Optimized Synthetic Aperture Sensitivity Enhancement of a Deep EM Marine Target

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SUMMARY

In October 2012 the Alvheim-Boa Field was surveyed as part of a North Sea acquisition campaign with the newly developed Towed Streamer EM System to provide resistivity estimates over a number of known oil and gas fields. The Alvheim-Boa field is medium sized, located 2,100m below the sea-floor, and half of the recoverable oil has already been produced but the gas cap is intact. The resulting maximum anomaly above background following conventional processing is 7-8 %. The anomaly is recognized as originating in the reservoir based on the following facts: The peak anomaly coincides with the maximum reservoir thickness in the Boa Field; the peak appears at the same location on both survey lines; the anomaly is only detected by the lowest frequencies and the longest offsets indicating a deep origin; and the uncertainty in the long offset data is less than 3 %. The optimized synthetic aperture processing is a way to focus the radiated energy from the source bi-pole towards the target of interest. This resulted in an increase in the maximum anomaly to 200 % above background. An additional strong advantage of the target focusing ability is that other nearby minor anomalies of no interest where de-emphasized.

Introduction

In October 2012 a number of known oil & gas fields in the North Sea were surveyed with the newly developed Towed Streamer EM System to provide resistivity measurements. The resulting data density is very similar to 2D seismic.

There are numerous benefits with a towed streamer EM acquisition system:

- Efficient data acquisition at 4 - 5 knots.
- Configurable receiver bi-pole lengths from 50 – 1,100 m
- Real time Quality Control (QC) of source signal and recorded data.
- Deterministic deconvolution
- Dense sampling facilitating noise reduction and synthetic aperture processing.
- On-board processing facilitating quick evaluation of target resistivity
- Allows simultaneous acquisition of 2D seismic from the same vessel.

Acquisition Method

The Towed Streamer EM acquisition system shown in Figure 1 below consists of an 800 m long source bi-pole towed 10 m below the sea-surface. It is powered by a signal strength of 1,500 Amperes. The resulting source strength, or bi-pole moment, is then: 1.2 MAm. Any kind of source signal can be used, although the Optimized Repeated Sequence (ORS) of our own design is the best general purpose signal. The duration of the source-sequence is 120 seconds. The source sends the signal for 100 s and the last 20 seconds are used for noise evaluation, characterization and attenuation in later processing. The EM streamer has effectively 26 offsets varying from 0 – 7,700 m. The streamer is also configurable with bi-pole lengths varying from 50 m for the nearest offset to 1,100 m for the longest offset. The streamer is towed at a maximum depth of 100 m. The maximum water depth is 400 m, and the acquisition speed is 4 – 5 knots.
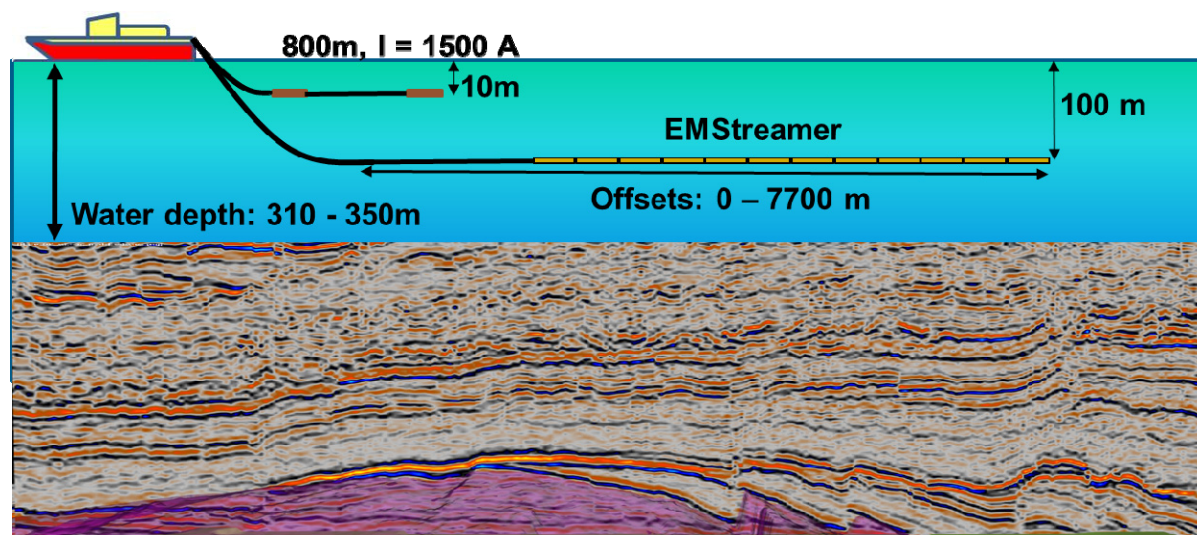

