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Joint inversion for transmitter navigation and seafloor resistivity for frequency-domain marine CSEM data

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A B S T R A C T

We present a joint inversion method for the transmitter navigation and the seafloor resistivity for frequency domain marine controlled-source electromagnetic (CSEM) data. The inversion approach is based on the modified BFGS scheme, which has an advantage that one can update the Hessian matrix by using the BFGS scheme rather than computing the Hessian matrix itself during the inversion process. The partial derivatives of the electromagnetic field responses with respect to both the seafloor resistivity and the transmitter navigation parameters including the azimuth, dip and horizontal positions of the transmitter antenna are analytically calculated. We invert for both the navigation parameters of the towed dipole source (including antenna azimuth, dip, and horizontal positions) and seafloor resistivity by using the whole range of data instead of the near-field data (usually source-receiver offset $<$1 km). An eigenparameter analysis shows that seafloor resistivities and transmitter navigation parameters can be independently resolved, and a better reconstruction can be obtained with multiple frequency data. The inversions of both the synthetical and field data sets indicate that our inversion method can simultaneously reconstruct seafloor resistivity structures and transmitter navigation parameters.

1. Introduction

In the last decade, the marine controlled-source electromagnetic (CSEM) method is widely used to detect offshore hydrocarbon reservoirs and to characterize seafloor gas hydrates (Constable, 2010; Zhdanov, 2010). The frequency domain marine CSEM system often uses a deep-towed electric dipole source to transmit low frequency energy to an array of seabed receivers. Reliable numerical modeling and interpretation tools are required for proper data interpretation. This leads to the development of various forward modeling and inversion algorithms for marine CSEM data sets (Chave and Cox, 1982; Flosadóttir and Constable, 1996; Li and Key, 2007; Abubakar et al., 2008; Commer and Newman, 2008; Sasaki, 2012). The 1D inversion still plays an essential role in the qualitative and quantitative analysis of marine CSEM data, as an alternative to 2D or 3D inversions of the high computational costs (Christensen and Dodds, 2007; Silva Crepaldi et al., 2011). The 1D inversion can be viewed as a quick reconnaissance tool, or as an initial step within an inversion workflow that uses higher-dimensional inversion subsequently.

Recently, the importance of accurate knowledge of transmitter and receiver geometry is emphasized in the interpretation of time domain marine CSEM data sets (Swidinsky and Edwards, 2011). The errors in the position and orientation of both the transmitter and receivers can propagate into errors on observed data. In interpreting marine CSEM data, observed errors caused by transmitter and receiver geometry uncertainty could not be ignored. Christensen and Dodds (2007) investigated the effects of transmitter height and the data uncertainty resulting from varying transmitter height above the seafloor. Mittet et al. (2007) estimated receiver orientation by a median filtering approach. Commer and Newman (2008) developed the source signature correction method for CSEM modeling, in which an unknown complex scaling factor to each CSEM source is assigned for estimating data distortions in terms of both amplitude and phase shifts. Key and Lockwood (2010) estimated the orientation of the seafloor EM receivers along with seafloor resistivity by using the orthogonal procrustes rotation analysis method, but assumed that the other navigation parameters were known. Swidinsky and Edwards (2011) inverted for both the location of the first receiver on a towed receiver streamer and the seafloor resistivity from a transient marine CSEM data set. Mütschard et al. (2014) estimated the horizontal and vertical orientation of seafloor electromagnetic receivers by minimum difference criteria. Weitemeyer and Constable (2014)

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proposed an inversion method to determine the transmitter orientation by utilizing the near-field data (source-receiver offset <1 km) of the electric dipole source. Since the source effects dominate in the close range to the source, the near-field data might be useful to determine the source geometry parameters. However, the exact range of the near-field is hard to be defined in practice, as it depends on the source excitation frequency and the unknown seafloor resistivity structures. Here we propose an inversion method which utilizes the whole range of EM data to estimate the transmitter geometry parameters.

In this paper, we invert for both the navigation parameters of the towed dipole source (including antenna azimuth, dip, and horizontal positions) and seafloor resistivity by using the whole range of data. Our inversion method is based on the quasi-Newton (QN) method with the modified Broyden–Fletcher–Goldfarb–Shanno (BFGS) update scheme.

2. Forward modeling

Consider the orientation of a deep-towed marine CSEM transmitter antenna. A horizontal electric dipole source is pointed along the x-axis of the survey reference coordinates (x, y, z). The dipole source can be rotated by an azimuth angle α with respect to z-axis into (ξ, y', z). Then it will be further tilted by a dip angle β around the vertical y'-axis into the coordinates (x', y', z') (Fig. 1).

