Multi-component Processing of Sea Bed Logging Data

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Abstract— Marine remote sensing of hydrocarbons based on EM-soundings does not work very well in case of shallow waters due to strong airwave contributions. In this paper we investigate a multi-component signal processing approach which has the potential to attenuate such airwaves. Tests of the technique employing synthetic North Sea data gave significant improvements.

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1. INTRODUCTION

In oil and gas exploration seismic is the far most important type of data used to image the subsurface. While the seismic waves have the ability to detect gas, they often fail to discriminate between water and oil as a pore fluid. On the contrary, electromagnetic waves are able to separate between the two fluids, based on their large differences in resistivity value. The reason for this is based on the fact that water supports free ions and easily transports electric current whereas oil acts as an insulator. This observation has motivated the development of a marine EM-based remote sensing method for hydrocarbons denoted Sea Bed Logging (SBL) [3]. This technique employs a mobile horizontal electric dipole (HED) source towed by a vessel and an array of seafloor electric field receivers. However, in the limit of shallow water (e.g., 200 m or less), the subsurface responses from potential high-resistivity zones like hydrocarbon reservoirs are masked by airwaves. The airwaves are energy which diffuses from the source to the air-sea interface, propagates as a lateral wave along this interface, and then diffuses downward to the receiver. In this paper we discuss how to minimize the influence of these waves employing multi-component processing of SBL-data.

2. MULTI-COMPONENT PROCESSING

As shown in Fig. 1, the generated electromagnetic soundings employing the SBL-method can in general be divided into three main contributions: direct EM field, guided modes (associated with high-resistivity zones like hydrocarbons) and airwaves. If the distance (offset) between the transmitting and receiving antenna is large enough (approx. 3 times the target depth) the direct field can be neglected. In case of deep water the guided modes will then dominate the large-offset measurements. However, when moving to shallow water depths this is no longer the case and the airwaves will mask the subsurface responses.

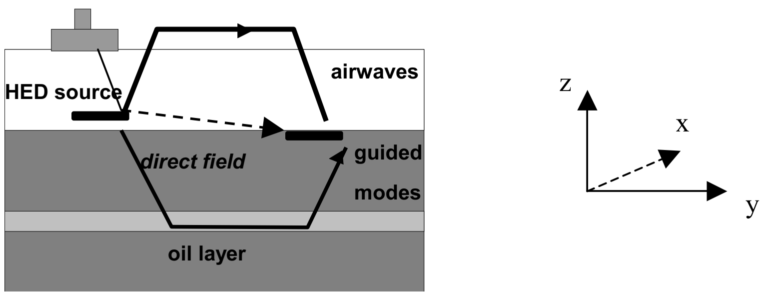


Figure 1: Main EM contributions recorded by the SBL-method (inline antenna).

These airwaves will diffuse in the downward direction and be almost normal incident to the seafloor, whereas the guided modes associated with a hydrocarbon reservoir will leak out and diffuse in the upward direction. Hence, these two contributions have the potential to be separated at the seafloor sensor if the measured EM field can be decomposed in upward and downward traveling modes. In seabed logging, both electric and magnetic field components are recorded at the seafloor. Amundsen et al. [1] have introduced a rigorous approach to EM field decomposition making use of both E and H field components. We investigate this idea further and introduce here a more straightforward approach to the same problem. In the following we assume that all EM modes exist along the vertical direction only. We introduce a Cartesian coordinate system as shown in Fig. 1, with the z-axis defining the vertical direction, the y-axis defining the inline horizontal direction and where the x-axis falls along the cross-line direction. Moreover, we assume that the EM fields can be approximated by plane-waves. In the case of an inline polarized HED-source, it follows from Maxwell's equations after Fourier transformation of the fields in space (x and y) as well as in time:

$$-k_y^2 \hat{E}_z + \partial_z \hat{E}_y = -i\omega\mu_0 \hat{H}_x \tag{1}$$

However, since only normal incident EM fields are assumed, this equation can be further simplified by setting $k_y = 0$

$$\partial_z \hat{E}_y = -i\omega\mu_0 \hat{H}_x \tag{2}$$

Let the received signal at the electric sensor be decomposed into upward (U) and downward (D) travelling modes, i.e.,

$$\hat{E}_y = \hat{U} + \hat{D} \tag{3}$$

Since $\hat{U}$ and $\hat{D}$ represent plane-wave modes propagating along the vertical, they are given by the following expressions (simplest form):

$$\hat{U} = \exp\left[ik_z z\right], \quad \hat{D} = \exp\left[-ik_z z\right] \tag{4}$$

where the sign convention of the vertical wavenumber is chosen as follows

$$k_z = k = \omega\sqrt{\mu_0 \varepsilon^*}, \quad \varepsilon^* = \varepsilon + i\sigma/\omega \tag{5}$$

