Feasibility study of the marine electromagnetic remote sensing (MEMRS) method for near-shore exploration

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Summary

Marine controlled source electromagnetic (MCSEM) surveys have become an important part of offshore petroleum exploration. However, there exist very near-shore areas, with the depth varying from tens of meters to a few hundred meters, where it is technically difficult to use a towed electrical bipole transmitter. In some cases, the operating of the controlled electric sources in the near-shore zones is prohibited by the environmental concerns of the impact of the powerful electric current on the marine fauna. To address the needs of EM exploration in the near-shore zones, a new marine EM method has been recently developed, which is called marine electromagnetic remote sensing (MEMRS). This method consists of a very high moment onshore electric bipole transmitter and a large array of offshore receivers. In this paper we present a feasibility study of the MEMRS method.

Introduction

During recent years marine controlled source electromagnetic (MCSEM) surveys have become intensively used for offshore petroleum exploration (e.g., Hesthammer et al., 2010, 2011; Gabrielsen et al., 2013). However, there exist very near-shore areas, with the depth varying from tens of meters to a few hundred meters, where it is technically difficult to use a towed electrical bipole transmitter. In some cases, the operating of the controlled electric sources in the near-shore zones is prohibited by the environmental concerns of the impact of the powerful electric current on the marine fauna. To address the needs of EM exploration in the near-shore zones, a new marine EM method has been recently developed by Velikhov and Zhdanov (2011), which is called marine electromagnetic remote sensing (MEMRS). This method consists of a very high moment onshore transmitter located on the coast with a large array of offshore receivers. Simplified conceptual model of MEMRS is shown in Figure 1.

In this paper we present a feasibility study of the MEMRS method for near-shore HC reservoir exploration based on the numerical modeling of the EM response in the arrays of near-shore receivers. We have also developed a method of 3D inversion of MEMRS data which uses a rigorous integral equation (IE) based forward modeling and regularized focusing inversion algorithm (Zhdanov, 2002, 2009).

We present in this paper the preliminary results of the application of the developed inversion method to the interpretation of the synthetic MEMRS data collected by the near-shore receivers.

Integral equation method in a model with inhomogeneous background conductivity

We consider, first, the typical MEMRS survey consisting of a set of sea-bottom electrical and magnetic receivers and a fixed horizontal electric dipole transmitter located onshore. The transmitter generates a frequency domain EM field. The operating frequencies are usually selected to be low enough (in a range of 0.001 - 1 Hz) to propagate through the conductive sea water and sea-bottom layers of the sediments and to illuminate the sea-bottom geological structures.

In order to take into account the transition zone from the land to the marine geoelectrical sections, we apply the IE method with inhomogeneous background conductivity (IBC) (Zhdanov et. al., 2006; Zhdanov, 2009). 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.

The EM field in this model can be represented as a sum of the normal fields, $\mathbf{E}^n$, $\mathbf{H}^n$, generated by the given source(s) in the model with normal distribution of conductivity, σ_n, a variable background effect, $\mathbf{E}^{\Delta\sigma_b}$, $\mathbf{H}^{\Delta\sigma_b}$**,** produced by the inhomogeneous background conductivity, $\Delta\sigma_b$, and the anomalous fields, $\mathbf{E}^{\Delta\sigma_a}$, $\mathbf{H}^{\Delta\sigma_a}$ due to the anomalous conductivity distribution, $\Delta\sigma_a$, as:

$$\mathbf{E} = \mathbf{E}^n + \mathbf{E}^{\Delta\sigma_b} + \mathbf{E}^{\Delta\sigma_a}, \mathbf{H} = \mathbf{H}^n + \mathbf{H}^{\Delta\sigma_b} + \mathbf{H}^{\Delta\sigma_a}. \quad (1)$$

The total EM field in this model can be written as:

$$\mathbf{E} = \mathbf{E}^b + \mathbf{E}^{\Delta\sigma_a}, \qquad \mathbf{H} = \mathbf{H}^b + \mathbf{H}^{\Delta\sigma_a}, \qquad (2)$$

where the background EM field, $\mathbf{E}^b, \mathbf{H}^b$ is a sum of the normal fields and those caused by the inhomogeneous background conductivity:

$$\mathbf{E}^b = \mathbf{E}^n + \mathbf{E}^{\Delta\sigma_b}, \qquad \mathbf{H}^b = \mathbf{H}^n + \mathbf{H}^{\Delta\sigma_b}. \qquad (3)$$

