Rapid Imaging of Towed Streamer EM Data for Reconnaissance Offshore Exploration Using the Optimal Synthetic Aperture Method

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Summary

Marine towed streamer electromagnetic (EM) surveys have become extensively used for offshore hydrocarbon (HC) exploration. The mainstream approach to interpretation of towed streamer EM data is based on 2.5D and/or 3D inversions of the observed data into the resistivity models of the sea-bottom formations. However, in the case of a reconnaissance towed streamer EM survey with the goal of scanning a vast area of the marine shelf, one needs to use a rapid imaging technique, which could provide a real-time evaluation of the potential prospects. This paper introduces an innovative technique of rapid imaging of towed streamer EM data based on the concept of the synthetic aperture method. We introduce an optimization technique to find the optimal parameters of the synthetic aperture method for a towed streamer EM survey, and demonstrate that this method increases the EM response from the potential sea-bottom targets effectively. Towed streamer EM data acquired over the Troll oil and gas fields in the North Sea are used as a test study. Our imaging results are shown to be consistent with those obtained by rigorous inversion and with the true location of the HC deposits.

Introduction

Interpretation of the multitransmitter and multireceiver EM data typical for the towed streamer surveys is a very challenging problem, which usually requires a large-scale inversion of the observed data. In this situation, it is desirable to develop a rapid imaging technique for the towed streamer EM data for reconnaissance surveying of vast areas of the shelf. We propose using for this purpose a concept of the synthetic aperture (SA) which has been widely used for processing and imaging the radiofrequency electromagnetic and acoustic waves recorded by radars and sonars. It is based on the idea that a virtual source constructed from different actual sources with specific radiation patterns can steer the interfered fields in the direction of an area of interest (DeGraaf, 1998; Cheney, 2001; Cetin and Karl, 2001; Korobov et al., 2010). A similar approach has been introduced for diffusive EM fields (Fan et al., 2010, 2012; Knaak et al., 2013; Mattsson and Engelmark, 2013), where the authors applied the SA method for the marine controlled-source electromagnetic (MCSEM) and towed streamer EM surveys by constructing an SA source to steer the generated fields in the direction of the target.

Another approach to achieving this goal has been introduced in Yoon and Zhdanov (2011) and Zhdanov (2013), where the authors increased the sensitivity of the EM response to the target using the concept of focusing controlled sensitivity by selecting the appropriate combination of the data weights.

In papers by Yoon and Zhdanov (2014, 2015), the authors introduced a concept of optimal SA by determining the optimal parameters of the SA for the MCSEM data, which enhances the EM anomaly from a target located in either deep or shallow marine environments. Note that the conventional MCSEM survey configuration uses fixed-node sea-bottom receivers and moving transmitters. In this paper, we develop an optimal SA method for towed streamer EM survey data with transmitter and receivers towed behind the vessel. This paper demonstrates that the developed method increases the EM response from the potential sea-bottom targets significantly, which can be effectively used in reconnaissance surveys for finding the locations of HC reservoirs.

Virtual Receivers

The towed streamer EM survey consists of a set of transmitter and receivers towed by a vessel, while the MCSEM survey deploys fixed receivers at the sea floor.

Consider a typical towed streamer EM survey, formed by a set of towed receivers with transmitter-receiver offset index, $s = 1, 2, \ldots, S$. A long bipole transmitter generates a low-frequency EM field from the points with coordinates $\tilde{\mathbf{r}}_j, j = 1, 2, \ldots, J$. The data recorded at the receivers by a transmitter at point $\tilde{\mathbf{r}}_j$ can be denoted by a vector-column, $\mathbf{d}_j = \left[d_j^{(1)}, d_j^{(2)}, \ldots, d_j^{(S)}\right]^{\mathrm{T}}$ where $d_j^{(s)}$ is the datum observed at offset, *s*, from the transmitter located at point $\tilde{\mathbf{r}}_j$.

In the marine environment, the measured electric field decays quickly with an increase in the distance (offset) between the transmitter and the receiver, which makes it difficult to detect an anomaly related to the target reservoir. In order to overcome this problem, the observed data are usually normalized by the amplitude of the background field data as follows:

$$d_j^{N(s)} = d_j^{(s)} / \left|d_j^{b(s)}\right|, \tag{1}$$

where $d_j^{(s)}$ and $d_j^{b(s)}$ describe the total and background field data, respectively, recorded at offset, *s*, from the transmitter located at point $\tilde{\mathbf{r}}_j$.

