Extended Abstract 22^{nd} Workshop
Weimar, Germany, August 25-30, 2014

Value of CSEM data at low signal-to-noise ratios

D. V. Shantsev, P. T. Gabrielsen, B. T. Lucien Tah and V. Markhus
EMGS, Trondheim, Norway

Summary

We have demonstrated that CSEM data with low signal-to-noise ratios contain valuable information about subsurface resistivity that can significantly improve inversion results. A set of 2.5D inversions including different range of offsets have been run on CSEM data acquired over the Snøhvit gas field in the Barents Sea. Including data for offsets beyond 10 km turned out to be critically important to resolve the gas reservoirs even though their response at these offsets was below the noise level. These findings are validated by inverting real data that are contaminated with an additional noise as well as noisy synthetic data. It is shown that a CSEM inversion with a proper weighting scheme can resolve a resistive target even if its response is smaller than the noise for all frequencies and offsets.

Keywords: Noise, inversion, CSEM

Introduction

In marine controlled-source electromagnetic (CSEM) surveys, the magnitude of the recorded EM fields decays as a function of the source-receiver offset. At long offsets the signal drops below the noise floor determined e.g. by MT, sensor or swell noise. Data close to the noise floor are often disregarded in inversion since they can drive it in a wrong direction.

At the same time, sensitivity of the CSEM method to hydrocarbon reservoirs comes mostly from data at long offsets due to guiding of EM fields within thin resistive layers. Sometimes the sensitivity is high only at those offsets where the signal-to-noise (SNR) ratio is pretty small. Then it can be difficult to decide which offset range should be included into inversion. The present study addresses this problem using CSEM data from the Barents Sea and by running a number of inversions with varying range of offsets.

It is very common to use SNR as a criterion deciding which data points should be used in inversion. One often masks out all data with SNR below some threshold, e.g. with SNR < 10. Another important consideration is the ratio between the noise and response from a particular target that inversion aims to recover. It is often believed that inversion can resolve a target only if the target response is larger than the noise level. Similarly, offsets where the target response is smaller than the noise can be considered useless for detecting the target. The present study suggests that these considerations can be wrong. We show that data points where SNR < 10 and the target response is below the noise level can be vitally important for inversion to resolve the target. Moreover, a target can be resolved even if its response for all offsets and frequencies is smaller than the noise level.

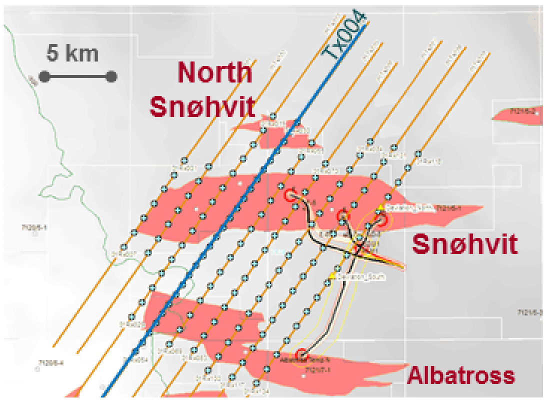

Figure 1: Outline of CSEM survey over the Snøhvit field.

Survey description

Our study is based on a marine CSEM survey acquired over the Snøhvit field in the Barents Sea. A horizontal electric dipole source generating EM fields at frequencies 0.5-10 Hz was towed ∼30 m above the seafloor, while the electric and magnetic fields have been recorded by seabed receivers. The Snøhvit Field is a proven gas discovery under production, the dataset was acquired for the EDDA consortium and the survey outline is shown in Figure 1. A 3D inversion of the dataset shows a resistive anomaly at the depth of ∼ 2.4 km, in agreement with available well logs (Shantsev et al., 2012). In this study we for simplicity analyse data from one towline (Tx004) only. It covers 25 receivers spaced by 1 km and crosses both compartments, Snøhvit and Snøhvit North, of a gas bearing reservoir. Inline electric field data for four frequencies 0.5, 1, 1.5 and 2 Hz have been used in 2.5D inversion, distance between shot positions was 100 m.