Following the paper by Zhdanov et al. (2006), we write the integral representations for the electric fields of the given current distribution,

$$\mathbf{j}^{\Delta\sigma}(\boldsymbol{r}) = \mathbf{j}^{\Delta\sigma_b}(\boldsymbol{r}) + \mathbf{j}^{\Delta\sigma_a}(\boldsymbol{r}) = \Delta\sigma_b\mathbf{E}(\mathbf{r}) + \Delta\sigma_a\mathbf{E}(\mathbf{r}),$$

within a medium of normal conductivity, σ_n:

$$\mathbf{E}(\mathbf{r}_j) = \mathbf{E}^n + \iiint_{D_b} \widehat{\mathbf{G}}_E(\mathbf{r}_j|\mathbf{r}) \cdot \Delta\sigma_b\mathbf{E}(\mathbf{r})d\upsilon$$
$$+ \iiint_{D_a} \widehat{\mathbf{G}}_E(\mathbf{r}_j|\mathbf{r}) \cdot \Delta\sigma_a\mathbf{E}(\mathbf{r})d\upsilon,$$

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where the first integral term describes the excess part of the background fields generated by the excess currents in the inhomogeneous background domain, D_b:

$$\mathbf{E}^{\Delta\sigma_b}(\mathbf{r}_j) = \iiint_{D_b} \widehat{\mathbf{G}}_E(\mathbf{r}_j|\mathbf{r}) \cdot \Delta\sigma_b \mathbf{E}(\mathbf{r}) d\upsilon = \mathbf{G}_E^{D_b}(\Delta\sigma_b \mathbf{E}).$$

and the second term describes the anomalous fields generated by the anomalous domain, D_a:

$$\mathbf{E}^{\Delta\sigma_a}(\mathbf{r}_j) = \mathbf{E}(\mathbf{r}_j) - \mathbf{E}^{\mathrm{n}}(\mathbf{r}_j) - \mathbf{E}^{\Delta\sigma_b}(\mathbf{r}_j)$$

$$= \iiint_{D_a} \widehat{\mathbf{G}}_E(\mathbf{r}_j|\mathbf{r}) \cdot \Delta\sigma_a \mathbf{E}(\mathbf{r}) d\upsilon = \mathbf{G}_E^{D_a}(\Delta\sigma_a \mathbf{E}), \qquad (4)$$

In the last equations, the symbols $\mathbf{G}_E^{D_a,D_b}$ denote the electric Greens operators with a volume integration of D_a or D_b, respectively.

Using integral expression 4, one can calculate the electric field at any point $\mathbf{r}_j$ if the electric field is known within the inhomogeneity. Similar expression can be obtained for the magnetic field as well. Expression 4 becomes the integral equation for the electric field E(r) if $\mathbf{r}_j \in D_a$. This equation can be solved using the standard IE approach (e.g., Zhdanov, 2009).

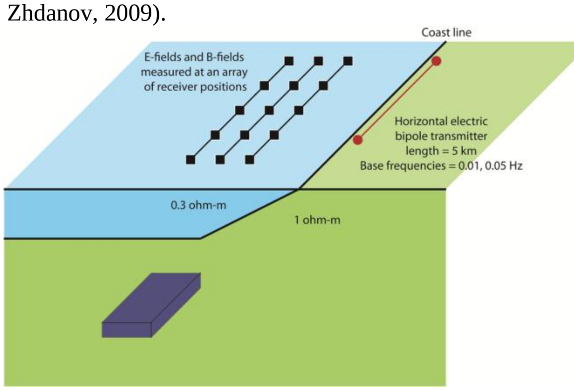

Figure 1: A simplified conceptual model of the MEMRS survey

Solution of the inverse problem for the models with inhomogeneous background conductivity

We use integral equations (4) to formulate both the forward and inverse problems of the MEMRS method. Indeed, in short form these equations can be written as:

$$\mathbf{d} = A(\boldsymbol{\Delta\sigma}), \qquad (5)$$

where A is a forward modeling operator, $\mathbf{d}$ stands for the observed EM data in the sea-bottom receivers, and $\boldsymbol{\Delta\sigma}$ is a vector formed by the anomalous conductivities within the targeted domain. The inversion is based on minimization of the Tikhonov parametric functional, $P^{\alpha}(\boldsymbol{\Delta\sigma})$, with the focusing stabilizer $s(\boldsymbol{\Delta\sigma})$ (Zhdanov, 2002):

$$P^{\alpha}(\boldsymbol{\Delta\sigma}) = \|A(\boldsymbol{\Delta\sigma}) - \mathbf{d}\|^2 + \alpha s(\boldsymbol{\Delta\sigma}). \qquad (6)$$