Figure 1 The Towed Streamer EM acquisition system. The source bi-pole is towed at 10 m depth and the EM streamer at 100 m. The receiver bi-pole lengths are 50 – 1,100 m long with the longest bi-poles for the longest offsets. The water depth for the Alvheim-Boa survey is 310 – 350m.

The Alvheim Boa Field

The Alvheim Boa Field was the most challenging target in the acquisition program with a depth of burial of 2,100 m below the seafloor. Further, it is a medium sized oil & gas field with half of the recoverable oil in place produced. The positioning of the two survey lines is also suboptimal due to permitting constraints and the location of existing infrastructure. Figure 2 shows the Alvheim Boa Field with the two NNE trending (red dash) survey lines superimposed on the seismically based

reservoir thickness map. Increasing reservoir thickness is shown with increasingly warmer colors. The Boa depocenter is indicated by the dark red color immediately west of the survey lines.
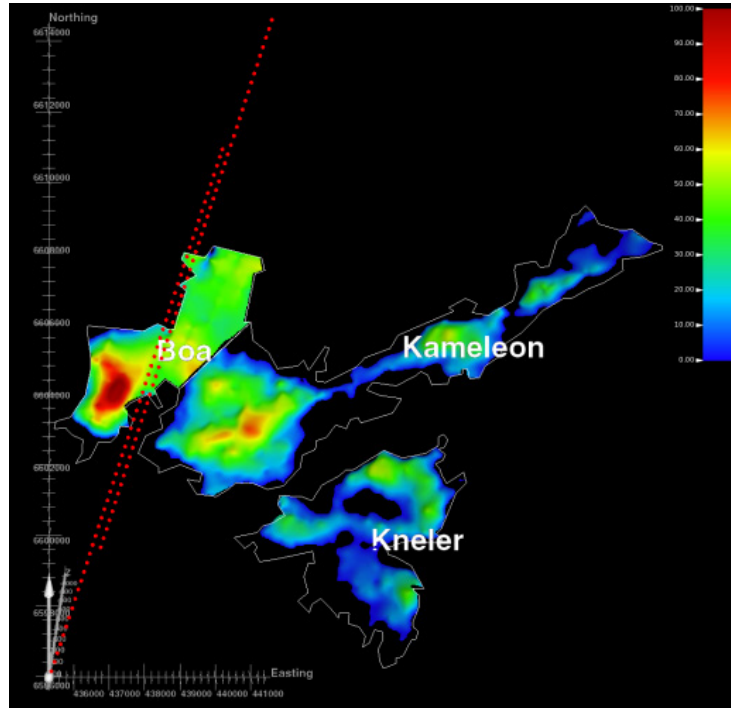
Figure 2 *The Alvheim Boa Field with the NNE trending survey lines in red. The colours indicate the reservoir thickness as determined from seismic data. The depocenter of the Boa reservoir is seen immediately west of the two survey lines.*