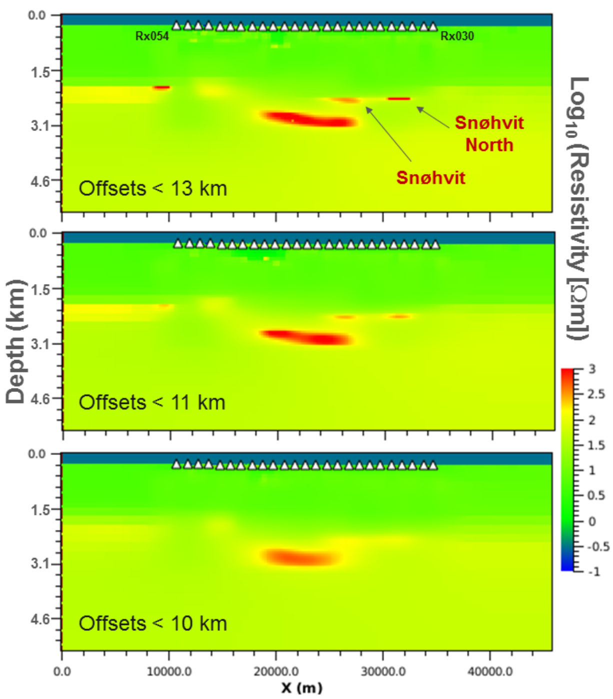

Figure 2: Resistivity section obtained by 2.5D inversion over the Snøhvit field using different range of offsets. Including offsets > 10 km into inversion is crucially important for imaging both compartments of the Snøhvit prospect.

Results

We have run three unconstrained 2.5D inversions including different range of offsets, and the final resistivity sections are shown in Figure 2. The inversions use a Gauss-Newton algorithm and regularization that favors horizontal layering, for more details see Hansen & Mittet (2009). The top image shows inversion results obtained including the largest range of offsets – up to 13 km. Here we can clearly see two thin horizontal resistors whose position and depth coincide very well with the main and North compartments of the Snøhvit field. They are also easily distinguished from a bigger resistor below. If inversion is based on data only up to offsets of 11 km (middle image), then the resistors appear less sharp and their transverse resistance roughly halves. The bottom image shows inversion results excluding all data with offsets beyond 10 km. Here one can hardly see the two resistors representing the Snøhvit field. It is obvious therefore that data at offsets beyond 10 km is critical for correct imaging of subsurface resistivity.

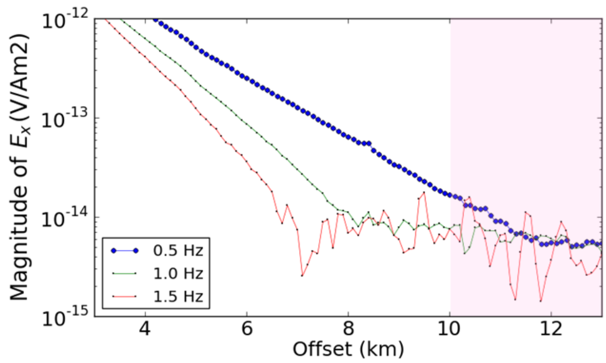

Figure 3: Magnitude versus offsets curves for inline electric field for receiver Rx036 for three frequencies. Data in the shaded region > 10 km proved to be critically important for inversion despite they are strongly affected by noise.

Let us now check to what degree these long offsets are affected by noise. Magnitude vs offsets curves for a few frequencies are shown in Figure 3 and one can see that even for the lowest frequency the curve at offsets > 10 km is not smooth and strongly affected by noise. It might be difficult to believe that including these data points into inversion would improve the inversion result, but this is exactly what happens, according to Figure 2.