The background field is determined as a field generated by a given transmitter in some background geoelectrical model, which is usually selected as a horizontally layered model (Zhdanov, 2009). There are different ways to determine the background field. One way is based on 1D inversion of the observed data. Another way uses the reference field in the observation point far enough from the expected target. Indeed, if we know that some measurements are made outside the location of the expected target, we can consider these data as a background (reference) field,

$$\mathbf{d}^b = \left[d_j^{(1)}, d_j^{(2)}, \dots, d_j^{(S)}\right]^{\mathrm{T}} = \left[d_{ref}^{(1)}, d_{ref}^{(2)}, \dots, d_{ref}^{(S)}\right]^{\mathrm{T}}, \quad (2)$$

where $ref \in j = 1, 2, \dots, J$.

In order to apply the optimal SA method, we first determine the positions of the virtual receivers to be shared by all the transmitters. For simplicity, consider all actual receiver positions for all transmitters coinciding with the corresponding virtual receiver positions. If we assume there are no exactly overlapped receiver positions for different sources in the original data, there will be $L = JS$ virtual receiver positions with coordinates, denoted as follows: $\mathbf{r}_l$, $l = 1, 2, \dots, L$. The normalized observed data are then interpolated into the virtual receiver positions for each source position j, forming an $[L \times 1]$ vector-column, $\mathbf{d}_j^N = \left[d_j^{N(1)}, d_j^{N(2)}, \dots, d_j^{N(L)}\right]^{\mathrm{T}}$, where $j=1,2,\dots,J$. Note that, the values $d_j^{N(l)}$ corresponding to the range exceeding the maximum offset from the corresponding transmitter, $\tilde{\mathbf{r}}_j$, are set to be 1 (a unit) because the normalized data are equal to 1 everywhere outside the anomaly (assuming for simplicity that the observed data are equal to the reference background field outside the anomaly).

Combining all the normalized data for all transmitters, we obtain a $[JL \times 1]$ vector-column of the data recorded in both the actual and virtual receivers,

$$\mathbf{d}^N = \left[\mathbf{d}_1^N, \mathbf{d}_2^N, \mathbf{d}_3^N, \dots, \mathbf{d}_J^N\right]^{\mathrm{T}} \quad (3)$$

Optimal Synthetic Aperture For Towed Streamer EM Survey

It was demonstrated in Yoon and Zhdanov (2015) that the SA data can be calculated as a linear combination of the responses for all the transmitters:

$$\mathbf{d}_A = \mathbf{W}_A \mathbf{d}^N, \quad (4)$$

where $\mathbf{d}_A$ is an $[L \times 1]$ vector-column of the SA data based on the normalized observed data, $\mathbf{d}_A = \left[d_A^{(1)}, d_A^{(2)}, d_A^{(3)}, \dots, d_A^{(L)}\right]^{\mathrm{T}}$; and $\mathbf{W}_A$ is a $[L \times JL]$ block-diagonal rectangular matrix of the weights,

$$\mathbf{W}_A = \begin{bmatrix} \mathbf{w}^{\mathrm{T}} & 0\cdots & 0\cdots & 0\cdots \\ 0\cdots & \mathbf{w}^{\mathrm{T}} & 0\cdots & 0\cdots \\ 0\cdots & 0\cdots & \ddots & 0\cdots \\ 0\cdots & 0\cdots & 0\cdots & \mathbf{w}^{\mathrm{T}} \end{bmatrix}. \quad (5)$$

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

$$\mathbf{w} = \left[w_1, w_2, \dots, w_J\right]^{\mathrm{T}}. \quad (6)$$

The goal is to find the optimal values of the weights, w_j, which would enhance the EM anomalies from the targets.