There are several different possible choices for the stabilizer. In this paper we use the minimum vertical support stabilizer (s_{MVS}), which is specially designed to invert for a thin, subhorizontal structure typical for HC reservoirs, and is defined by the formula:

$$s_{MVS}(\boldsymbol{\Delta\sigma}) = \iiint_V \left[\frac{(\boldsymbol{\Delta\sigma})^2}{\iint_S (\boldsymbol{\Delta\sigma})^2 dxdy + e^2}\right] dv, \qquad (7)$$

where S is a horizontal section of the rectangular domain V.

We use the regularized conjugate gradient (RCG) algorithm for minimization of the parametric functional $P^{\alpha}(\boldsymbol{\Delta\sigma})$ (Zhdanov, 2002). The critical element of the RCG inversion is computing the Fréchet derivative of the forward modeling operator. Direct computation of the Fréchet derivative is very time consuming even when the reciprocity principle is utilized. It was demonstrated in the paper by Gribenko and Zhdanov (2007) for MCSEM data inversion that the number of forward modeling can be reduced to one on every iteration step if we compute the Fréchet derivative using the modified form of the quasi-analytical (QA) approximation with the variable background conductivity or using the quasi-Born approximation (Zhdanov, 2009). In this case, no extra computation is required to compute the Fréchet derivative.

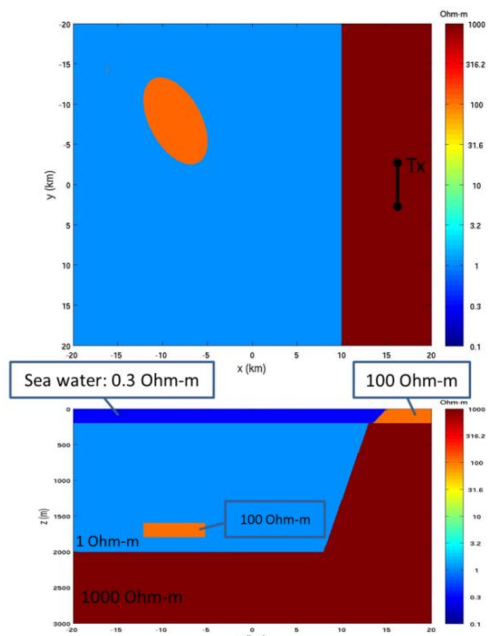

Figure 2: Geoelectrical model consists of a sea water layer with a thickness of 200m, a resistivity of 0.3 Ohm-m, and homogeneous sea-bottom sediments with a resistivity of 1 Ohm-m, and a resistive basement with a resistivity of 1,000 Ohm-m. An oval shape reservoir is located at a depth of 1.6 km below the sea level with the resistivity of 100 Ohm-m, a thickness of 200 m.

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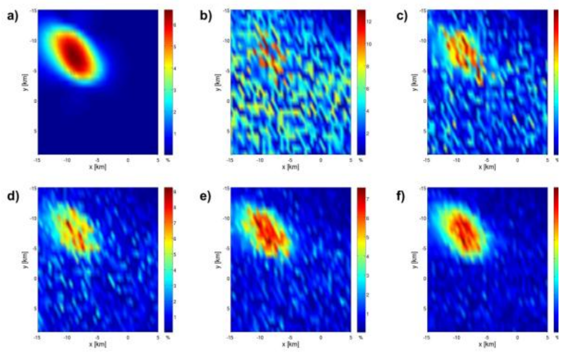

Figure 3: The maps of the absolute values of the y- component of anomalous electric field, normalized by the absolute values of the horizontal component of the background electric field at a frequency of 0.127 Hz. Panel a shows the noise free data; panel b presents the same data contaminated with the 8% noise; panels c, d, e, and f present the data obtained as a result of 5, 10, 20, and 40 times stacked noisy data.

Synthetic MEMRS data inversion

We have investigated several models of near-shore MEMRS surveys. In the majority of these model studies we have considered an electric bipole transmitter parallel to the coast with a large array of offshore electric field receivers. A simplified conceptual model of the MEMRS survey is shown in Figure 1.

