An optimal synthetic aperture method for the creation of directional sensitivity and removal of the airwave effect in MCSEM data

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Summary

This paper introduces a novel approach to the optimal design of the synthetic aperture method for marine controlled source electromagnetic (MCSEM) surveys. We demonstrate that the sensitivity of the MCSEM survey to a specific geological target could be enhanced by selecting the appropriate amplitude and phase coefficients of the corresponding synthetic aperture. We have developed a general optimization technique to find the optimal parameters of the synthetic aperture method. This approach makes it possible to increase the corresponding ratio between total and background fields within the area of an expected reservoir anomaly and in this way improve the resolution of the EM data with respect to potential subsurface targets. We also demonstrate that this optimal synthetic aperture method can be used for a removal of the distorting airwave effect from the MCSEM data collected in shallow water.

Introduction

The synthetic aperture (SA) method is based on designing sources with specific radiation patterns, which would "steer" a generated field in the direction of an area of interest (e.g., Degraaf, 1998; Cheney, 2001; Çetin and Karl, 2001; Korobov et al., 2010; Fan et al., 2010). A similar approach was recently discussed by Fan et al. (2010, 2012), where the authors applied a synthetic aperture method to the marine controlled-source electromagnetic (MCSEM) survey, formed by one line of transmitters and receivers. Knaak et al. (2013) applied synthetic aperture method to MCSEM surveys with multiple lines of transmitters and receivers. The method uses the interference of the fields radiated by different sources to construct a virtual source with a specific radiation pattern, according to which the field is steered toward the target. In order to find the optimal parameters of the synthetic aperture which increases the EM anomaly, associated with the target, the authors of the cited papers searched for all the possible combinations of the parameters within the given ranges.

Another approach to achieving this goal is based on introducing data weights in order to increase the integrated sensitivity of a survey to a specific target area of subsurface formation. For example, it was demonstrated by Kaputerko et al. (2007) that data weighting could dramatically affect the sensitivity distribution of a given survey. In the papers by Yoon and Zhdanov (2011) and Zhdanov (2013), the authors demonstrated how the sensitivity of the MCSEM survey could be "controlled" by selecting the appropriate data weights. The controlled sensitivity also results in an increase in the anomalous EM response from the target.

In the present paper, we introduce a general optimization technique to find the optimal parameters of the synthetic aperture method. This approach makes it possible to increase the corresponding ratio between total and background fields within the area of expected reservoir anomaly and in this way improve the resolution of the EM data with respect to potential subsurface targets. We also demonstrate that the optimal synthetic aperture method can be used for removal of a distorting airwave effect on MCSEM data collected in shallow water. As an illustration, we apply this method to the model exampled by Knaak et al. (2013), and to analysis of the synthetic MCSEM data computer simulated for the Harding oil and gas field in the North Sea.

Representation of the synthetic aperture method using data weights

Consider a typical marine controlled-source electromagnetic (MCSEM) geophysical survey, formed by a set of sea-bottom electric and magnetic field receivers, located at points with the coordinates $\mathbf{r}_l, l = 1, 2, \ldots, L$. The transmitting horizontal electric bipole is towed behind the ship and sends a low-frequency EM field from points with coordinates $\tilde{\mathbf{r}}_j, j = 1, 2, \ldots, J$. Receivers record the EM data, denoted by vector-column $\mathbf{d}^{(l)} = \left[d_1^{(l)}, d_2^{(l)}, \ldots, d_J^{(l)}\right]^{\mathrm{T}}$, where the upper index, l, corresponds to the position of a receiver at point $\mathbf{r}_l$, and the component $d_j^{(l)}$ describes the response recorded by a receiver at point $\mathbf{r}_l$ for a transmitter located at the point $\tilde{\mathbf{r}}_j$.

