Application of the Optimal Synthetic Aperture for Rapid Imaging of Towed Streamer EM Data acquired in the Barents Sea

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Summary

The Synthetic Aperture (SA) method is one of the key techniques in remote sensing using radio frequency signals. During recent years this method has also been applied to low frequency electromagnetic (EM) fields used for geophysical exploration. This paper demonstrates that the concept of the SA EM method can be extended to rapid imaging of large volumes of towed streamer EM data. We introduce a notion of virtual receivers, which complement the actual receivers in the construction of the SA for the towed streamer data. The method is illustrated by imaging of towed streamer EM data acquired in the Barents Sea. Remarkably, imaging the entire towed streamer EM survey requires just a few seconds of computation time on a desktop PC. This result is significant because it opens a possibility for real-time imaging of towed streamer EM survey data.

Introduction

Marine electromagnetic (EM) methods have found wide application in offshore hydrocarbon (HC) exploration because of their sensitivity to the resistive zones associated with HC reservoirs. With the recent development of towed streamer EM technology by PGS, marine EM surveys can be applied for rapid exploration of large areas in order to image the subsurface resistivity structure (e.g., Mckay et al., 2015). However, interpretation of the multi transmitter and multi receiver EM data typical of towed streamer surveys is a very challenging problem, which usually requires a large-scale inversion of the observed data. We propose 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, respectively. The method 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. A similar approach has been introduced for diffusive EM fields (Fan et al., 2010, 2012; Knaak et al., 2013; Mattsson and Engelmark, 2013; Yoon and Zhdanov, 2014, 2015; Zhdanov et al., 2017), where the authors applied the SA method to 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 resistive regions.

In the current paper we demonstrate that the optimal SA increases the EM response from the potential sea-bottom targets significantly, which can be effectively used in reconnaissance surveys.

Virtual receivers

A towed streamer EM survey consists of a transmitter and a set of receivers in a cable towed by a vessel, while the MCSEM survey deploys fixed receivers at the sea floor. This means that in the latter system, the receiver positions are the same for all the different transmitter shots, but in the former system, the receiver positions for one transmitter shot are different from those for another shots. The fundamental concept of the SA method is that the signals generated at different source positions are measured at the same receiver positions, so that they can be integrated to increase the potential anomaly. Unlike the conventional MCSEM system, the towed streamer system consists of a set of towed receivers which can measure a signal generated at a certain transmitter position only. In order to integrate the signals generated by different sources at the same receiver positions in the towed streamer EM system, we have to interpolate and/or extrapolate the fields from each source to virtual receiver positions, which can be shared by all transmitter shots. Note that the concept of virtual receivers is also quite common in radar applications. We use a linear interpolation of the data from the actual to the virtual receivers, if the virtual receivers are located within the maximum offset from the corresponding transmitter, and we use an extrapolation, if the virtual receivers are located outside this range. More specifically, the normalized observed data are linearly interpolated from the closest actual receivers into the virtual receiver positions for each source position j, forming an $[L\times1]$ vector-column, $\mathbf{d}_j^N=\left[d_j^{N(1)},d_j^{N(2)},\cdots,d_j^{N(L)}\right]^T$ (where $j=1,2,\cdots,J$), if the values $d_j^{N(l)}$ correspond to the range within the maximum offset from the corresponding transmitter, $\tilde{\mathbf{r}}_j$. The values $d_j^{N(l)}$ corresponding to the range exceeding the maximum offset from the corresponding transmitter, $\tilde{\mathbf{r}}_j$, are obtained by extrapolating from the actual receivers. However, for simplicity, we set the extrapolated values to 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 $[JL\times1]$ vector-column of the data recorded in both the actual and virtual receivers,

$$\mathbf{d}^N = \left[\mathbf{d}_1^N, \mathbf{d}_2^N, \mathbf{d}_3^N, \cdots, \mathbf{d}_J^N\right]^T. \quad (1)$$

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:

$$\mathbf{d}_A = \mathbf{W}_A \mathbf{d}^N, \quad (2)$$

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

$$\mathbf{W}_A = \begin{bmatrix} \mathbf{w}^T & 0 \ldots & 0 \ldots & 0 \ldots \\ 0 \ldots & \mathbf{w}^T & 0 \ldots & 0 \ldots \\ 0 \ldots & 0 \ldots & \ddots & 0 \ldots \\ 0 \ldots & 0 \ldots & 0 \ldots & \mathbf{w}^T \end{bmatrix}. \quad (3)$$

In the last formula, $\mathbf{w}$ is a $[J\times 1]$ vector-column of the corresponding SA weights, w_j, $\mathbf{w} = \left[w_1, w_2, \cdots, w_J\right]^T$. The goal is to find the optimal values of the weights, w_j, which would enhance the EM anomalies from the resistive regions.