The rotation of the source dipole can be described by the following rotation matrix

$$\mathbf{R}' = \mathbf{D}_z \mathbf{D}_y \mathbf{R}, \tag{1}$$

where $\mathbf{R}$ and $\mathbf{R}'$ are an x-oriented horizontal electric dipole and a rotated source dipole, respectively. $\mathbf{D}_z$ and $\mathbf{D}_y$ are the rotation matrices with respect to the vertical and horizontal axes, respectively, and they are given by

$$\mathbf{D}_z = \begin{pmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}, \mathbf{D}_y = \begin{pmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{pmatrix}, \mathbf{R} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}. \tag{2}$$

Eq. (1) can be used to decompose the "dipole" moment along the direction of the rotated coordinate axes. In fact, the source dipole moment of a transmitter antenna with arbitrary orientation can be converted into three equivalent dipole moments on three orthogonal axes of the survey reference coordinate system. Electromagnetic fields due to a tilted dipole source can be seen as the superposition of those generated by three equivalent dipole sources: the vertical electric dipole (VED), and both the x- and y- directed horizontal dipole sources (x-HED and y-HED). The electric/magnetic field is given by

$$\mathbf{F} = \mathbf{F}_{x\text{-HED}} + \mathbf{F}_{y\text{-HED}} + \mathbf{F}_{\text{VED}}, \tag{3}$$

where $\mathbf{F}$ denotes the electric field $\mathbf{E}$ or the magnetic field $\mathbf{H}$. Combining Eqs. (1) and (2), Eq. (3) can be expressed as

$$\mathbf{F} = \bar{\mathbf{F}}\mathbf{R}', \mathbf{F} = \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix}, \bar{\mathbf{F}} = \left({}^x\mathbf{F}', \ {}^y\mathbf{F}', \ {}^z\mathbf{F}' \right) = \begin{pmatrix} {}^xF'_x & {}^yF'_x & {}^zF'_x \\ {}^xF'_y & {}^yF'_y & {}^zF'_y \\ {}^xF'_z & {}^yF'_z & {}^zF'_z \end{pmatrix}, \tag{4}$$

where $\mathbf{F} = (F_x, F_y, F_z)^T$ is the electric or magnetic field generated by an electric dipole source with an arbitrary orientation, $\bar{\mathbf{F}}$ is a matrix consisting of ${}^x\mathbf{F}'$, ${}^y\mathbf{F}'$ and ${}^z\mathbf{F}'$, and ${}^x\mathbf{F}' = ({}^xF'_x, {}^xF'_y, {}^xF'_z)^T$, ${}^y\mathbf{F}' = ({}^yF'_x, {}^yF'_y, {}^yF'_z)^T$ and ${}^x\mathbf{F}' = ({}^zF'_x, {}^zF'_y, {}^zF'_z)^T$ are the electromagnetic (EM) field caused by the x-directed unit HED source, the y-directed unit HED source and the unit VED source, respectively. For the survey reference coordinates (x, y, z), the fields due to the dipole oriented arbitrarily will be decomposed into the fields due to the three components along x-, y-, and z-axes.

We derived the electromagnetic field expressions in both the wavenumber domain and the space domain from both the horizontal and vertical electric dipoles, which can be located in any conductivity layer. The approach follows the electric and magnetic Schelkunoff potential formulation described in Ward and Hohmann (1988). But we extend and generalize the formulation to enable calculation of electromagnetic fields at any depth generated by a horizontal or/and a vertical electric dipole.

The CSEM fields in layered isotropic media is based on Løseth and Ursin (2007). The electric and magnetic fields in layered conducting medium generated by a point HED or VED source located at (x_s, y_s, z_s) can be expressed as (Li and Li, 2016)

$$F'(x_s, y_s, z_s, x, y, z) = P(x_s, y_s, x, y) \int_0^\infty \sum_{\nu=0}^{1} f_\nu(\sigma, z_s, z, \lambda) J_\nu(\lambda r) d\lambda, \tag{5}$$

where $F'(x_s, y_s, z_s, x, y, z)$ is the electric or magnetic field at a location (x, y, z), and F' is the component of ${}^x\mathbf{F}'$, ${}^y\mathbf{F}'$ and ${}^z\mathbf{F}'$. $P(x_s, y_s, x, y)$ is related to the horizontal positions of both the source and the measuring site as well as the dipole source moment, $J_\nu(\lambda r)$ is a ν-th order Bessel function of the first kind where the integer $\nu = 0$ or 1, and $f_\nu(\sigma, z_s, z, \lambda)$ is the corresponding kernel function depending on the subsurface physical properties (conductivity σ and thickness h of conductive layers) as well as the vertical positions of both the source and the measuring site. $r = \sqrt{(x - x_s)^2 + (y - y_s)^2}$ is the horizontal distance between the source and the measuring site. The Hankel transformations are computed by using the digital filter convolution procedure (Anderson, 1982).

For a short source-receiver offset, the dipole approximation is inaccurate and one can ensure accurate fields by using a finite dipole. Our code also allows for a finite-length dipole source with arbitrary orientation. The finite-length dipole fields are obtained by using the Gauss quadrature integration of point dipole fields over the dipole length. In this paper, a finite length dipole is used for all tests, and the antenna angles are assumed constant for the whole antenna, no bulges in the cables and thereby the angle represents an average along the cable, etc. The antenna of the rotation is also assumed constant as the antenna is dragged through the water.

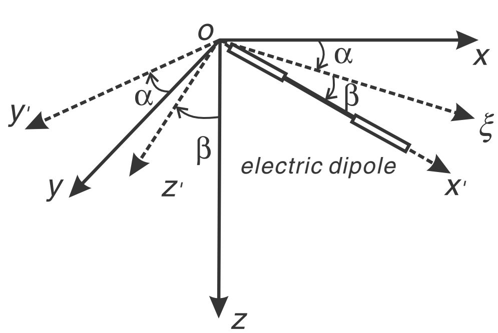

Fig. 1. Transmitter orientation parameters.