Electromagnetic migration of marine CSEM data in areas with rough bathymetry

Michael S. Zhdanov and Martin Čuma, University of Utah*

Summary

In this paper we present a new approach to the interpretation of the marine controlled-source electromagnetic (MCSEM) data in areas with rough bathymetry. This approach is based on a new formulation of the integral equation EM modeling method in models with inhomogeneous background conductivity. The developed technique allows us to incorporate known geological structures and bathymetry effects in the method of iterative EM migration/holographic imaging and inversion. This approach provides us with the ability to precompute only once the effect of a known geoelectrical structure (e.g., the bathymetry effect) and keep it unchanged during the entire modeling and migration process. The method is illustrated by numerical examples of modeling and inversion of marine CSEM data in areas with rough bathymetry.

Introduction

During recent years, the marine controlled-source electromagnetic (MCSEM) method has become widely used for active geophysical surveying of sea-bottom geological structures in hydrocarbon exploration. The interpretation of MCSEM data over complex 3D geoelectrical structures is a very challenging problem. This problem becomes even more complicated in areas with rough sea-bottom bathymetry, because the relief of a sea bottom makes a profound effect on the EM data observed by the receivers located in close proximity to the bottom.

In this paper we introduce a new approach to interpretation of MCSEM data in areas with rough bathymetry. This approach is based on a new formulation of the integral equation (IE) EM modeling method in models with inhomogeneous background conductivity (Zhdanov et al., 2006).

The developed technique allows us to incorporate known geological structures and bathymetry effects in the method of iterative EM migration/holographic imaging and inversion. This approach provides us with the ability to precompute only once the effect of the known geoelectrical structure (e.g., the bathymetry effect) and keep it unchanged during the entire modeling and migration process. Taking into account that precomputing the bathymetry effect constitutes the most time-consuming part of the EM modeling, this approach allows us to increase the effectiveness of the interpretation of the MCSEM data significantly

Accounting for bathymetry using EM migration with the inhomogeneous background conductivity (IBC) method

A marine CSEM survey typically consists of an array of receivers, which record the response of the earth to EM signals transmitted by single or multiple transmitters.
Figure 1 illustrates the principles of EM migration in a model with inhomogeneous background conductivity (IBC). We consider a 3D geoelectrical model with horizontally layered (normal) conductivity σ_n, inhomogeneous background conductivity $\sigma_b = \sigma_n + \Delta\sigma_b$ within a domain D_b, and anomalous conductivity $\Delta\sigma_a$ within a domain D_a (Figure 1). The model is excited by an EM field generated by an arbitrary transmitter which is time-harmonic as $e^{-i\omega t}$. The EM field is measured by a set of electric and/or magnetic field receivers, as shown in Figure 1. The goal is to develop a method of migration of the EM field recorded by the receivers in order to generate an image of the anomalous conductivity distribution.

The EM fields in this model satisfy Maxwell's equations:

$$\nabla \times \mathbf{H} = \sigma_n \mathbf{E} + \mathbf{j} = \sigma_n \mathbf{E} + \mathbf{j}^{\Delta\sigma_b} + \mathbf{j}^{\Delta\sigma_a} + \mathbf{j}^e, \qquad (1)$$
$$\nabla \times \mathbf{E} = i\omega\mu_0 \mathbf{H},$$

where:

$$\mathbf{j}^{\Delta\sigma_a} = \begin{cases} \Delta\sigma_a \mathbf{E}, & \mathbf{r} \in D_a \\ 0, & \mathbf{r} \notin D_a \end{cases} \qquad (2)$$

is the anomalous current within the local inhomogeneity D_a, and

$$\mathbf{j}^{\Delta\sigma_b} = \begin{cases} \Delta\sigma_b \mathbf{E}, & \mathbf{r} \in D_b \\ 0, & \mathbf{r} \notin D_b \end{cases} \qquad (3)$$

is the excess current within the inhomogeneous background domain D_b.