Note that, the towed streamer EM system measures the in-line component of the electric field, E, (Engelmark et al., 2012; Mckay et al., 2015). In this case, following Yoon and Zhdanov (2015), we can write equation (4) as follows:

$$\mathbf{d}_A = \mathbf{E}^{\mathrm{N}} \mathbf{w}, \quad (7)$$

where $\mathbf{E}^{\mathrm{N}}$ is an $[L \times J]$ matrix of the normalized in-line components of the electric fields, $E_{\mathrm{j}}^{\mathrm{N(l)}}$, recorded by a virtual receiver at point $\mathbf{r}_l$ for a transmitter, $\tilde{\mathbf{r}}_j$:

$$\mathbf{E}^{\mathrm{N}} = \begin{bmatrix} E_1^{N(1)} & E_2^{N(1)} & \cdots & E_J^{N(1)} \\ E_1^{N(2)} & E_2^{N(2)} & \cdots & E_J^{N(2)} \\ \vdots & \vdots & \ddots & \vdots \\ E_1^{N(L)} & E_2^{N(L)} & \cdots & E_J^{N(L)} \end{bmatrix}. \quad (8)$$

By analogy with equation (7), the SA response for the normalized background electric field can be expressed as $\mathbf{d}_B = \mathbf{E}^{\mathrm{Nb}} \mathbf{w}$, where $\mathbf{d}_B$ is an $[L \times 1]$ vector-column, and $\mathbf{E}^{\mathrm{Nb}}$ is an $[L \times J]$ matrix of the normalized background electric fields at the virtual receivers, with the scalar components, determined as follows:

$$E_j^{Nb(l)} = E_j^{b(l)} / \left|E_j^{b(l)}\right|, l = 1, 2, \dots, L;\ j = 1, 2, \dots, J \quad (9)$$

We also introduce vector-column, $\mathbf{d}_R$ of the ratio between the SA data and the SA response for the normalized background electric field:

$$\mathbf{d}_R = \left[\frac{d_A^{(1)}}{d_B^{(1)}}, \frac{d_A^{(2)}}{d_B^{(2)}}, \dots, \frac{d_A^{(L)}}{d_B^{(L)}}\right]^{\mathrm{T}} = \mathbf{A}(\mathbf{w}), \quad (10)$$

where

$$d_A^{(l)} / d_B^{(l)} = \left[\sum_{j=1}^{J} E_j^{N(l)} w_j\right] / \left[\sum_{j=1}^{J} E_j^{Nb(l)} w_j\right], \quad (11)$$

where $\mathbf{A}$ is a forward operator for the normalized SA data $\mathbf{d}_R$, which is a function of the SA weights $\mathbf{w}$. Note that, if all the SA weights $\mathbf{w}$ are equal to 1, then according to Yoon and Zhdanov (2015), the corresponding data $\mathbf{d}_R$ are called the SA data without steering. The $\mathbf{d}_R$ computed based on the optimal SA weights, are called optimal SA data.

It was shown in Yoon and Zhdanov (2015) that one can find the optimal SA weights by solving a minimization problem for the corresponding parametric functional:

$$P(\mathbf{w}) = \|\mathbf{D} - \mathbf{A}(\mathbf{w})\|^2 + \alpha\left\|\mathbf{w} - \mathbf{w}_{\mathrm{apr}}\right\|^2 = \min, \quad (12)$$

where $\mathbf{D}$ is a so-called designed synthetic aperture (DSA), α is a regularization parameter, and $\mathbf{w}_{\mathrm{apr}}$ is an a priori vector-column of the data weights, which, for simplicity, can be selected as follows: $\mathbf{w}_{\mathrm{apr}} = [1, 1, \dots, 1]^{\mathrm{T}}$. The designed synthetic aperture, DSA, according to its name, is selected (designed) with the purpose of enhancing the EM anomalies from the potential targets. The minimization problem in equation (12) is solved using the regularized conjugate gradient method (Yoon and Zhdanov, 2015; Zhdanov, 2015).

Synthetic Model Study

We consider a complex model, which consists of two thin reservoirs and near-seafloor inhomogeneities. The background geoelectrical model consists of 300 m seawater with a resistivity of 0.33 Ohm-m, and five conductive sediment layers as shown in Figure 1. The first top sediment layer with a thickness of 200 m represents the near-seafloor inhomogeneities, with resistivities varying randomly from 1 to 4 Ohm-m. The resistivities of the second sediment layer and below including the bottom half space are 3, 2, 5, and 4 Ohm-m, respectively. The reservoirs have the same size of 4 km x 4 km x 200 m but they are located at different depths of 1100 m (the left reservoir) and 800 m (the right reservoir) below the sea surface, with resistivities of 50 Ohm-m and 100 Ohm-m, respectively. The separation between the reservoirs is 4 km in the x direction.