In the first set of numerical experiments, we assume that a synthetic MEMRS survey is conducted in relatively shallow water with a sea depth of 200 m. The survey consists of 41 x 25 = 1025 sea-bottom electric receivers with 500 m and 1000 m separations in the x and y directions, respectively. The electric bipole transmitter of 5 km length is located onshore, 250 m inland from the coast. The transmitter generates a frequency domain EM field in the frequencies range from 0.001 to 1 Hz. The background geoelectrical model consists of a sea water layer with a thickness of 200 m, a resistivity of 0.3 Ohm-m, and homogeneous sea-bottom sediments with a resistivity of 1 Ohm-m, and a resistive basement with a resistivity of 1,000 Ohm-m (Figure 2). There is an oval shape reservoir located in the sea-bottom sediments at a depth of 1.6 km below the sea level with the resistivity of 100 Ohm-m, a thickness of 200 m, and horizontal maximum and minimum dimensions of 10 km by 5 km.

First, we have computed the synthetic observed data for this survey, using the IE IBC method. We have also contaminated the data with 8% random noise. In Figure 3 we plot the maps of absolute values of the y-component of anomalous electric field, $\left|E_y^{\Delta\sigma_a}\right|$, normalized by the absolute value of the horizontal component of the background electric field, $|E_y^b|$.

We have also computer simulated the data acquisition with repeated measurements for the same position of the transmitter and receivers, which allows us to apply stacking to the observed data. Panels c, d, e, and f in Figure 3 present the data obtained as a result of 5, 10, 20, and 40 times stacked noisy data. One can see how stacking improves the signature of the reservoir in the observed data.

We have run inversions for all these synthetic data sets. Figures 4 and 5 show a comparison between the inversion results for the noise free data, for the data contaminated with 8% random noise, and for the noisy data stacked 40 times, respectively. One can see how the inverse images are improved as a result of stacking the data.

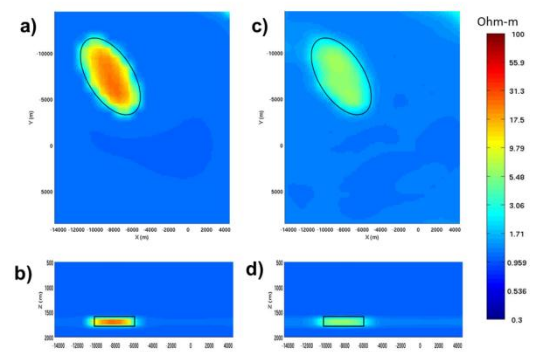

Figure 4: Comparison between the inversion result for the noise free data (left panel), and the data contaminated with 8% random noise (right panel).

We have investigated also the effect of the number of the receivers on the resolution of the inverse images. The original survey consisted of 41 x 25 = 1025 sea-bottom electric receivers with 500 m and 1000 m separations in the x and y directions, respectively. First, we have modified this survey by reducing the number of the receivers and considering 11 x 13 = 143 sea-bottom electric receivers with 2000 m and 2000 m separations in the x and y directions. The corresponding inversion results are shown in Figure 6. Next, we consider a survey with 7 x 9 = 63 sea-bottom electric receivers with 3000 m and 3000 m separations in the x and y directions. We still can see the location of the resistive reservoir in the inverse images (Figure 7).

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Finally, we have reduced the receiver's number to only 5 x 5 = 25 receivers. The inverse image of the reservoir is distorted, but still it can be seen in almost correct position (Figure 8).

Conclusions

We have conducted a feasibility study of marine electromagnetic remote sensing (MEMRS) method of EM-led exploration in environmentally sensitive offshore setting with the fixed onshore electric bipole transmitter and array of the offshore sea-bottom receivers. Our study demonstrates that the signal-to-noise ratio can be increased by stacking the signal in the multiple receivers.

We have developed a rigorous method for 3D inversion of MEMRS data based on the integral equation formulation. This method can be used for interpretation of field MEMRS data collected for offshore petroleum exploration. We have tested this method on a simple geoelectrical model, simulating the typical transmitter-receiver layout which can be used for the practical EM acquisition. Our modeling study shows that the MEMRS method is very robust to the noise, and it does not require a large number of the sea-bottom receivers in order to locate the resistive HC reservoir near-shore.