According to the basic principles of the integral equation method with inhomogeneous background conductivity (IE IBC (Zhdanov et al., 2006), one can represent the EM field in this model as a sum of the normal fields $\mathbf{E}^n$ and $\mathbf{H}^n$ generated by the given source(s) in the model with normal distribution of conductivity σ_n, a variable background effect $\mathbf{E}^{\Delta\sigma_b}$ and $\mathbf{H}^{\Delta\sigma_b}$ produced by the inhomogeneous background conductivity $\Delta\sigma_b$, and the anomalous fields $\mathbf{E}^{\Delta\sigma_a}$ and $\mathbf{H}^{\Delta\sigma_a}$ related to the anomalous conductivity distribution $\Delta\sigma_a$:

$$\mathbf{E} = \mathbf{E}^n + \mathbf{E}^{\Delta\sigma_b} + \mathbf{E}^{\Delta\sigma_a}, \ \mathbf{H} = \mathbf{H}^n + \mathbf{H}^{\Delta\sigma_b} + \mathbf{H}^{\Delta\sigma_a}, \quad (4)$$

The total EM fields in this model can be written as follows:

$$\mathbf{E} = \mathbf{E}^b + \mathbf{E}^{\Delta\sigma_a}, \quad \mathbf{H} = \mathbf{H}^b + \mathbf{H}^{\Delta\sigma_a}, \qquad (5)$$

where the background EM fields $\mathbf{E}^b$ and $\mathbf{H}^b$ are sums of the normal fields and those caused by the inhomogeneous background conductivity:

$$\mathbf{E}^b = \mathbf{E}^n + \mathbf{E}^{\Delta\sigma_b}, \quad \mathbf{H}^b = \mathbf{H}^n + \mathbf{H}^{\Delta\sigma_b}, \qquad (6)$$

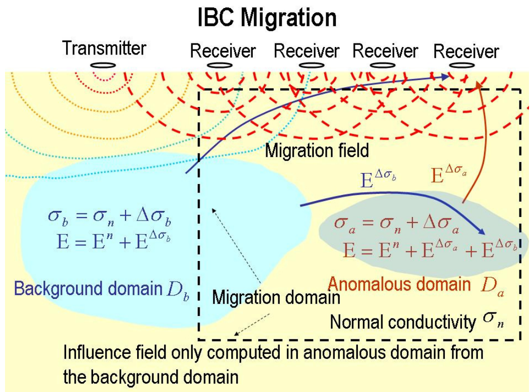

Figure 1. A sketch of a 3D geoelectrical model with horizontally layered (normal) conductivity, inhomogeneous background conductivity within a domain D_b, and anomalous conductivity within a domain D_a.

We assume that we know the given IBC model $\Delta\sigma_b$ and the corresponding background EM field in the receivers. Therefore, we can calculate the anomalous EM field in the receivers as follows:

$$\mathbf{E}^{\Delta\sigma_a}(\mathbf{r}_j) = \mathbf{E}(\mathbf{r}_j) - \mathbf{E}^b(\mathbf{r}_j), \; \mathbf{H}^{\Delta\sigma_a}(\mathbf{r}_j) = \mathbf{H}(\mathbf{r}_j) - \mathbf{H}^b(\mathbf{r}_j). \qquad (7)$$

In order to produce the migration field, we replace a set of the receivers with a set of auxiliary transmitters located in the receivers' positions. These transmitters generate an EM field, which is called a backscattering or migration field, $\mathbf{E}^m$. The vector cross-power spectrum of the background field $\mathbf{E}^b$ and the migration field, $\mathbf{E}^m$, produces a numerical reconstruction of a volume image of the conductivity distribution (Zhdanov, 2002):

$$\Delta\boldsymbol{\sigma}_1^m \approx \alpha^{-1}\left(\mathbf{W}_m^{\text{å}}\mathbf{W}_m\right)^{-1} Re \sum_{\omega_n} (\mathbf{E}^b \cdot \mathbf{E}^m), \qquad (8)$$

where summation is taken over the multiple frequencies, ω_n, and the model parameter weighting matrix $\mathbf{W}_m$ is computed using the integrated sensitivity $\mathbf{S}$ as follows (Zhdanov, 2002):

$$\mathbf{W}_m = \mathbf{S}^{\frac{1}{2}}, \qquad (9)$$

Note that, we migrate the anomalous field $\mathbf{E}^{\Delta\sigma_a}$, $\mathbf{H}^{\Delta\sigma_a}$ only, which is obtained by subtraction of the corresponding background field from the observed total field according to formulas (7).