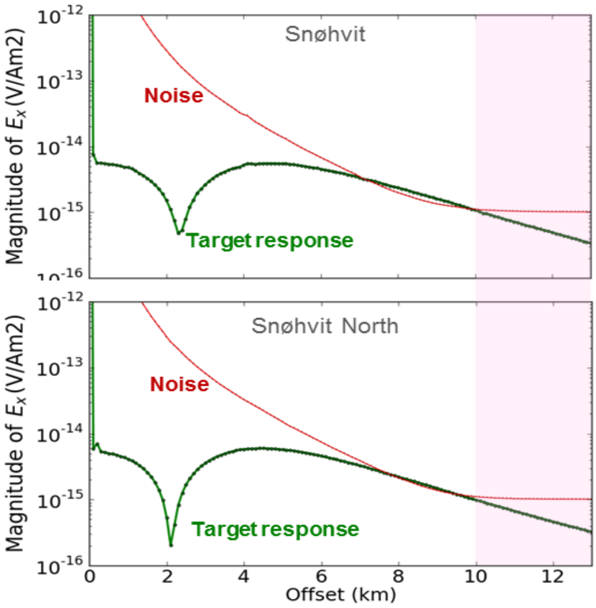

Figure 4: Green curves: Scattered field from a resistive reservoir: Snøhvit (top) and Snøhvit North (bottom). Red curves: noise level. For offsets > 10 km the scattered field is below the noise.

The measured field may be considered as a sum of background response and a scattered field from a particular target. We evaluated the response of the Snøhvit and the Snøhvit North targets by erasing each of the resistors from the final resistivity model obtained by inversion and computing the resulting difference in the EM fields. Magnitudes of these scattered fields for 0.5 Hz are plotted in Figure 4 as green curves, while the red curves represent the total noise N given by a combination of the noise floor term and a term proportional to the observed field E_{obs}:

$$N = \sqrt{\alpha^2 |E_{obs}|^2 + N_{\text{floor}}^2} \qquad (1)$$

The noise floor was evaluated from the long-offset behavior of observed data, e. g., for 0.5 Hz it was 10^{-15}V/Am^2. The relative uncertainty α was set to 3% which is even lower than 5% suggested by Barker et al. (2012) for the conventional CSEM equipment. Now one can see from Figure 4 that both targets should be detectable since their scattered fields are slightly above the noise level within a certain range of offsets. However, for offsets beyond 10 km, the target response is clearly below the noise level. Note that the plots show data only for one receiver and one frequency which provide the strongest target response (Rx041 for the Snøhvit and Rx036 for the Snøhvit North, both at 0.5 Hz). It means that noise exceeds the signal from the targets for all receivers, all frequencies and all offsets larger than 10 km. It is therefore remarkable that inversion managed to extract useful information from these offsets and they turned out to be essential to image the two resistive targets.

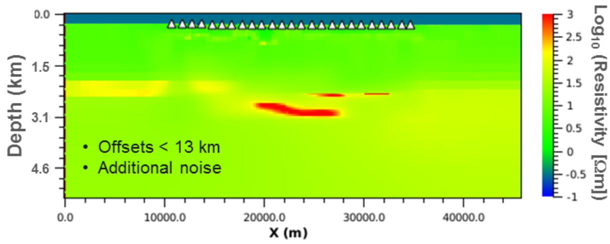

Figure 5: Inversion results like in Figure 2 (top), but the real data were contaminated with additional noise whose magnitude exceeds the CSEM response for both resistive targets.

Validation

Unfortunately, we cannot know precisely the noise level in the acquired data and therefore had to rely on its estimate in the analysis above. If the noise is underestimated, our conclusions could be wrong. To make sure this is not the case, we ran inversions on real data after contaminating them with an *additional* noise:

$$E = E_{obs}(1 + P(\alpha)e^{i\phi_1}) + P(N_{\text{floor}})e^{i\phi_2} \qquad (2)$$

Here P denotes an uncorrelated random number satisfying the Gaussian distribution with a given dispersion, the relative noise α was taken as 3%, while the noise floor N_{floor} was 1.8 larger than that estimated from the real data. Phases ϕ_1 and ϕ_2 were random numbers within $[0;2\pi]$. This choice of parameters guarantees that the additional noise alone exceeds the responses from the Snøhvit and Snøhvit North compartments for all receivers, frequencies and offsets. Moreover, the real data obviously has some intrinsic noise too, which makes recovery of these targets by inversion even more problematic. Nevertheless, inversion was able to recover both resistors, as one can see from Figure 5. Their position and depth remain correct and they are clearly disconnected from a bigger resistor below.