By combining Eqs.(3)–(5) we obtain for an attenuating medium

$$\hat{H}_x = \frac{i}{\omega\mu_0}\frac{\mathrm{d}\hat{E}_y}{\mathrm{d}z} = \frac{i}{\omega\mu_0}\frac{\mathrm{d}\left(\hat{U}+\hat{D}\right)}{\mathrm{d}z} = \frac{k_z}{\omega\mu_0}\left(\hat{D}-\hat{U}\right) = \sqrt{\frac{\varepsilon^*}{\mu_0}}\left(\hat{D}-\hat{U}\right) \cong e^{i\pi/4}\sqrt{\frac{\sigma}{\omega\mu_0}}\left(\hat{D}-\hat{U}\right) \tag{6}$$

Finally, Eqs.(3) and (6) can be combined to give (after double inverse spatial Fourier transform)

$$U = \frac{1}{2}\left[E_y - e^{-i\pi/4}\sqrt{\frac{\mu_0\omega}{\sigma}} H_x\right] \tag{7}$$

where U represents the 'airwave corrected' version of the electric field E_y. The factor that is multiplying the magnetic field we recognize as the intrinsic plane-wave impedance in case of a well conducting medium. A similar result has also been derived by [1].

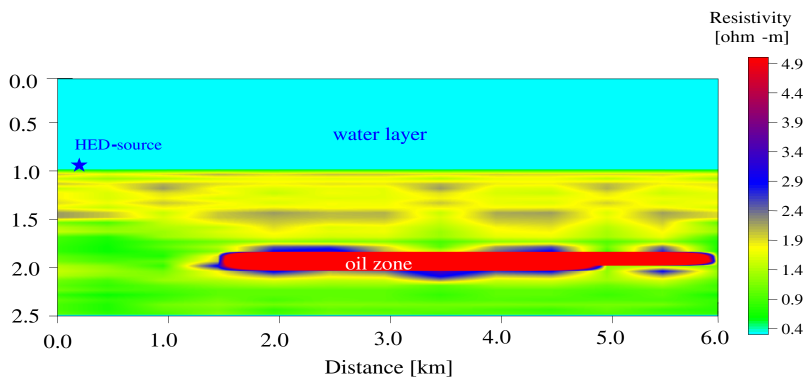


Figure 2: 2-D North-Sea resistivity model.

3. NORTH SEA TEST MODEL

A 2-D resistivity model was constructed based on typical resistivity-log values from the North Sea. An oil-reservoir of thickness 100 metres and thinning out to 50 metres was assumed at a depth of 0.9 km below the seafloor. The resistivity of the thin oil zone was varying between 40 and 50 Ω-m. We considered two different water depths: 200 m and 1000 m. Fig. 2 shows a plot of the 2-D resistivity model (deep-water case).

The HED-source, with an operating frequency of 1Hz, was placed 20 meters above the seafloor and at a lateral distance of 200 meters from the left boundary of the model (see Fig. 2). We considered the case of an inline polarized (i.e., along the y-direction) antenna and computed synthetic data employing a 2.5D hybrid EM-modeling program [2] tailored for the SBL-case. Fig. 3 shows a (logarithmic) plot of the magnitude of the electric field component E_y (which is polarized in the same direction as the source). The figure represents a vertical slice through the 3-D computational volume (with the plane including the source).

Figure 3 clearly demonstrates that strong guided modes leaking from the thin oil zone can be detected at the sea floor, especially for source-receiver offsets larger than approximately 3.5–4.0 km (e.g., about 3–4 times the target depth).