The towed streamer EM survey consists of one survey line, running in the x direction at y = 0. The horizontal electric dipole transmitter oriented in the x direction with a moment of 1 Am is towed from 20 km to -20 km in the x direction at a depth of 10 m below the sea surface. Sixty receivers with offsets between 900 m and 7720 m are towed at a depth of 100 m and measure inline electric fields at a frequency of 0.4 Hz.

The data were contaminated with the random 5 % Gaussian noise.

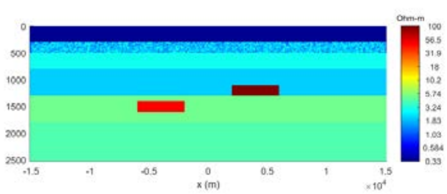

Figure 1: Scketch of the geoelectrical model.

We first construct a SA source using all the transmitters in the survey line, and select the background (reference) field as the observed data generated by the very first transmitter located at x=20 km. Then, we plot the normalized SA data without steering as shown by the black line in panel (a) of Figure 2. In this complex model, the SA data without steering are distorted due to the near-surface inhomogeneities and the noise in the observed data, which makes it difficult to determine the locations of the targets from the anomalous responses in the plot of the SA data without steering.

We select a uniform designed synthetic aperture shown by a blue line in panel (a) of Figure 2. After applying the optimal SA method to the observed data, we have generated optimal SA data shown by the red line. One can see that the anomalies of the SA data increased over the reservoirs, while the magnitude of the data elsewhere remains practically the same as for the SA data without steering. Lastly, to clearly see the increased anomalies only, we plot the ratio between the optimal SA data and the SA data without steering in panel (b) of Figure 2. As one can see the areas of the increased anomalies agree well with the true horizontal locations of the targets (black bars in panel (b) of Figure 2).

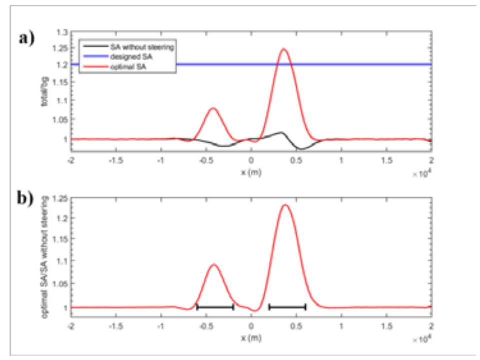

Figure 2: Panel a shows the normalized SA data without steering (black line), designed synthetic aperture (blue line), and optimal SA data (red line). Panel b presents the plot of the ratio between the optimal SA data and that without steering (red line); the horizontal locations of the reservoirs are shown by the black segments.

Application of The Optimal Synthetic Aperture Method To The Towed Streamer EM Data Collected In The Troll West Oil and Gas Provinces

We applied the optimal SA method to the towed streamer EM data collected in the Troll West Oil and Gas Provinces. These data were studied in Zhdanov et al. (2014a, b), where a rigorous 3D inversion was conducted for these data, making them a suitable dataset for testing the optimal SA method.

The towed streamer EM data used in our numerical study were collected at seven survey lines at a frequency of 0.496 Hz. Figure 3 shows the seven survey lines over the true locations of Troll West Oil Province (TWOP) and Troll West Gas Province (TWGP). The 8700 m long EM streamer was towed at a depth of 100 m below the sea surface. Eleven receivers with offsets between 1860 and 7554 m were selected. The electric current source was towed at a depth of 10 m below the sea surface. We applied the optimal SA method to the data collected at all the lines 1-7. The reference field was selected using a set of the observed data generated by the first transmitter located at the left end of line #1, assuming that this field was least affected by the anomalous resistivity of the Troll oil and gas fields. This reference field was used as the background field for all the towed streamer EM data collected in all seven lines.