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) and Zhdanov et al. (2017), we can write equation of SA data as follows:

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

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

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

$$E_j^{Nb(l)} = E_j^{b(l)} \Big/ \left|E_j^{b(l)}\right|, l = 1,2,\cdots,L; j = 1,2,\cdots,J. \quad (5)$$

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:

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

$$\frac{d_A^{(1)}}{d_B^{(1)}} = \frac{\sum_{j=1}^J E_j^{N(l)} w_j}{\sum_{j=1}^J E_j^{Nb(l)} w_j}, \quad (6)$$

where $\mathbf{A}$ is a forward operator for the normalized SA data $\mathbf{d}_R$, which is a function of the SA weights $\mathbf{w}$. The $\mathbf{d}_R$ computed based on the optimal SA weights, are called *optimal SA data*.

One can find the optimal SA weights by solving a minimization problem for the corresponding parametric functional:

$$P(\mathbf{w}) = \|\mathbf{D} - \mathbf{A}(\mathbf{w})\|^2 + \alpha\left\|\mathbf{w} - \mathbf{w}_{\text{apr}}\right\|^2 = \min, \quad (7)$$

where $\mathbf{D}$ is a so-called *designed synthetic aperture (DSA)*, α is a regularization parameter, and $\mathbf{w}_{\text{apr}}$ is an a priori vector-column of the data weights, which, for simplicity, can be selected as follows: $\mathbf{w}_{\text{apr}} = [1, 1, \ldots, 1]^{\text{T}}$. The designed synthetic aperture, DSA, according to its name, is selected (designed) with the purpose of enhancing the EM anomalies from the potential targets. In the case of a reconnaissance survey, it is reasonable to select a uniform DSA with the constant value greater than one to enhance the anomalies, present in the survey area.

The minimization problem in (9) is solved using the regularized conjugate gradient method (Zhdanov, 2015).

Selection of a designed normalized synthetic aperture data

We should note that different selections of the designed synthetic aperture, DSA, for the optimal SA method can result in different optimal SA weights.

Consider, for example, a geoelectrical model consisting of 300 m seawater layer with a resistivity of 0.33 ohm-m, and 1 ohm-m half space of sediment. A reservoir with sizes of 4 km x 4 km x 200 m is located at a depth of 800 m below the sea floor, and the resistivity of the reservoir is 100 ohm-m (panel (a) of Fig. 1). Note that the ratio of the resistivity of the reservoir to the resistivity of the sediment is equal to 100. 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 the inline electric fields at a frequency of 0.4 Hz. The data were contaminated with the random 10 % Gaussian noise.

In order to apply the optimal SA method, we construct a SA source using all the transmitter points on the survey line, and select the background (reference) field as the observed data generated by the very first transmitter located at x=20 km. Panel (b) of Fig. 1 shows the plot of the normalized SA data without steering. We have considered four different designed synthetic apertures in order to demonstrate how they affect the optimal SA data. We first select a boxcar function as the designed SA, setting the maximum value equal to 100 (we call this value *an amplification factor*) within the area of the expected reservoir anomaly and to 1 outside of the targeted zone. Thus, the amplification factor of the designed SA is equal to the ratio of the resistivity of the reservoir to the resistivity of the sediment in Model 1. Then we move the boxcar function along the axis x, as shown in panels (c)-(e) of Fig. 1. Panel (c) demonstrates that if there is no anomalous field within the area of the maximum of the boxcar function, the optimal SA method does not generate any false anomaly. Panels (d) and (e) indicate that the boxcar function has to fully cover the area of the anomalous field, otherwise only the anomalous fields inside of the boxcar area increase. Panel (f) presents a plot of the optimal SA data (red line) obtained using a uniform designed synthetic aperture (blue line). One can see that the optimal SA data shown in panels (e) and (f) are practically identical. This result illustrates the fact that the uniform SA can be successfully used in the reconnaissance towed streamer EM survey, where the location of the potential target is not a priori known.

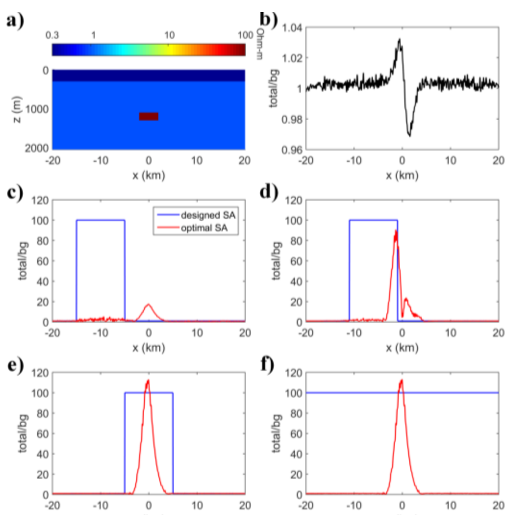

Figure 1: (a) Sketch of Model 1. (b) Synthetic aperture data without steering. The observed data were contaminated with the random 10 % Gaussian noise. (c), (d), and (e) Plots of the optimal SA data (red lines) obtained using a boxcar function with different locations (blue lines) as a designed synthetic aperture. (f) Plot of the optimal SA data (red line) obtained using a uniform designed synthetic aperture (blue line).