Iterative IBC migration

It is known (Zhdanov, 2002), that one can produce a better quality migration image by repeating the migration process iteratively. We begin with the migration of the observed data and migration conductivity analysis using the migration transformation and imaging conditions outlined above. In order to check the accuracy of our migration imaging, we apply the forward modeling and compute a residual between the observed and predicted data for the given conductivity model.

In this forward modeling step we apply the IBC IE method developed by Zhdanov et al. (2006). In the framework of the IBC IE method, we solve the following equation to find the predicted data in the receivers for the anomalous conductivity model $\Delta\boldsymbol{\sigma}_1^m$:

$$\mathbf{E}^{\Delta\boldsymbol{\sigma}_1^m}(\mathbf{r}_j) = \iiint_{D_a} \widehat{\mathbf{G}}_E(\mathbf{r}_j|\mathbf{r}) \cdot \Delta\boldsymbol{\sigma}_1^m[\mathbf{E}^b + \mathbf{E}^{\Delta\boldsymbol{\sigma}_1^m}]dv = \mathbf{G}_E^{D_a}(\Delta\sigma_a[\mathbf{E}^b + \mathbf{E}^{\Delta\boldsymbol{\sigma}_1^m}]), \qquad (10)$$

If the residual between the observed and predicted data is smaller than the prescribed accuracy level, we use the migration image as a final geoelectrical model. In a case where the residual is not small enough, we migrate the residual field and produce a new anomalous conductivity model, $\Delta\boldsymbol{\sigma}_2^m$, using the same conductivity analysis which we applied to the original migration.

The iterative migration is terminated when the residual field becomes smaller than the required accuracy level of the data fitting. The mathematical details of the iterative migration algorithm are outlined in Ueda and Zhdanov (2008). It was demonstrated in that paper that the iterative migration, as well as the iterative inversion, could be implemented using a smooth or focusing regularization. Particularly, images with sharp boundaries can be recovered using the minimum support (MS) or minimum gradient support (MGS) stabilizing functionals. This technique is implemented in our algorithm of the focusing migration of electric and/or magnetic field data in models with inhomogeneous background conductivity (IBC).

We apply iterative migration with the adaptive regularization. The regularization parameter α is updated in the process of the iterative inversion as follows:

$$\alpha_n = \alpha_1 q^{n-1}; \quad n = 1,2,3\ldots..; \quad 0 < q < 1. \qquad (11)$$

Note that every iteration of the migration algorithm requires two forward modeling computations: one to compute the migration field, and the other one for computing the predicted data in the receivers.

There are several options for implementing the IBC method in the iterative migration scheme. One possibility is to calculate the contribution of the IBC domain at the receivers, subtract it from the observed data, and migrate only the contribution of the unknown anomaly. This option ignores the induction of the IBC field inside the anomalous domain, but, is still capable of producing fairly good result as the direct contribution of the IBC domain is dominant. We call this IBC option 1.

Another option is to precalculate the IBC field contribution at the receivers, and also the induced field in the anomalous domain before the iterative migration process, and then include this induced field at each migration iteration when calculating the predicted field at the receivers. This includes the inducted field at the anomaly but does not count in the induced field at the IBC domain caused by the anomaly. We call this IBC option 2. The computational cost of IBC option 2 is only slightly more than that of IBC option 1.

Finally, we can recalculate the induced fields both at the IBC and anomalous domains at each migration iteration and thus improve the accuracy of these fields iteratively, similar to the iterative IBC forward modeling introduced in Zhdanov et al. (2006). We call this method IBC option 3. The drawback of this method is considerably increased computational cost, since we need to calculate the induced fields in both domains at each migration iteration.

We implemented all three of these methods in the parallel computer code for our iterative IBC migration, and we used option option 2 for the model presented in this abstract. In tests not detailed in this paper, we did not find a major difference in the migrated results between options 2 and 3.