The synthetic aperture method is based on constructing a synthetic aperture source, $G_A(\mathbf{r};\omega)$, as a superposition of the spatially distributed sources, $g(\mathbf{r}, \tilde{\mathbf{r}}_j \omega)$ located at the points $\tilde{\mathbf{r}}_j, j = 1, 2, \ldots, J$:

$$G_A(\mathbf{r};\omega) = \sum_{j=1}^{J} a_j \exp(i\varphi_j)\, g(\mathbf{r}, \tilde{\mathbf{r}}_j \omega), \qquad (1)$$

where a_j is an amplitude weighting, and φ_j is a phase shift (Fan et al., 2010). We denote by $d_A^{(l)}$ the response recorded by receiver $\mathbf{r}_l, l = 1, 2, \ldots, L$ for a synthetic aperture source, G_A. Due to superposition principle, this signal can be calculated as a linear combination of the responses for the original transmitters:

$$\mathbf{d}_A = \mathbf{W}_A \mathbf{d}, \qquad (2)$$

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where $\mathbf{d}$ is a $[JL \times 1]$vector-column of the observed data,

$$\mathbf{d} = \left[\mathbf{d}^{(1)}, \mathbf{d}^{(2)}, \mathbf{d}^{(3)}, \ldots, \mathbf{d}^{(L)}\right]^{\mathrm{T}},$$

$\mathbf{d}_A$ is an $[L \times 1]$ vector-column of the synthetic aperture data,

$$\mathbf{d}_A = \left[d_A^{(1)}, d_A^{(2)}, d_A^{(3)}, \ldots, d_A^{(L)}\right]^{\mathrm{T}},$$

and $\mathbf{W}_A$ is a $[L \times JL]$ block-diagonal rectangular matrix of the weights,

$$\mathbf{W}_A = \begin{bmatrix} \mathbf{w}^{(1)} & 0\cdots & 0\cdots & 0\cdots \\ 0\cdots & \mathbf{w}^{(2)} & 0\cdots & 0\cdots \\ 0\cdots & 0\cdots & \ddots & 0\cdots \\ 0\cdots & 0\cdots & 0\cdots & \mathbf{w}^{(L)} \end{bmatrix}. \qquad (3)$$

In the last formula, $\mathbf{w}^{(l)}$ is a $[1 \times J]$ vector-row of the corresponding synthetic aperture weights, w_j,

$$\mathbf{w}^{(l)} = \left[w_1^{(l)}, w_2^{(l)}, \ldots, w_J^{(l)}\right];$$

and

$$w_j^{(l)} = a_j^{(l)} \exp\left(i\varphi_j^{(l)}\right). \qquad (4)$$

Application of the synthetic aperture weights, variable from receiver to receiver, is physically equivalent to "steering" the field generated from the transmitters in different directions for different receivers. As a result, one would obtain better "focusing" of the transmitting EM field on the geological target, e.g., the HC reservoir.

Definition of the optimal synthetic aperture for marine CSEM survey

For simplicity, we consider now the case of the weights, independent of the receiver positions. We also assume that the recorded data represent the in-line component of electric field. In this case, matrix equation (2) can be simplified as follows:

$$\mathbf{d}_A = \begin{bmatrix} E_1^{(1)} & E_2^{(1)} & \cdots & E_J^{(1)} \\ E_1^{(2)} & E_2^{(2)} & \cdots & E_J^{(2)} \\ \vdots & \vdots & \ddots & \vdots \\ E_1^{(L)} & E_2^{(L)} & \cdots & E_J^{(L)} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_J \end{bmatrix} = \mathbf{E}\mathbf{w} \qquad (5)$$

where $\mathbf{E}$ is a $[L \times J]$ matrix of rearranged observed in-line components of electric fields, $E_j^{(l)}$, recorded by a receiver at point $\mathbf{r}_l$ for a transmitter, and $\mathbf{w}$ is a $[J \times 1]$ vector-column of the corresponding synthetic aperture weights, w_j,

$$\mathbf{w} = \left[w_1, w_2, \ldots, w_J\right]^{\mathrm{T}}, \qquad \mathrm{w}_j = a_j \exp\left(i\varphi_j\right).$$