Synthetic aperture response – formulation

The measured electric field is deconvolved with the output source current to obtain the frequency (earth) responses for all offsets and frequencies in the ORS sequence at all shot points along the survey lines, (Mattsson et al. 2012). The sensitivity in the frequency responses with respect to resistivity and bathymetry variations is effectively visualized as normalized frequency responses.
Synthetic aperture processing is a data driven approach to increase the sensitivity in the frequency response data to a deeply buried resistive anomaly. This can be done by summing the frequency responses over a selected offsets range with optimized weighting functions multiplied to each term according to (Fan et al. 2012):

$$S(Q,f) = \sum_{P=1}^{M} F(P,Q,f)\, e^{\left(ic_1(Q,f)-c_2(Q,f)\right)\alpha(f)\Delta x_P} \tag{1}$$

where

$$F(P,Q,f) = A(P,Q,f)e^{i\phi(P,Q,f)}$$

P = offset index

Q = cmp index

f = frequency

M = number of offsets in the summation $\hspace{2cm}$ (2)

$\alpha = \sqrt{\pi f \mu_0 \sigma_w}$ = Real part of the wave number in the sea - water

$\Delta x_P = \big(s(M,Q) - r(M,Q)\big) - \big(s(P,Q) - r(P,Q)\big)$

The functions $A(P,Q,f)$, $\phi(P,Q,f)$ are the amplitude and phase of the frequency responses.

The outlined methodology in (Fan et al. 2012) has been extended to achieve an efficient focus and increase in the sensitivity of the synthetic aperture at an arbitrary cmp Q_T along a survey line. The extension consists in determining the weighting functions $c_1(Q,f)$ and $c_2(Q,f)$ so that the quotient:

$$\left| \frac{S(Q_T,f)}{\sum_{Q_0 \in \Omega(Q)} S(Q_0,f)} \right| \tag{3}$$

is maximized at Q_T. The c_1 function is applied to the phase to focus the radiated energy on the target, and the c_2 function balances the amplitudes for the various offsets used. The set of cmps $\Omega(Q)$ in the normalization sum is selected to obtain an increase in $\left| \frac{S(Q_T,f)}{S(Q,f)} \right|$ for every cmp outside the focus region around Q_T. In practice, the normalization cmp set can be chosen as $\Omega(Q) = Q$. Hence, the functions $c_1(Q,f)$ and $c_2(Q,f)$ are uniquely determined for every cmp. A coordinate system relating the P and Q indices in a simplistic geometry is shown in figure 3.
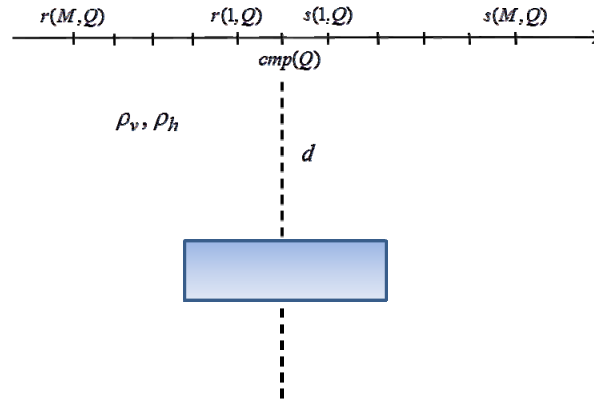
Figure 3 *Geometry description.*

To focus and increase the sensitivity with respect to the block anomaly in figure 3, the optimizing point Q_T should be selected over the center of the block.

**Synthetic aperture processing applied to the Alvheim Boa Field**

The synthetic aperture response (1) is calculated at the frequency 0.3 Hz for offsets between 5000 and 7500 m at each common mid-point (cmp) position along the two Alvheim Boa survey lines. The maximization of (3) is done for the cmps where it is assumed to have a response from the associated Alvheim Boa resistive anomaly. The normalization cmp set in (3) is chosen as:

$$\Omega(Q) = \begin{cases} [1,\cdots,10], \ \forall Q \in [1,\cdots,35] \\ [46,\cdots,56], \ \forall Q \in [36,\cdots,56] \end{cases} \tag{4}$$

There are 56 cmps in each of the two survey lines and the maximization points are taken as $Q_T = 30$ for the westernmost line and $Q_T = 35$ for the other line. For comparison, the synthetic aperture summation is also calculated without weighting, i.e. with $c_1 = c_2 = 0$.

