Development of a 2D inversion code for marine CSEM using rotational invariants

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Figure 1: The transmitter – Sputnik.

Introduction

For GEOMAR's time-domain CSEM data excited with two perpendicular horizontal dipole polarizations (Figure 1, Hölz et al., 2015), the use of rotational invariants is advantageous because it can provide representations of measured horizontal field components which are independent of the orientations of both the transmitters (TXs) and receivers (RXs, Figure 2). The use of rotational invariants was successfully applied for the 1D interpretation of time-domain CSEM data in Hölz et al. (2015) and Swidinsky et al. (2015).

For performing 2D CSEM inversion in frequency domain, the GEOMAR's time-domain data is first transformed into frequency-domain. It is worth mentioning that the acquired data were first processed to yield transient *E* fields for each RX-TX pair. The CSEM data selected in a varying frequency range can be used for interpretation, which includes both the low and high frequency data.

In this study, we have developed a frequency-domain 2D inversion code using rotational invariants, which could be used for inverting the GEOMAR's CSEM data. The forward solver for 2D inversion is based on a staggered finite-difference code for simulating frequency-domain CSEM responses using the total field approach (Li et al., 2017). The singular source point is distributed by a pseudo delta function for numerical accuracy. The rotational invariants will also be computed in the frequency domain. For inversion, the Gauss-Newton (GN) optimization is used for fast convergence and accutate resistivity image reconstruction. Synthetic tests indicate its validity. Future work will focus on the interpretation of CSEM data collected in the Black Sea area for gas hydrate exploration.

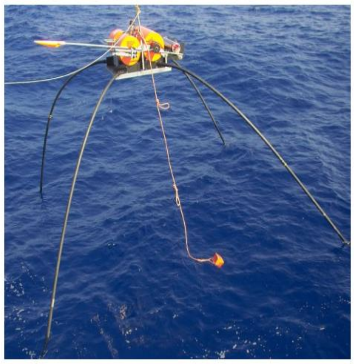

Figure 2: OBEM receivers.

Theory

A. Forward modeling

The commonly used frequency-domain marine CSEM inversion code only deals with electric/magnetic fields which assume that the orientations and tilts are accurate. A new frequency-domain forward & inversion code using the concept of rotational invariants should be developed for dealing the GEOMAR's CSEM data in which orientations of both the transmitters and receivers are not well known.

The forward modeling is based on a frequency-domain marine CSEM solver using finite-difference grids, which implements boundary conditions as perfectly matched layer (PML) or conventional Dirichlet condition (Li et al., 2017). Dirichlet boundary conditions assume field values to be zero at the boundaries which requires that the boundaries should be sufficiently far away from the area of interest. In this study, for a 2D conductivity structure, the 3D governing equations can be transformed to 2D by Fourier transformation with respect to the strike direction. We use the total field approach and the singular source point is implemented by a pseudo delta function for weakening the source singularity. Rotational invariants are computed directly in the frequency-domain similar as described by Hölz et al. (2015) and Swidinsky et al. (2015):

$$I_1 = \sqrt{E_{xx}E_{yy} - E_{xy}E_{yx}}, \quad I_4 = \sqrt{E_{xx}^2 + E_{xy}^2 + E_{yx}^2 + E_{yy}^2},$$

where the first subscript of *E* denotes the transmitter and the second one indicates the receiver orientation. The partial derivatives with respect to seafloor conductivity for these rotational invariants are given by:

$$\frac{\partial I_1}{\partial \sigma} = \frac{1}{2I_1}\left(\frac{\partial E_{xx}}{\partial \sigma}E_{yy} + E_{xx}\frac{\partial E_{yy}}{\partial \sigma} - \frac{\partial E_{xy}}{\partial \sigma}E_{yx} - E_{xy}\frac{\partial E_{yx}}{\partial \sigma}\right),$$
$$\frac{\partial I_4}{\partial \sigma} = \frac{1}{I_4}\left(E_{xx}\frac{\partial E_{xx}}{\partial \sigma} + E_{xy}\frac{\partial E_{xy}}{\partial \sigma} + E_{yx}\frac{\partial E_{yx}}{\partial \sigma} + E_{yy}\frac{\partial E_{yy}}{\partial \sigma}\right).$$

B. Inversion

The inversion algorithm is based on Gauss-Newton (GN) optimization for fast convergence rate and improved resistivity image reconstruction accuracy. For the GN method, the forward response function is linearly approximated using Taylor's series expansion. The Conjugate Gradient Least Squares (CGLS) method is used for solving the resulting GN equations. Note that the adjoint method is used for computing the Jacobian (sensitivity) matrix, in which only two sets of forward solutions are required:

- the first set is the solution with the sources located at the source locations;
- the second is the solution with the sources located at the receiver locations.

Conclusions

We present a 2D Gauss-Newton (GN) inversion algorithm for frequency-domain marine controlled-source electromagnetic (CSEM) data. The rotational invariants are used which are independent of the orientations of both transmitters and receivers. Synthetic test indicates its validity. Future work will focus on interpreting GEOMAR's CSEM data acquired in the Black Sea.

Synthetic test

In this section, we present a synthetic example for testing the developed 2D inversion code. We present a synthetic test to demonstrate the performance of the inversion code. The test model consists of a seawater layer with 1 km thickness and 0.3 Ωm, and a 100 m thick, 100 Ωm reservoir layer starting at a depth of 500 m below the seafloor embedded into the sediment background of 1 Ωm resistivity (Figure 3a). 25 transmitters at 500 m intervals, each realized with *x*- and *y*- directed sources and 21 receivers located on the seafloor at 1000 m intervals are used. The transmitting frequency is 0.25 Hz. The synthetic rotational invariants are contaminated with 5% random Gaussian noise.

The starting model for the synthetic inversion is a three-layer conductivity model (air, seawater, seafloor) with the seafloor halfspace of 1 Ωm resistivity (Figure 3b). The inversion result at iteration 10 with an RMS misfit of 4.4 is shown in Figure 3c. The location of the reservoir is well reconstructed, especially the upper edge at a depth of 500 m below the seafloor. Figure 4 shows synthetic data (INV1) compared to the final inversion responses calculated by our 2.5D code, which shows a good agreement.

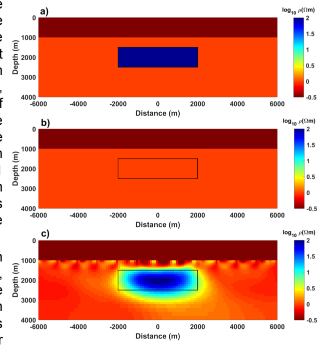

Figure 3: A synthetic test. (a) The true model, (b) the starting model and (c) the finial inversion result at iteration 10 with RMS misfit 4.4.

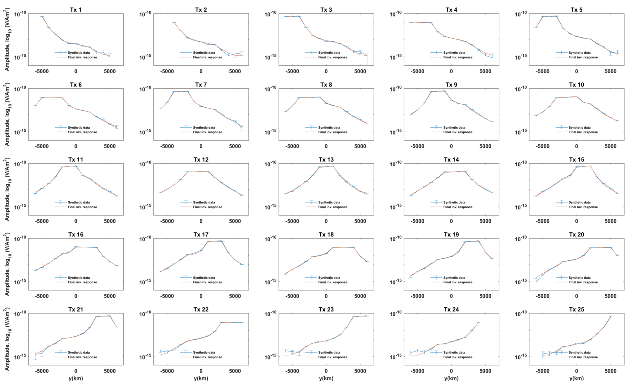

Figure 4: Synthetic data generated from the model shown in Figure 3a vs inverted responses.

Acknolegement

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