Surface towing versus deep towing in marine CSEM

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Summary

We compare two approaches for acquiring marine controlled-source electromagnetic (CSEM) surveys: one towing the horizontal electric dipole antenna close to the seabed (deep towing), and the other one towing the antenna just below the sea surface (surface towing). For both approaches, the sensitivity of the CSEM method to thin hydrocarbon layers in the subsurface using 3D forward modeling and 2.5D inversion is evaluated. The main trend is that attenuation of the EM signal in the seawater favors the use of deep towing at large water depths, while more accurate source navigation and operational efficiency favor surface towing in shallow waters. We evaluate the threshold water depth and analyze how the the sensitivity changes with frequency, target depth, navigation uncertainties and how it can be improved by using the upgoing component of the electric field in the inversion.

Introduction

Marine CSEM surveying has become an established method for hydrocarbon exploration during the last 10 years (Eidesmo et al., 2002; Ellingsrud et al., 2002; Constable, 2010). It uses low-frequency (0.1 – 10 Hz) electromagnetic fields that are usually generated by a horizontal electric dipole (HED) source towed in the water and recorded by seafloor receivers. The measured fields carry information about the distribution of electrical resistivity in the subsurface and are especially sensitive to thin resistive layers typical for hydrocarbon-filled reservoirs. Use of CSEM can thus substantially reduce the drilling risks in oil and gas exploration (Hesthammer et al., 2010).

In the conventional setup, the HED source is towed as close to the seafloor as possible in order to maximize the amount of electromagnetic energy transmitted into the subsurface. In this deep towing setup, the source is usually kept at 30 – 50 m above the seafloor to avoid any risk of impact with the seabed, see Figure 1(top). An alternative setup is to tow the source just below the sea surface as illustrated in Figure 1(bottom). The surface towing setup offers an improved operational efficiency, in particular, faster towing speeds. Besides, uncertainties in the source positioning are significantly reduced since it is easy to maintain both electrodes at fixed depth and accurately measure their lateral position using GPS.

The choice between deep and surface towing crucially depends on the water depth. Starting from the first applications for hydrocarbon exploration (Ellingsrud et al., 2002), the CSEM technology has been mostly used in deep water environments (deeper than ∼ 1 km). There, surface towing is not an option since most EM energy generated by the source would be lost while it propagates through the water column. In shallow waters, where its sensitivity to resistive subsurface targets is reduced because of the presense of the even more resistive air, CSEM has been used rarely. The EM wave propagating along the air-water interface often dominates the measured signal and thus masks the response coming from the earth. How-
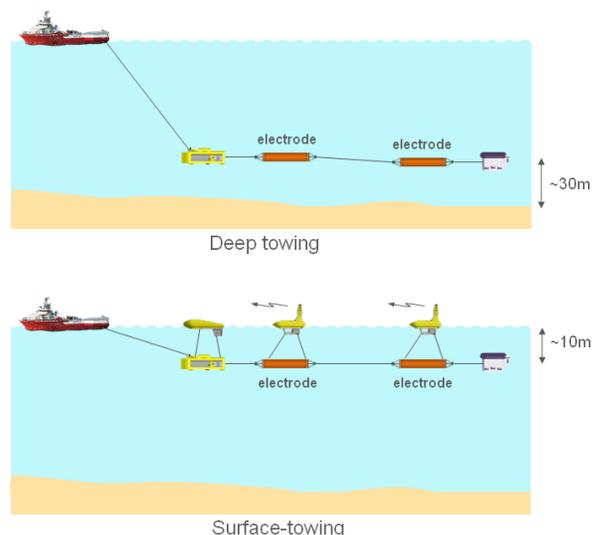
Figure 1: Two approaches for towing a HED source in CSEM surveys. Top: Deep towing where the source is kept at ∼ 30 m elevation above the seafloor. Bottom: Surface towing where the electrodes are suspended from GPS positioned buoys at a fixed depth, ∼ 10 m, below the sea surface.

ever, increased understanding of shallow-water CSEM signal propagation, significant progress in acquisition and interpretation tools as well as use of airwave mitigation methods has made the shallow water environment quite attractive for CSEM exploration during the last years (Mittet, 2008).

Since an increasing number of surveys is now being acquired in water depths below 1 km, surface towing of the EM source becomes a serious alternative to the more conventional deep towing. Use of a surface-towed source in combination with seabed receivers have been reported in (Shantsev et al., 2010), while a full towed EM system has been described in (Anderson and Mattsson, 2010; Linfoot et al., 2011). In the coming years, explorationists wishing to utilize marine CSEM will often have possibility to choose between a surface-towed and a deep-towed system. The aim of the present paper is to discuss what considerations should be taken into account when making this choice, and what is the typical threshold water depth that separates areas favoring surface towing and deep towing.