The resulting percentage change in magnitude of the synthetic aperture, i.e. $100(|S(Q,f)|/\min|S(Q,f)| - 1)$ is plotted for both lines in figure 4. The optimized synthetic aperture is shown to the right and the non-optimized to the left. It can be seen that the location of the synthetic aperture responses occur at

(N 6606000, E 438500) which coincides well with the thickest part of the Boa reservoir. This is a strong indication the resistivity increase seen in the data is associated with the reservoir.
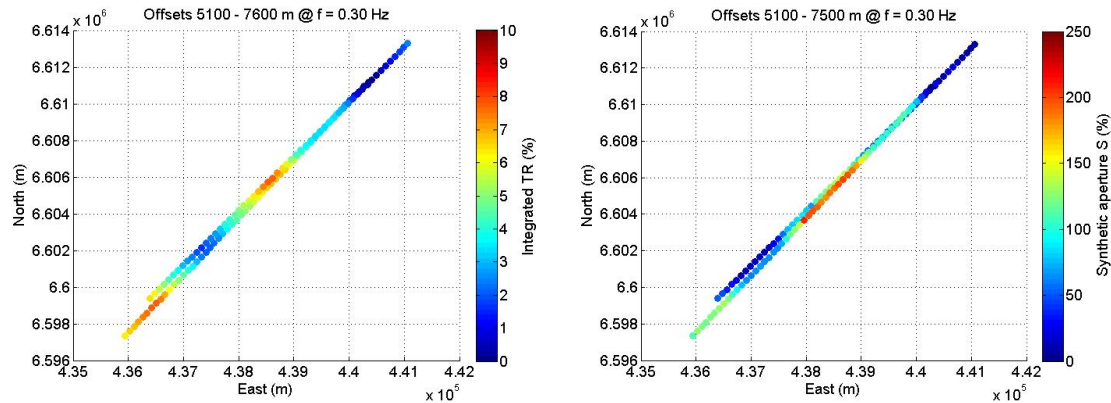
Figure 4 *Synthetic aperture response for offsets between 5,000 and 7,500 m along the survey lines. The plot the right shows the optimized response while the plot to the left shows the non-optimized response without any weighting.*

The maximum sensitivity in the non-optimized synthetic aperture is 7-8 % for the assumed Boa anomaly, whereas for the optimized synthetic aperture, the strongest response is about 200 %. It should also be emphasized that the anomalies at the southern part of the lines have decreased relatively to the Boa response by a factor of 2-4. The optimized synthetic aperture shows that it is possible to focus the signal on the target of interest and thereby de-emphasize the influence of the nearby anomalies of no interest and at the same time maintain the signal to noise ratio in the data. The total uncertainty in the frequency response data at the offsets (5,000 – 7,500 m) and frequencies (0.15 – 0.3 Hz) is less than 3 %.

The anomalies seen in the southernmost part are detected in all offsets and frequencies, indicating they are caused by something very shallow, probably the combined effects of the water depth increase from 110 to 125 m and shallow resistivity changes. Hence, it is possible to de-emphasize the effect from neighboring unwanted shallow resistivity effects as well as the air-wave contributions in relation to a more deeply buried resistive anomaly by optimizing the synthetic aperture sum for the anomaly of interest.

Also, the anomaly of interest in the middle parts of both lines is seen only by the longest offsets (5,000 – 7,500 m) and lowest frequencies: the anomaly is only consistent with a deep target.

Conclusions

The accuracy in the frequency responses enables detection of a 7-8 % change in a non-optimized synthetic aperture processing. The optimized synthetic aperture can increase the sensitivity to 200 % and by focusing the energy on the target also de-emphasize the strength of the anomalies of no interest located in proximity to the reservoir under evaluation. The fact that the strongest anomaly is seen at the same location on both survey lines, that it is located exactly where the Boa reservoir reaches maximum thickness, and it is only seen in the far offsets and lowest frequencies, all consistently support our interpretation that the anomaly originates in the Boa reservoir.

References

Fan, Y., Snieder, R., Slob, E., Hunziker, J., Singer, J., Sheiman, J. and Rosenquist, M. [2012] Increasing the sensitivity of controlled-source electromagnetics with synthetic aperture. *Geophysics,* **77**(2), E135-E145.

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