By analogy with expression (2), we denote by $d_B^{(l)}$ the electric field response recorded by receiver $\mathbf{r}_l, l = 1, 2, \ldots, L$ for a synthetic aperture source, computed for a geoelectrical model with the known background conductivity. Similar to formula (5), the synthetic aperture response for the background geoelectrical model, $\mathbf{d}_B$ can be expressed as follows:

$$\mathbf{d}_B = \mathbf{E}^{\mathrm{b}}\mathbf{w} \qquad (6)$$

where $\mathbf{E}^{\mathrm{b}}$ is an $[L \times J]$ matrix of rearranged background electric fields, and $\mathbf{d}_B$ is an $[L \times 1]$ vector-column,

$$\mathbf{d}_B = \left[d_B^{(1)}, d_B^{(2)}, d_B^{(3)}, \ldots, d_B^{(L)}\right]^{\mathrm{T}}.$$

The vector-column, $\mathbf{d}_R$ of the ratio between the observed in-line electric fields and the background fields of the synthetic aperture can be expressed as follows:

$$\mathbf{d}_R = \left[d_A^{(1)}/d_B^{(1)}, d_A^{(2)}/d_B^{(2)}, \ldots, d_A^{(L)}/d_B^{(L)}\right]^{\mathrm{T}} = \mathbf{A}(\mathbf{w}), (7)$$

where

$$d_A^{(l)}/d_B^{(l)} = \left[\sum_{j=1}^{J} E_j^{(l)} w_j\right] / \left[\sum_{j=1}^{J} E_j^{b(l)} w_j\right]$$

and $\mathbf{A}$ is a forward operator for the normalized synthetic aperture data $\mathbf{d}_R$, which is a function of the synthetic aperture weights, $\mathbf{w}$.

The fundamental concept of the synthetic aperture method is based on an assumption that one can design a synthetic aperture source which will steer the EM energy toward the target and in this way increase the ability to detect the target (Fan et al., 2010, 2012) by increasing the anomalous response from the target. This effect can be achieved automatically by selecting the synthetic aperture weights with the property that they magnify the normalized synthetic aperture data, $\mathbf{d}_R$, in the anticipated area of the location of the potential target. For example, let us introduce a vector-column $\mathbf{P}$, describing a designed normalized synthetic aperture data, which have a maximum over a specific area of the survey where we would like to steer the EM energy from a synthetic aperture source. We will determine the optimal synthetic aperture weights by solving a minimization problem for the following objective functional:

$$\varphi(\mathbf{w}) = \|\mathbf{P} - \mathbf{A}(\mathbf{w})\|^2 = \min. \qquad (8)$$

We can solve the minimization problem (8) by using the regularized conjugate gradient method (Zhdanov, 2002).

$$\mathbf{r}_{\mathrm{n}} = \mathbf{A}(\mathbf{w}_{\mathrm{n}}) - \mathbf{P},$$

Once we find the synthetic aperture weights, $\mathbf{w} = \left[w_1, w_2, \ldots, w_J\right]^{\mathrm{T}}$, we can convert them into the synthetic aperture parameters as follows:

$$a_j = |w_j|;\ \varphi_j^{(l)} = arg(w_j).$$

This concludes the definition of the optimal synthetic aperture for marine CSEM survey.

Numerical model study

Knaak et al. (2013) presented an example of the application of synthetic aperture method to a 3D synthetic CSEM data with a 2D source distribution. We used the same model to demonstrate the advantages of the developed optimal synthetic aperture method. The model consisted of 2 km deep seawater layer with a resistivity of 0.33 Ohm-m, and anisotropic layered sea-bottom sediments (background

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model). A 4km x 4km x 50m reservoir structure is located at 3.5 km depth with an isotropic resistivity of 35 Ohm-m. The receivers were located at the sea bottom and spanned from -7 km to 7 km in the in-line (x) direction and from -4km to 4km in the cross line (y) direction spaced every 250 m. The source was a 300-m horizontal dipole with a frequency of 0.2 Hz. The outlines of the reservoir and source locations are shown by black and red solid lines, respectively, in Figure 1.