Migration of synthetic MCSEM data

To demonstrate the principles of EM migration in a model with an inhomogeneous background conductivity (IBC), we have designed a synthetic MCSEM surveys for model shown in Figure 2.

This model represents a practical case of modeling and inversion of marine controlled-source electromagnetic (MCSEM) data in the Sabah area of Malaysia to evaluate the feasibility of the IBC methods for routine MCSEM use. It also shows that our current migration programs are capable of modeling and inversion of realistic geoelectrical structures on massively parallel computers.

Sarawak Shell Berhad, Shell International Exploration and Production, and a PETRONAS managing unit performed a bathymetry survey over geologically favorable target reservoirs in the Sabah area in 2004. The location of the hydrocarbon reservoir in this area has been estimated from seismic surveys. We used the measured bathymetry data and positioned a synthetic reservoir-like geoelectrical structure at the similar location where the actual reservoir had been found. The synthetic structure has a complex 3D geometry and contains two layers: a water-filled layer with a resistivity of 0.5 Ohm-m, and an oil-filled layer with a resistivity of 100 Ohm-m (Figure 2). This model mimics a practical MCSEM survey conducted in the Sabah area with complex relief of the sea bottom. The survey consists of 81 horizontal bipole transmitters generating the EM field for two frequencies, 0.25 Hz and 0.75 Hz, and 16 receivers measuring E_x component of the electric field. The transmitters are spaced at 200 m at distance +/- 8000 m from the receivers. The receiver spacing is 1000 m. The bathymetry domain extends from the depth of $z = 1{,}070$ m to z = 1500 m, and from x = 15 km to x = 35 km, and from y = -3 km to y = 3 km in the horizontal directions. The sea depth varies from 1,070 m to 1,510 m (see Figure 3). The resistivity of cells in the bathymetry domain that are located below the sea bottom is the same as that of the background layer; the resistivity above the sea bottom equals that of the seawater. The complex reservoir is located between x = 22 km and x = 26 km and between y = -3,000 m and y = 3,000 m in the horizontal plane, and at the depth between z = 2,050 m and z = 2,146 m.

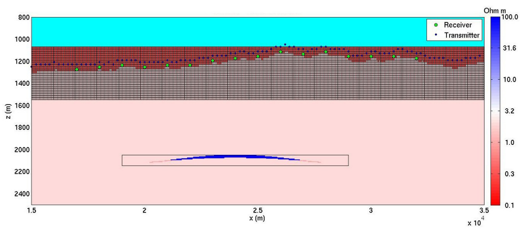

Figure 2. Resistivity plot of a vertical section of geoelectrical model. The bathymetry is in the upper part, and the discretization of this domain is shown in the figure. An outline of the anomalous domain appears in the lower part of the figure.

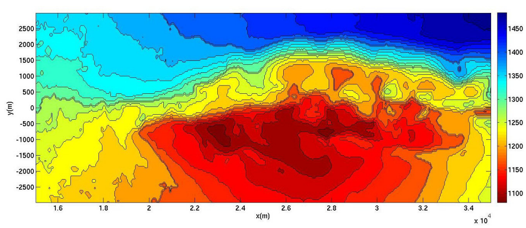

Figure 3. Contour plot of the bathymetry used in the model.

We have generated the fields at the receivers using our PIE3D forward modeling code. The bathymetry was discretized by $700 \times 120 \times 24 = 2{,}016{,}000$ cells with a cell size $50 \times 50 \times 20$ m. The anomalous domain was discretized with $400 \times 240 \times 16 = 1{,}535{,}000$ cells with a cell size $25 \times 25 \times 6$ m. The size of this problem requires running IBC forward modeling using significant parallel resources. We have utilized recently developed two level parallelization algorithm, parallelizing over the Z dimension of the domain and over the 16 receivers, using a total of 256 processors on a PC cluster. A total of 5 IBC iterations were needed to reach convergence. This is a typical number for the given separation between the two domains.