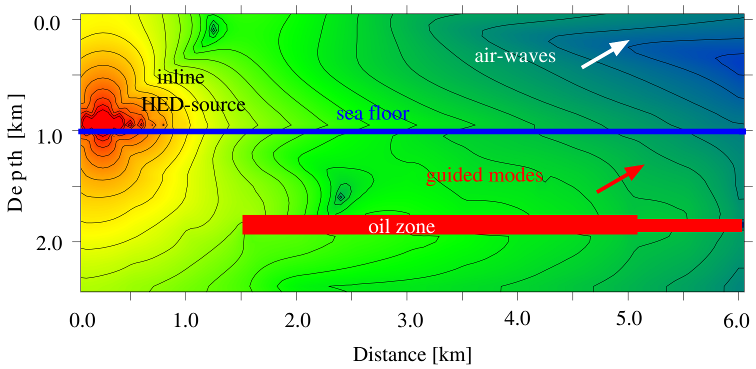


Figure 3: Plot of the magnitude (after taking the logarithm) of the electric field component E_y. Inline polarized HED-source and deep water.

Up till now we have considered the deep-water resistivity model as given by Fig. 1. The result obtained in Fig. 3 shows that for such water depths the airwaves are so attenuated that when they reach the sea floor only negligible energy remains at larger offsets (compared to the guided EM energy leaking from the resistive layer). However, if we assume a shallow water depth this will no longer be the case. Fig. 4 is identical to Fig. 3 except that the water depth now has been set to 200 meters. Note how the airwaves dominate along the sea floor, masking the leaking guided modes almost completely. In order to reveal the signature of the oil zone, these airwaves should be removed or at least strongly attenuated.

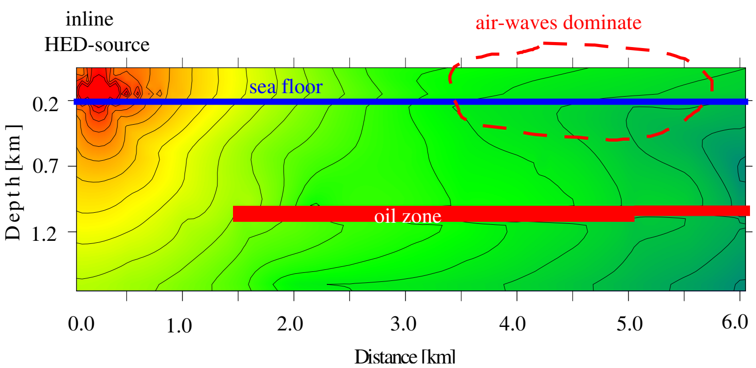
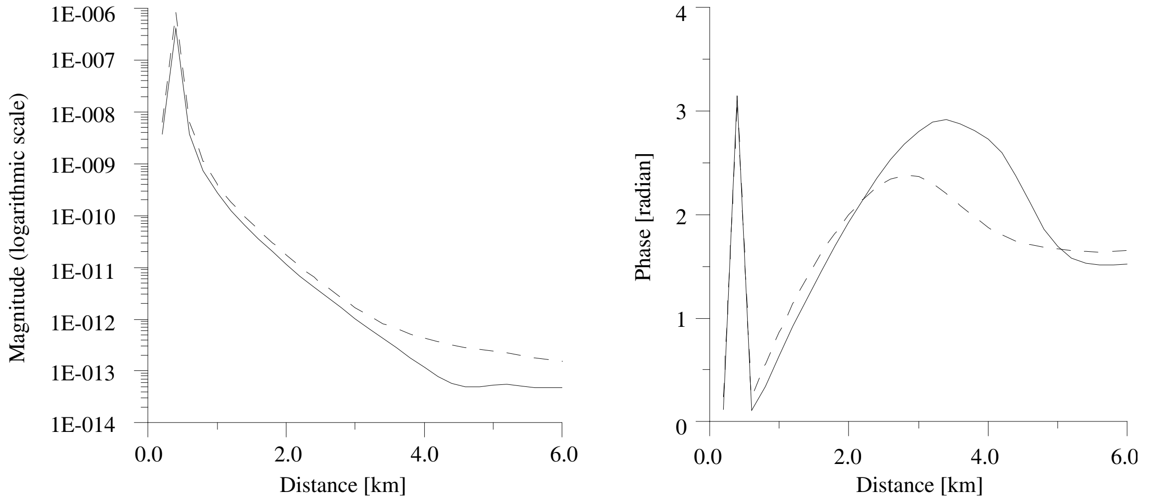


Figure 4: Same as Fig. 3 except that the water depth now is 200 m.