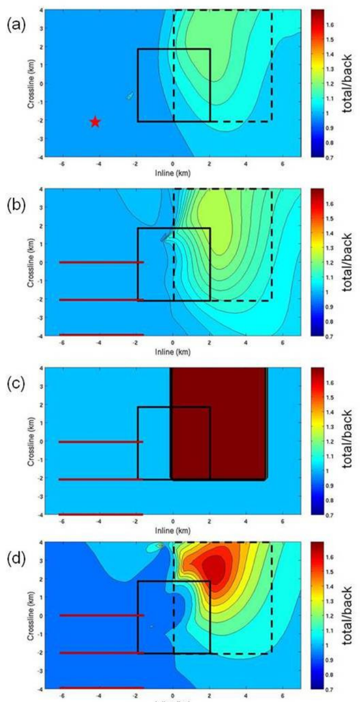

Figure 1: Illustration of an application of the optimal synthetic aperture method to the synthetic MCSEM data computed for deep water model of Knaak et al. (2013).

We have conducted the numerical experiments similar to those presented by Knaak et al. (2013). Panel (a) in Figure 1 presents the original plot of the normalized data, computed as the ratio of the in-line electric field responses generated by a single source for the model with HC reservoir and the corresponding background electric fields (without the HC reservoir). Panel (b) shows the normalized synthetic aperture data for synthetic aperture source without steering. Panel (d) presents the normalized data produced by our optimal synthetic aperture method. In the latter case we used a designed normalized synthetic aperture data **P**, which were introduced as a simple boxcar function covering the area of the expected reservoir anomaly (dashed line in panel (b)) detected by a single 100 m bipole source, as shown in panel (c) of Figure 1. One can see that our method successfully found optimal synthetic aperture weights for this model which significantly increases the ratio of the observed and background fields.

Reduction of the air wave effect in shallow water using synthetic aperture method

One of the problems of interpretation of MCSEM data in shallow water is the effect of the so-called air wave, which represents that part of an EM signal from the transmitter propagating over the sea surface. Analysis and removal of the airwave effect has been a subject of a number of publications (e.g., Amundsen et al., 2006; Constable and Weiss 2006; Um and Alumbaugh, 2007; Andréis and MacGregor, 2008). In this paper, we develop a new method of solving this problem based on our optimal synthetic aperture method.

In the original model of Knaak et al. (2013), the authors considered deep water model (depth 2 km), in order to weaken the air wave effect at the acquisition level (sea bottom). We have designed a new model, which is similar to that of Knaak et al. (2013) with the only difference being that in our model the water depth is just 200 m. In this case one should expect a strong air wave effect in the observed data.

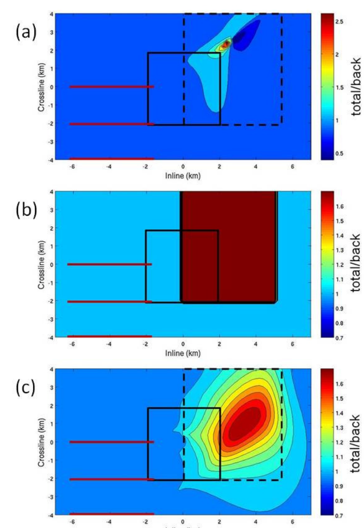

Figure 2: Illustration of an application of the optimal synthetic aperture method to the synthetic MCSEM data computed for shallow water model.