Finally, we did a test inversion run on purely synthetic data, see Figure 6. The background resistivity was taken from inversion of real data and then we inserted two resistors representing the Snøhvit prospects and a bigger resistor below. The start model was the background resistivity smoothed over a scale of 1.0 (0.3) km horizontally (vertically).The data were contaminated with noise according to Equation 2 with $\alpha = 3\%$ and unrealistically large noise floor so that the total noise exceeded the response of each Snøhvit target by at least a factor of 4 for all frequencies and offsets. Nevertheless, both targets were very accurately recovered by inversion.

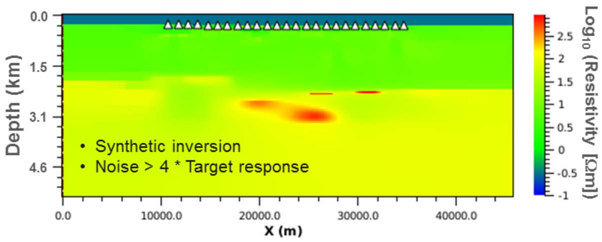

Figure 6: Both target resistors are well resolved by inversion of synthetic data contaminated with noise which is at least two times above the target responses

Discussion

We have shown that inversion can recover a resistive target even if the signal from that target for every data point is smaller than noise. This is possible because the noise to a large degree is uncorrelated between different data points, while the target response is always correlated. When one considers a combined effect from thousands of data points, the random (though stronger) effect of noise is averaged out, while weaker, but coherent effort from the target signal drives inversion in the right direction. Effectively, inversion performs "stacking" of CSEM data, thus mitigating low SNR of individual data points.

L2 norm used in inversion implies that noise in data is least harmful if it is uncorrelated and Gaussian. For real data, the noise is partly correlated due to e.g. MT activity, errors in source (receiver) navigation that affect many data points at once, etc. Moreover, there exist spikes that make the noise non-Gaussian. Note that in the present study we did not follow the standard routine of removing spikes from the data (see e.g. a spike at ~ 8.5 km at 0.5 Hz in Figure 3). In addition, 2.5D assumption used by the inversion scheme inevitably introduces correlated errors since the observed data describe a 3D subsurface. Having all this in mind, the ability of inversion to image targets with responses below the level of real-life correlated non-Gaussian noise is especially remarkable.

Despite inversion takes all data points into account, it should weight them differently, with a smaller weight given to data points with low SNR. In the present study the data misfit was defined as the following sum over all data points,

$$\epsilon = \sum \frac{|E_{obs} - E_{syn}|^2}{\alpha^2 |E_{obs}|^2 + N_{\text{floor}}^2} \tag{3}$$

where E_{syn} is the synthetic data.

Conclusion

We have demonstrated that inversion of CSEM data can recover resistive targets in the subsurface even if response from these targets is smaller than the noise in data. This holds true not only for synthetic data contaminated with uncorrelated Gaussian noise, but also for real data, on an example of a CSEM survey over the Snøhvit gas field in the Barents Sea. It is shown that CSEM data at long offsets carry useful information about resistive targets in the subsurface even if the noise level is comparable to the total measured signal and exceeds the signal from these targets. Including these data into inversion is sometimes the only way to get a correct image of deep resistive targets.

Acknowledgments

The authors wish to thank EMGS for permission to publish the results.

References

Barker, N. D., Morten, J. P., & Shantsev, D. V. (2012). Optimizing EM data acquisition for continental shelf exploration. *The Leading Edge*, *31*(11), 1276-1284.

Hansen, K. R., & Mittet, R. (2009). Incorporating seismic horizons in inversion of csem data. *SEG Expanded Abstracts*, 694-698.

Shantsev, D. V., Gabrielsen, P. T., & Fanavoll, S. (2012). 3D CSEM for hydrocarbon exploration in the Barents sea. *5th EAGE Conference & Exhibition in St. Petersburg, Russia*, C002.