Application of the optimal synthetic aperture method to towed streamer EM data collected in the Barents Sea

We applied the optimal SA method to towed streamer EM data collected in the Barents Sea. There is a known salt dome located at almost the center of the survey area. However, its shape is unclear, and we investigated how the optimal SA method might help to enhance the EM response from this salt dome, which is more resistive than the surrounding sea-bottom sediment.

The towed streamer EM data used in our numerical study were collected at seven survey lines at five frequencies of 0.2, 0.4, 0.8, 1.8, and 2.6 Hz. Figure 2 shows the shot points along five survey lines in the survey area in the Barents Sea. The 8700 m long EM streamer was towed at a depth of approximately 100 m below the sea surface. Twenty-three receivers with offsets between 2057 and 7752 m were selected. The electric current source was towed at a depth of approximately 10 m below the sea surface.

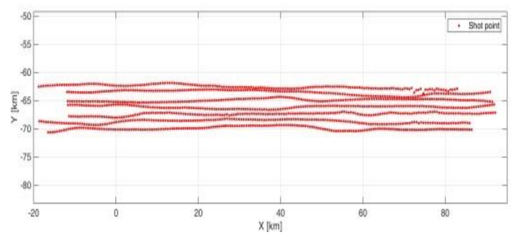

Figure 2: Configuration of the towed streamer EM survey conducted in the Barents Sea. The red dots show the locations of the shot points along seven survey lines.

We applied the optimal SA method to the data collected at all seven lines for each frequency. 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 (bottom line in Figure 2) for all frequencies, assuming that this field was least affected by the anomalous resistivity in the survey area. This reference field was used as the background field for all the towed streamer EM data collected at all seven lines. We should note that, in practice, we recommend selecting several different locations of the reference receiver to determine the one least affected by the anomalous resistivity.

Figure 3 shows maps of the optimal SA data at all five frequencies. Note that, in this figure the map of the optimal SA data for the highest frequency (2.6 Hz) is located at the top, and the map for the lowest frequency (0.2 Hz) is located at the bottom, so that the optimal SA data (top to bottom) correspond from the shallower to deeper parts of the sea-bottom structure. One can clearly see that the high value of the optimal SA data (red color) forms s "dome-like" structure.

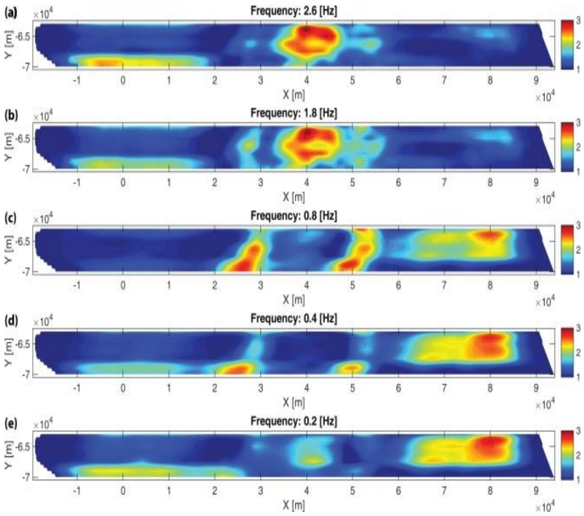

Figure 3: Maps of the optimal SA data at frequencies (a) 2.6, (b) 1.8, (c) 0.8, (d) 0.4, and (e) 0.2 Hz.

This case study demonstrates the remarkable effectiveness of the optimal SA method not only to find the horizontal locations of the anomalous structure, but also to estimate the 3D shape of the anomalous structure, without any inversion. Indeed, the SA images for the various frequencies represent the resistivity at corresponding various depths. The high frequency's image gives the shallow picture and the images at the lower frequencies reflect a geoelectrical structure located deeper down. Another advantage of this method is its very short computational time. We computed the optimal SA data using a PC with Intel Core i7 running at 2.5 GHz, and 32 GB of RAM, in a couple of minutes, while a rigorous 3D inversion usually requires several hours or even days of computation on a PC cluster. Note that the computational time mostly depends on the number of data points, which were about 950,000 in this case. Therefore, the optimal SA method can be considered as an effective technique for real-time scanning of the survey area for anomalous structures using EM data. Further, one can construct an appropriate 3D a priori model based on the optimal SA data, and this a priori model may help significantly in solving an extremely ill-posed 3D EM inverse problem.

Conclusions

We have introduced a novel method for fast imaging of towed streamer EM data based on the concept of an optimal synthetic aperture. It has been shown that this method increases the EM response from potential sea-bottom anomalous structures significantly. A case study with towed streamer EM data acquired in the Barents Sea has demonstrated the effectiveness of the optimal SA method in mapping the sea-bottom resistive structure (e.g., a salt dome) and in estimating the 3D shape of the structure. The method is extremely fast: the computational time on a standard PC is only a couple of minutes for large survey data (up to 950,000 data 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, and can help to solve an ill-posed 3D EM inverse problem.

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EDITED REFERENCES

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