbf{J})\delta\mathbf{m} \;=\; -\Re(\mathbf{J}^\dagger\mathbf{W_d}\delta\mathbf{d}) \tag{4}$$

where **J** is the sensitivity matrix.

Reparameterization of the problem

The sensitiviy **J** decreases rapidly with the distance from the source, resulting in a very poorly conditioned linear system to be solved. In POLYEM3D, this linear system is solved with LSQR that is known to be efficient for poorly conditioned linear systems. Preconditionning is also applied by model reparameterization. Instead of performing inversion of ρ, we can inverse **m**:

$$\mathbf{m} \;=\; \mathbf{G}^{-1}\mathbf{D}^{-1}\,C(\rho) \tag{5}$$

with C a change of variable (such as logarithm), D an arbitrary linear operator that rescale the sensitivity loss with depth (as for instance in (Plessix & Mulder, 2008)), and G a linear operator that change the basis of description of the model (for instance a basis of splines described on a coarse grid). Each line of the sensitivity matrix thus can be written:

$$\mathbf{J^c_{s,r}} \;=\; \mathbf{G}^t\mathbf{D}^t\frac{1}{C'(\rho)}\mathbf{E_s}\frac{\partial\mathbf{A}}{\partial\rho}\mathbf{A}^{-1}\wp_r^{ct} \tag{6}$$

A pseudo-MT formulation

The reparameterization allows to perform efficient 3D inversion for MT or multiple source CSEM. However it is still not enough to inverse CSEM data when a single source is used, as the sensitivity singularity at the source cumulates over each line of **J**. We found that recasting the data acquired with two different transmiters using a MT tensor formulation mitigates the singularity due to the transmiter both in the data and in the sensitivities. Taking for a station the definition of a Z tensor as a transfer function:

$$\left(\begin{array}{c} E^x \\ E^y \end{array}\right) \;=\; \left[\begin{array}{cc} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{array}\right]\left(\begin{array}{c} H^x \\ H^y \end{array}\right), \tag{7}$$

and considering two different sources (it can be typically two polarization of a single transmiter), we can obtain for each station the 4 components of this pseudo-MT tensor by a combination of the 8 electric and magnetic fields generated by those two sources:

$$Z_{ij} \;=\; f(E^c_s, H^c_s). \tag{8}$$

Recasting the CSEM data under this form reduce the number of data by 2 and results in a sensitivity matrix that is a linear combination of the common CSEM sensitivities weighted by the values of the fields:

$$J_{Z_{ij}} \;=\; f(J_{E^c_s}, J_{H^c_s}, E^c_s, E^c_s) \tag{9}$$

The pseudo-MT tensor is not to be linked to an apparent resistivity or a MT tensor because depending on the frequency and the source-receiver distance considered, the far field condition is not always respected. It is however a well balanced observable that can be inverted if an accurate modeling of the real transmiters is considered.

VALIDATION ON A SYNTHETIC CASE

We illustrate the behavior of the new formulation on a 3D synthetic resistivity inspired from the model of (Grayver et al., 2013). The survey is composed of 100 stations over a $5\Omega.m$ medium with 3 anomalies at $1\Omega.m$, $50\Omega.m$ et $100\Omega.m.$ We consider the inversion of MT data (far field), and inversion of CSEM data generated with two orthogonal polarization located at 2km from the closest station, and 5 frequencies from 32s to 16Hz. The CSEM data are inverted first using normalized electric fields and with pseudo-MTtensor formulation.