To apply the optimal SA method to the Troll data, we first selected a uniform DSA with a constant value of 1.5, which was selected based on some preliminary numerical tests to enhance the SA data. Figure 4 shows the plots of the normalized SA data without steering (black lines) and the optimal SA data (red lines) along the different lines of the towed streamer survey. As one can see, the optimal SA method increases the observed anomalies of the SA data significantly (up to 1.5 times in the maximum value). Panel (a) of Figure 5 represents a map of the ratio between the optimal SA data and the SA data without steering. Panel (b) in the same figure shows a horizontal section of the inversion results for the same data at a depth of 1475 m, produced by conventional 3D regularized inversion. As one can see, this map agrees very well with the true horizontal locations of hydrocarbon (HC) reservoirs of the TWOP and TWGP. This case study demonstrates the remarkable effectiveness of the optimal SA method to find the horizontal locations of the targets without any inversion. Another advantage of this method is its very short computational time. We computed the optimal SA data using a PC with Intel Core i7, 32 GB, and 2.5 GHz, in less than a few seconds, while a rigorous 3D inversion required several hours or even days of computation on a PC cluster.

Conclusions

We have introduced a novel method for fast imaging of the towed streamer EM data based on the concept of the optimal synthetic aperture. It has been shown that this method increases the EM response from potential sea-bottom HC reservoirs significantly. A case study with towed streamer EM data acquired over the Troll oil and gas fields in the North Sea has demonstrated the effectiveness of the optimal SA method in mapping the sea-bottom resistive targets (e.g., HC reservoirs). We should note also that, the SA can be useful in a more complicated geology with varying resistivity in the whole subsurface. The SA would then enhance the response from all features that differ from a selected background model. The method is extremely fast: the computational time on a standard PC is less than a few seconds for large survey data (up to 40,000 observation points). The developed innovative technique can be used as a fast data processing technique for real-time evaluation of the data collected in a reconnaissance towed streamer EM survey with the goal of scanning a vast area of the marine shelf.

Acknowledgments

The authors acknowledge TechnoImaging, the University of Utah's Consortium for Electromagnetic Modeling and Inversion (CEMI), and Petroleum Geo-Services for support of this research and permission to publish.

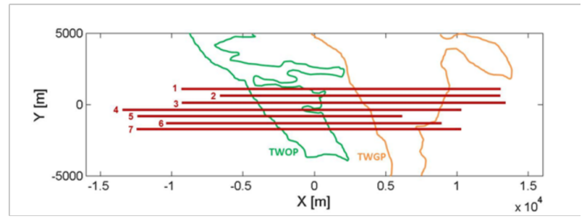

Figure 3: Configuration of the towed streamer EM survey conducted in the Troll West Oil and Gas Provinces. The red lines show the locations of the seven survey lines

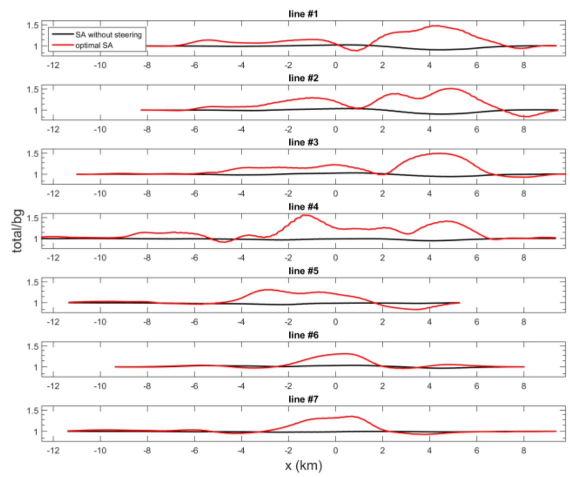

Figure 4: Plots of the normalized SA data without steering (black lines) and the optimal SA data (red lines) along seven lines of the towed streamer survey

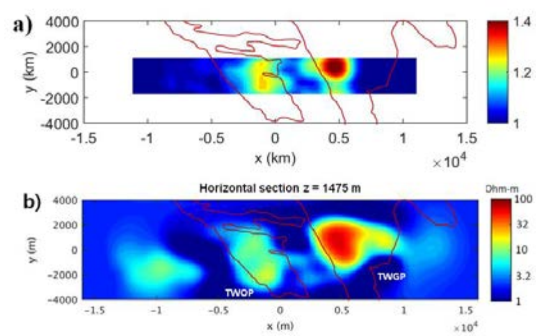

Figure 5: Panel (a) shows a map of the ratio between the optimal SA data and the SA data without steering. Panel (b) shows a horizontal section of the inversion results for the same data at a depth of 1475 m, produced by conventional 3D regularized inversion

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