Migration input data obtained by the forward modeling were constructed by adding 1-7% Gaussian random noise, increasing with the distance from the transmitter. We used the same bathymetry as in the forward model. The anomalous domain extended from 17 to 32 km in the x direction, from -3 to 3 km in the y direction and from 1700 to 2500 m in the z direction. The cell size was $100 \times 100 \times 10$ m, resulting in total of 720,000 cells. We ran 25 iterations with a smooth minimum norm stabilizer followed by 5 iteration with a focusing minimum support stabilizer. The IBC domain fields were precalculated and kept constant during the migration (IBC option 2). We used 160 cores on a PC cluster, parallelizing over 80 Z layers and over 2 frequencies. We have found this to be the optimal performing configuration, using more processors overloaded the relatively weak I/O subsystem of the cluster, slowing down the performance. The migration took about 1 hour per iteration, about 30 hours total to finish. Our PC cluster consists of nodes with two 2.8 GHz Intel quad-core CPUs per node, 16 GB of RAM and InfiniBand network interconnect. We should note here that we also ran many faster migration runs with larger cell size in order to determine the optimal inversion parameters, and also optimal survey configuration.

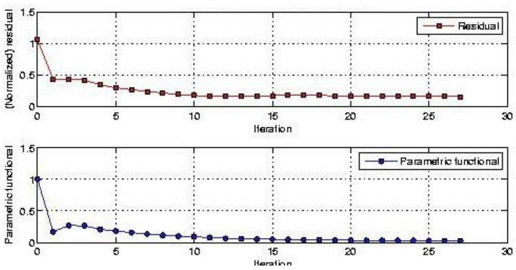

Figure 4. Convergence curves for the misfit and parametric functional.

The convergence curve of the migration is shown in Figure 4. We have achieved final misfit of 16%. A cross section of the anomaly at the survey line (y = 0 m) is shown in Figure 5. We resolved the location of the anomaly fairly well, although it is slightly too deep and too thick. The shape is not recovered exactly either, but, it is bent in the same way as the true model.

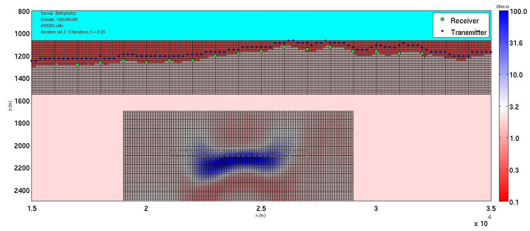

Figure 5. A cross section of bathymetry and migration result along $y = 0$ m. An approximate extent of the true oil anomaly is denoted with a dashed square.

Conclusions

In this paper we introduce the inhomogeneous background conductivity (IBC) method to the iterative migration method. We have developed the theoretical principles and a computer algorithm of a new imaging technique for frequency domain marine controlled-source electromagnetic (MCSEM) data interpretation with incorporation of known geological structures in an inhomogeneous background. We have implemented this method into our parallel iterative migration program. This method allows us to account for regional conductivity inhomogeneities in the area of investigation. The prime application of this method is to account for, e.g., salt dome structures or bathymetry effects in the MCSEM survey data. The models studied with this method show its applicability for interpretation of large and complex MCSEM surveys.

Acknowledgments

The authors acknowledge the support of the University of Utah Consortium for Electromagnetic Modeling and Inversion (CEMI) and allocation of computer time by University of Utah's Center for High Performance Computing.

.

We are thankful to Dr. Mark Rosenquist of Shell for providing the Sabah area bathymetry data and for permission to publish the modeling results.

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2009 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Ueda, T., and M. S. Zhdanov, 2008, Fast numerical methods for marine controlled-source electromagnetic (EM) survey data based on multigrid quasi-linear approximation and iterative EM migration: Exploration Geophysics, **39**, 60–67.

Zhdanov, M. S., 2002, Geophysical inverse theory and regularization problems: Elsevier.

Zhdanov, M. S., S. K. Lee, and K. Yoshioka, 2006, Integral equation method for 3D modeling of electromagnetic fields in complex structures with inhomogeneous background conductivity: Geophysics, **71**, no. 6, G333–G345.