The footprint of the transmiter in the sensitivity is not completly removed but is reduced enough to allow convergence of the inversion. We show in figures 1 to 4 the inversion result obtained for MT data (far field), normalized CSEM data and pseudo-MT tensor formulation using 5 frequencies (32s, 8s, 1Hz, 4Hz and 16Hz). For the CSEM data, the station array is in far field condition for the highest frequencies and in near field for the lowest. Sharper results should be obtained with more efficient regularization but the conclusions should not differ. Even though the deep resistive anomaly is underestimated and a few artefacts appear around the shallow anomaly, the MT data inversion reconstructs quite well the 3 anomalies in very few iterations ($<$ 15 iterations). The inversion of CSEM weighted data fails to converge. It gets stuck in a local minimum after the 1st iteration. We clearly see in the inverted model the footprint of the transmiter sensitivity anomaly which affect the reconstruction. The deep anomalies are shifted and smoothed along the wavepath between the transmiter and the stations. The shallow anomaly is not reconstructed, and several artefacts appear close to the surface. Using the pseudo-MT tensor formulation, the footprint of the transmiter in the sensitivity is reduced. Artefacts are still visible under the transmiter, but the deep anomalies are better reconstructed and the shallow anomaly is well imaged. Convergence is also better (15 iterations).

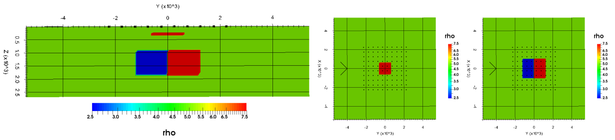

Figure 1: Exact resistivity model (a) YZ plane (b) XY plane at z =280m (c) XY plane at z =1300m.

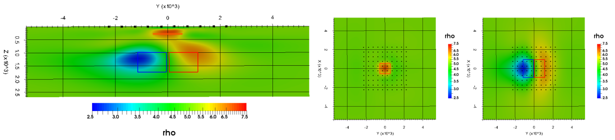

Figure 2: Final inverted model for the MT data - 4 components of the complex MT tensor

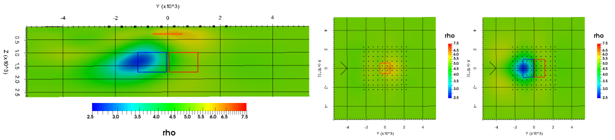

Figure 3: Final inverted model for the CSEM data - both components of the complex electric and magnetic fields normalized by a the modulus of a reference field $\mathbf{E_0}$

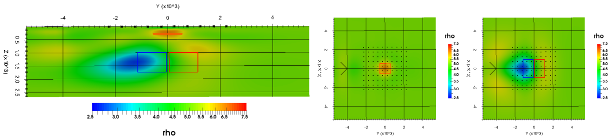

Figure 4: Final inverted model for the CSEM data - 4 components of the complex pseudo-MT tensor

REAL DATA EXAMPLE

The methodology has been applied to a land CSEM survey acquired with a single transmiter position and 2 polarizations in an area where the geology is quite complex with faults and strong 3D effects. The acquisition was performed using 60 stations around the village of Givet in France, close from the Belgium border. The survey is located at 5 km from a nuclear power plant, and high level of cultural noise clearly prevent from the use of MT. The target was the intersection of the top of a deeping limestone layer with a regional fault zone at an expected depth of about 800m. Robust processing have been used to estimage transfer functions and provide noise estimation for both component of electric and magnetic field. We used for the inversion both electric and magnetic fields recorded from 0.125Hz to 1024Hz. In this configuration, even with appropriate preconditionning and scaling, inversion of the electric and magnetic fields could not converge and provide a consistent 3D resistivity model. The inverted model was dominated by the footprint of the sensitivity singularity of the transmiter. Inversion of pseudo-MT tensors allowed to build a 3D model consistent with geology. Figure 5 shows slices at different depths. The image is in good accordance with geological knowledges of the area. The footprint of the transmiter is no more visible. The fault limits are well imaged at the surface as well as in depth where 2 different geological units are clearly identifed of for side of the fault, and the targeted layer appear shallower than expected. The deep structure is also confirmed by regional gravity map (figure 5). Furthermore, a long DC electric profile have been acquired in the same area. The comparison of this profile with a slice extracted from the 3D model is displayed figure 6, and show very similar features.