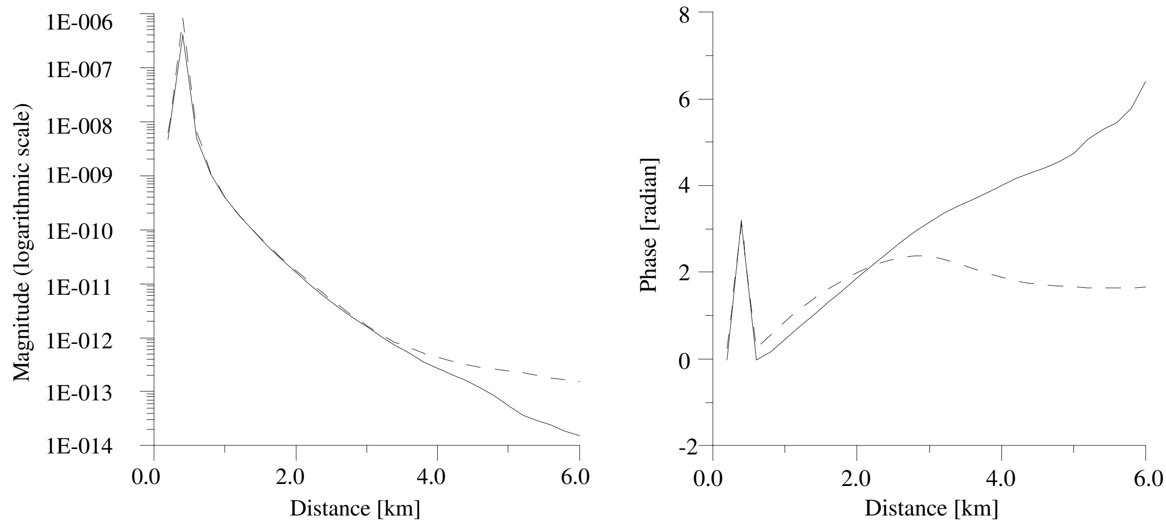
Let us now investigate the potential of the correction scheme given by Eq. (7) employing the same North Sea test model as above and a shallow water depth of 200 meters. Hence, in addition to computing the inline horizontal electric field (cf. Fig. 4), the cross-line horizontal magnetic field was also computed. First, we carried out tests with the decomposition carried out just above the seabed. Figs. 5(a) and (b) show that the method is not working very well for this case.

A better idea is to carry out the decomposition just below the seafloor, since it is known from EM geophysical techniques that the plane-wave impedance senses the material below the sensor and has no sensitivity to the material above it [4]. Using this idea we obtained the results shown in Figs. 6(a) and (b). We now easily see that the EM field decomposition method has worked satisfactorily and that the contribution from the airwaves has been efficiently attenuated (note the fairly straight phase curve after correction in Fig. 6(b) as expected).



(a) (b)

Figure 5: (a) Magnitude (log scale) and (b) phase of the inline field component E_y for a shallow-water case of 200 m. Before (broken curve) and after (solid curve) application of the air-removal technique. Wavefield decomposition **above** seafloor.



(a) (b)

Figure 6: Magnitude (log scale) and (b) phase of the inline field component E_y for a shallow-water case of 200 m. Before (broken curve) and after (solid curve) application of the air-removal technique. Wavefield decomposition **below** seafloor.

4. CONCLUSIONS

Marine remote sensing of hydrocarbons based on EM-soundings gives strongly distorted subsurface measurements in case of shallow waters. However, by combining the measured electric and magnetic field components the contribution from the airwaves can be strongly attenuated.

ACKNOWLEDGMENT

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REFERENCES

1. Amundsen, L., L. Løseth, R. Mittet, S. Ellingsrud, and B. Ursin, "Decomposition of electromagnetic fields into upgoing and downgoing components," accepted for publication in *Geophysics*, 2006.
2. Gelius, L., "Modeling the response of a seafloor antenna in the limits of low frequency and shallow water," paper accepted for *PIERS 2007*.
3. Kong, F., H. Westerdahl, S. Ellingsrud, T. Eidesmo, and S. Johansen, "'Seabed logging': A possible direct hydrocarbon indicator for deepsea prospects using EM energy," *Oil & Gas Journal*, May 13 edition, 2002.
4. Wait, J. R., "Theory of magnetotelluric fields," *Radio Science*, Vol. 66D, 509–541, 1962.