Our analysis is based on the setup with a towed source and seabed receivers described in (Shantsev et al., 2010). First, we compare the sensitivities of the deep-towed and surface-towed systems to a resistive target using 3D forward modeling, and then verify our conclusions with a 2.5D inversion study. In the modeling and inversion studies we take into account not only the different towing depth, but also the different uncertainty in the source navigation measurements.

Surface versus deep towing in mCSEM

Sensitivity study

In this section we examine the sensitivity of the CSEM method to an example hydrocarbon target using 3D forward modeling. Our target is a 50 m thick disk with a resistivity of 100 Ωm and diameter of 5 km. It is buried 2 km below the mudline in a uniform background with resistivity 2 Ωm, while the seawater resistivity is 0.3125 Ωm. A HED source is towed at an elevation of 30 m above the seabed (deep towing) or at 10 m depth below sea surface (surface towing). The towline passes above the target center. We shall analyze the inline electric field recorded by a seabed receiver deployed above the target edge. The computation was performed using the 3D time-domain finite-difference code detailed in (Mittet, 2010).

To characterize sensitivity of the CSEM method to the given target, we use the following quantity:

$$S = \frac{|E_{TA} - E_{BG}|}{\alpha|E_{BG}| + \eta} \,, \qquad (1)$$

The numerator represents the absolute value of the scattered field, i.e. the difference between the field in the presence of target E_{TA} and the background field E_{BG}. It is normalized to the total uncertainty in the recorded field, which consists of two terms. The first term is proportional to the field itself and arises due to uncertainties in the source and receiver parameters such as their positions and orientations, the source current and receiver calibration. The relative uncertainty α for a typical CSEM survey can be taken as 5% (Zach et al., 2009). The second term is the noise floor, which is determined by magneto-telluric noise, sensor noise, swell noise, etc. It is set to $\eta = 10^{-15}$V/Am^2 (after scaling by the source dipole moment). The target can be detected only if the scattered field from the target exceeds the total uncertainty, i.e. if the sensitivity S is well above 1.

First, the sensitivity is computed as a function of the source-receiver offset for a given frequency f and water depth. Then we select its maximal value over all offsets and plot it as a map in the plane (f – water depth) in Figure 2. Let us first consider the top panel showing the sensitivity map for the deep towing. As expected, the sensitivity is very small at high frequencies, due to their strong attenuation, and also small at very low frequencies, since the corresponding wavelengths exceed significantly the target extent. A less obvious results is that there exist two separate domains with high values of sensitivity: at deep and at shallow waters. At deep waters the sensitivity is large because basically all EM signal reaching the receiver propagates through the subsurface. At intermediate water depths the primary air-wave sets in, the relative contribution of the propagation path through the target becomes weaker and the sensitivity is reduced. However for very shallow water, multiple reflections from the air surface will again increase the fraction of the EM energy probing the subsurface.

In the map for surface towing, Figure 2(middle), the sensitivity domain at deep waters disappears completely because the EM signal is heavily attenuated in the conductive seawater. However, at water depths below $\sim$ 450 m the surface towing offers an equally good sensitivity to the selected target as the deep towing. Let us now recall that the surface towing allows more
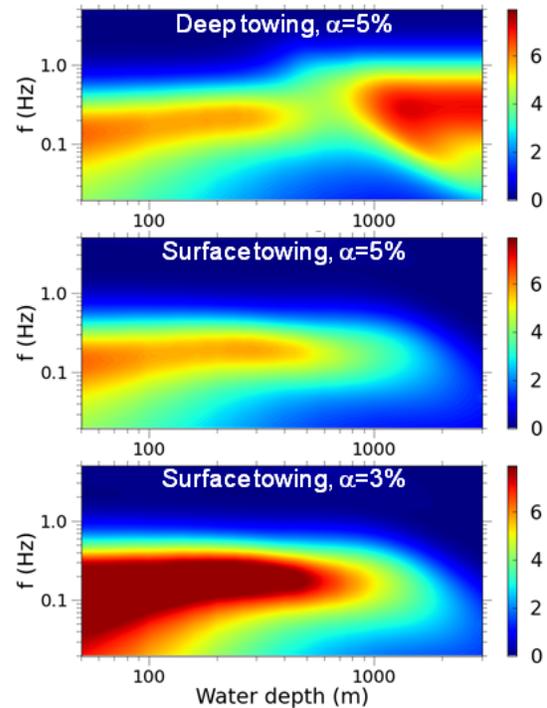
Figure 2: Sensitivity maps of the CSEM method for deep towing (top) and surface towing for $\alpha = 5\%$ (middle) and $\alpha = 3\%$ (bottom). The sensitivity is defined as the target response normalized to uncertainty, Eq. 1. The surface towing provides equal or better sensitivity if the water depth is smaller than 450 m. Reduction in the navigation uncertainty ($\alpha = 3\%$) moves the threshold depth to 700 m. Target depth is 2 km.