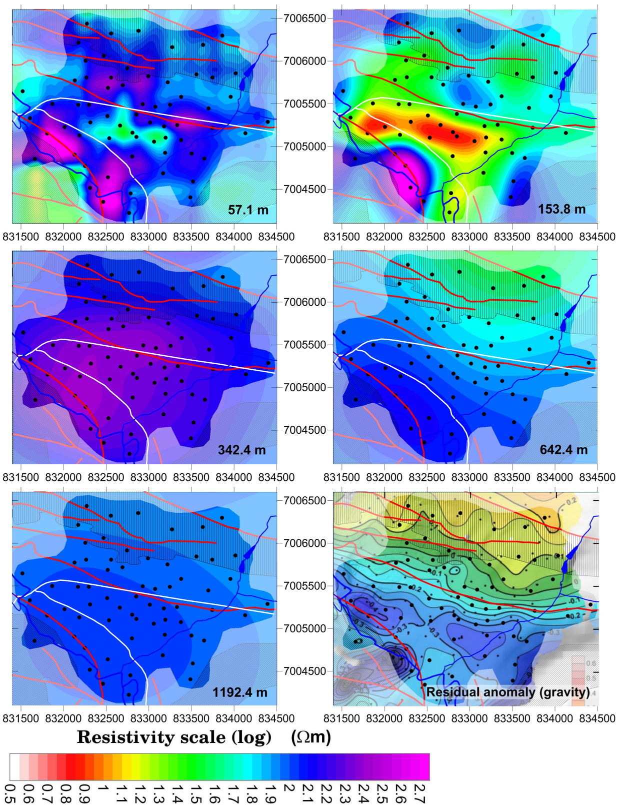

Figure 5: Slices of the 3D resistivity model and (f) gravity map, with contours from the geological map.

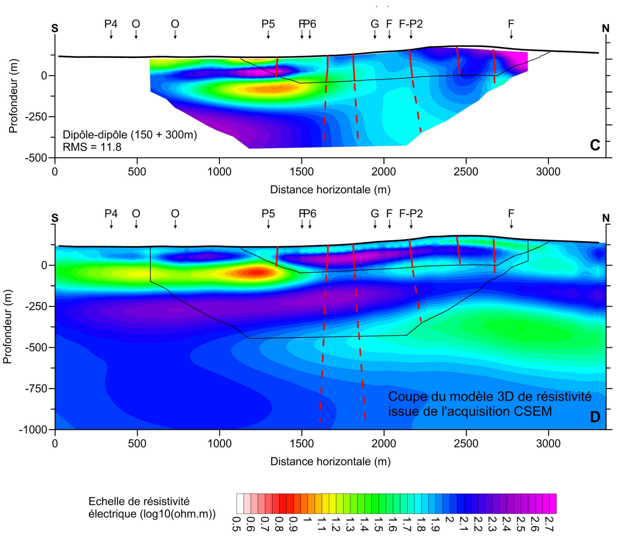

Figure 6: Cross section extracted from the 3D resistivity model and 2D long DC resistivity profile.

Conclusions and discussion

We proposed an alternative formulation of the CSEM inversion problem by recasting data as a pseudo-MT tensor. We show on a synthetic case that this formulation, when used with an accurate Gauss-Newton inversion and an efficient reparameterization allows to perform 3D inversion of CSEM land data using a single transmiter where common field inversion fails. The strategy show its effeciency on both synthetic and real data. It could be also extended to multiple transmiter CSEM survey, using multiple pseudo-MT tensors for each station. However, it requires to always record high quality magnetic data, otherwise the whole station can't be used. Furthermore, there is still acquisition configurations where the benefit of this approach is not so evident. The behavior of the formulation in different contexts should be investigated more in depth.

Acknowledgements

The research leading to these results has received funding from the EC Seventh Framework Program under agreement No. 608553 (IMAGE).
Large scale modeling and inversion was performed on the SRV185 BRGM supercomputer and thanks to GENCI (Grand Equipement National de Calcul Intensif) and CINES (Centre Informatique National de lâEnseignement Supérieur) supercomputing facilities. All modelisations and inversions were performed using the POLYEM3D software developped at BRGM in the framework of the IMAGE project.

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