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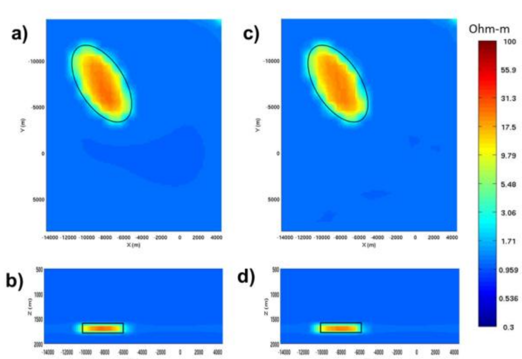

Figure 5: Comparison between the inversion result for the noise free data (left panel), and for the noisy data stacked 40 times (right panel).

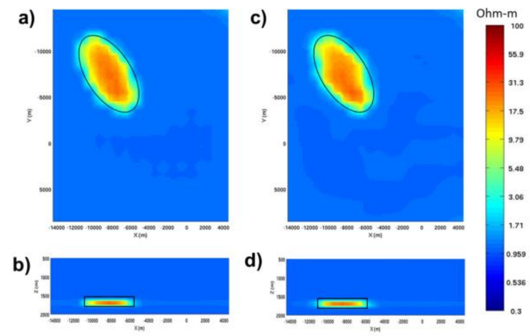

Figure 6: Horizontal and vertical sections of the inverse resistivity model generated for a survey with 11 x 13 = 143 sea-bottom electric receivers for the noise free data (left panel) and for the noisy data stacked 40 times (right panel).

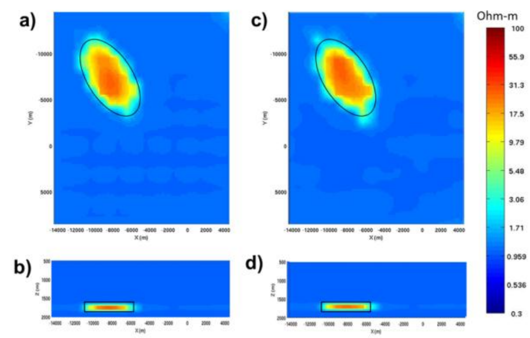

Figure 7: Horizontal and vertical sections of the inverse resistivity model generated for a survey with 7 x 9 = 63 sea-bottom electric receivers for the noise free data (left panel) and for the noisy data stacked 40 times (right panel).

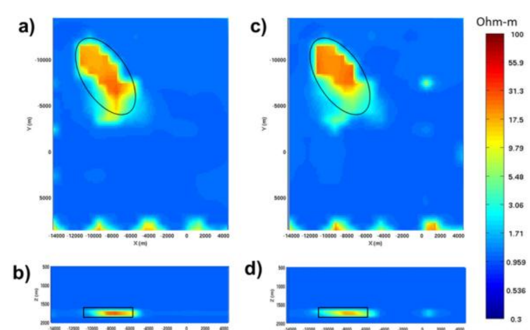

Figure 8: Horizontal and vertical sections of the inverse resistivity model generated for a survey with 5 x 5 = 25 sea-bottom electric receivers for the noise free data (left panel) and for the noisy data stacked 40 times (right panel).

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EDITED REFERENCES

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REFERENCES

Gabrielsen, P. T., P. Abrahamson, M. Panzner, S. Fanavoll, and S. Ellingsrud, 2013, Exploring frontier areas using 2D seismic and 3D CSEM data, as exemplified by multi-client data over the Skrugard and Havis discoveries in the Barents Sea: First Break, **31**, 63–71.

Gribenko, A., and M. S. Zhdanov, 2007, Rigorous 3D inversion of marine CSEM data based on the integral equation method: Geophysics, **72**, no. 2, WA73–WA84, http://dx.doi.org/10.1190/1.2435712.

Hesthammer, J., A. Stefatos, M. Boulaenko, S. Fanavoll, and J. Danielsen, 2010, CSEM performance in light of well results: The Leading Edge, **29**, 34–41, http://dx.doi.org/10.1190/1.3284051.>

Hesthammer, J., J. I. Rykkelid, S. Sperrevik, and D. Cumming, 2011, Use of CSEM data to aid a revised interpretation from the Norwegian Sea: First Break, **29**, 57–66.

Velikhov, E. P., and M. S. Zhdanov, 2011, Systems and methods for measuring sea-bed resistivity: US Patent No. 7,969,152.

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

Zhdanov, M. S., 2009, Geophysical electromagnetic theory and methods: Elsevier.

Zhdanov, M. S., S. K. Lee, and K. Yoshioka, 2006, Integral equation method for 3-D modeling of electromagnetic fields in complex structures with inhomogeneous background conductivity: Geophysics, **71**, no. 6, G333–G345, http://dx.doi.org/10.1190/1.2358403.