We have plotted in panel (a) of Figure 2 the original normalized data for shallow water model, computed as the ratio of the in-line electric field responses generated by synthetic aperture source for the model with HC reservoir and corresponding background electric fields (without the

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HC reservoir). Comparison of this plot with a similar plot of the data recorded in the original model with the 2 km water depth (Figure 1, panel b) shows that, in shallow water the response from the target, HC reservoir, is dramatically distorted by the effect of the air wave. In order to remove this distorting effect, we have designed a synthetic aperture data in a form of a boxcar function covering the area of the expected reservoir anomaly (Figure 2, panel b). Finally, panel (c) presents the normalized synthetic aperture data produced by our optimal synthetic aperture method based on the designed boxcar function response. We can see that the plot of the normalized synthetic aperture data in Figure 2 (panel b) has a regular shaped oval structure, similar to the one shown in Figure 1, panel d, for a deep-water anomaly. This observation confirms that we have successfully removed the distorting effect of the air wave from the observed shallow water data.

Application of the optimal synthetic aperture method to the Harding field MCSEM data

We have applied the developed optimal synthetic aperture method to synthetic MCSEM data computer-simulated for a Harding oil and gas field located in the UK sector of the North Sea, about 320 km northeast of Aberdeen.

The Harding field porosity and fluid saturation models were obtained from history matched reservoir simulations constructed from production data, well logs, and 3D seismic interpretations (Ziolkowski et al., 2010; Zhdanov et al., 2012). The corresponding 3D resistivity model consists of a 110 m 0.3 Ohm-m water column overlying an otherwise homogeneous half-space of 1.0 Ohm-m in which the Harding reservoir model is embedded.

The MCSEM data were then simulated for these models and then subjected to multiple synthetic aperture scenarios. In one of the numerical experiment we considered three transmitter lines shown by the bold red lines in Figure 3.

We have plotted in panel (a) of Figure 3 the original normalized data for the Harding field model. The effect of the HC reservoir is very weak in this image due to the effect of the air wave. In order to remove this distorting effect, we used a designed synthetic aperture data in the form of a boxcar function covering the area of the expected electric field anomaly (Figure 3, panel b). The result of application of the optimal synthetic aperture method based on the designed boxcar function response is shown in panel (c). The electric field anomaly due to the HC reservoir clearly manifests itself in the last image. This modeling study for the synthetic MCSEM data computer-simulated for the Harding field demonstrate again a capability of the developed method for removing the air wave effect from the observed shallow-water data.

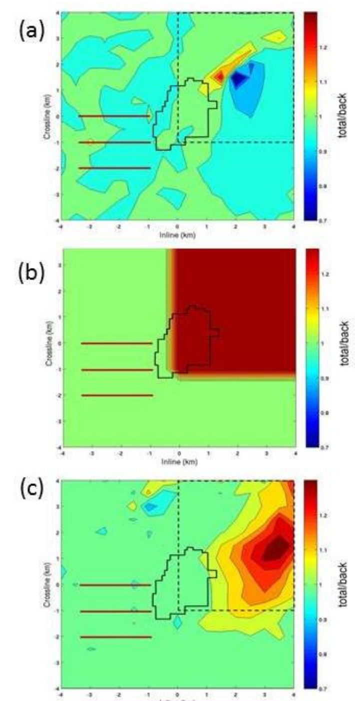

Figure 3: Illustration of an application of the optimal synthetic aperture method to the Harding field MCSEM data.

Conclusions

The synthetic aperture method, introduced for the marine CSEM method in the papers by Fan et al. (2010, 2012), uses an integrated source as a combination of multiple individual sources, in order to increase the detectability of hydrocarbon reservoirs. We have demonstrated in this paper that this method can be mathematically described as the data weighting with a special way of selecting the data weights in order to construct the synthetic aperture source. We have developed a general optimization technique to find the optimal parameters (data weights) of the synthetic aperture method. This approach makes it possible to increase the corresponding ratio between total and background fields within the area of an expected reservoir anomaly and in this way improve the resolution of the EM data with respect to potential subsurface targets. We have also demonstrated that the optimal synthetic aperture method can be used for a removal of the distorting airwave effect from the MCSEM data collected in shallow water.

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EDITED REFERENCES

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