accurate measurements of the source navigation, which should lead to an improved sensitivity. For the surface towing setup presented in our previous work (Shantsev et al., 2010), (i) the depth of both electrodes was kept nearly constant with variations below 0.5 m, the corresponding variations in the source pitch being < 0.1 degrees, and (ii) the lateral positions of both electrodes were measured using a GPS system with a single-measurement error as small as 3 m. All this implies that the relative uncertainty parameter α for the surface-towed source must be smaller than for the deep-towed system. Therefore we replot the sensitivity map for the surface towing in Figure 2(bottom) and now use $\alpha = 3\%$. It gives a substantial uplift of sensitivity at shallow waters, and the threshold water depth increases up to $\sim$ 700 m.

Inversion study

The threshold water depth of $\sim$ 700 m for the use of surface towing found in the sensitivity study applies only to the considered resistivity model with the specific target buried 2 km below the mudline. For example, if we choose the buried depth to be smaller than 1 km, a similar sensitivity analysis gives the threshold water depth of the order of 250 m. This is because the sensitivity peak shifts to higher frequencies which are attenuated more severely in the sea water if the source is towed near the surface. Similar arguments suggest that the surface
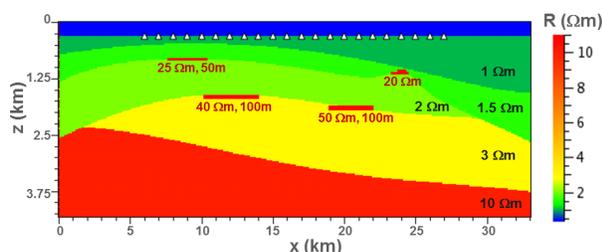
Figure 3: True resistivity model used for 2.5D inversion with 4 resistive targets embedded in a non-uniform background. White triangles indicate positions of 22 EM receivers placed on the seabed with 1 km spacing.
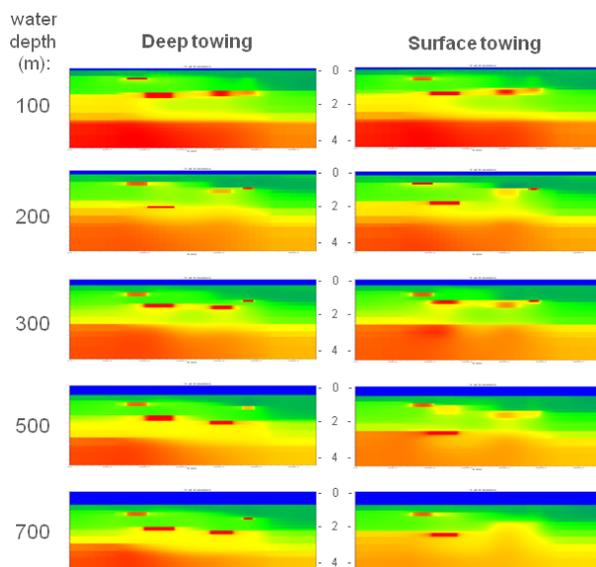
Figure 4: Resistivity models obtained by 2.5D inversion for deep and surface towing for 5 different water depths. For deep waters, deep towing gives significantly better inversion results, while for shallow waters the inversion results seem essentially independent of the towing depth. Color coding is the same as in Figure 3 showing the true resistivity model.

towing will be less sensitive also to the background resistivity distribution in the shallow overburden. In order to make a qualified choice between surface and deep towing, one needs to know how accurately the inversion of CSEM data can image the overall resistivity distribution in the subsurface.

In this section, we present a synthetic isotropic 2.5D inversion study where the true resistivity model shown in Figure 3 contains four resistive targets located at different depths and a variable background resistivity distribution consisting of five layers. Synthetic data for inline electric field and a transverse horizontal magnetic field (E_x and H_y) have been computed for 22 seabed receivers placed with 1 km spacing along the source towline. Source-receiver offsets up to 10 km were recorded at frequencies 0.1, 0.3, 0.5, 1 and 1.5 Hz. An unconstrained inversion started from a 1 Ωm half-space model. The final resistivity distributions for a range of different water depths
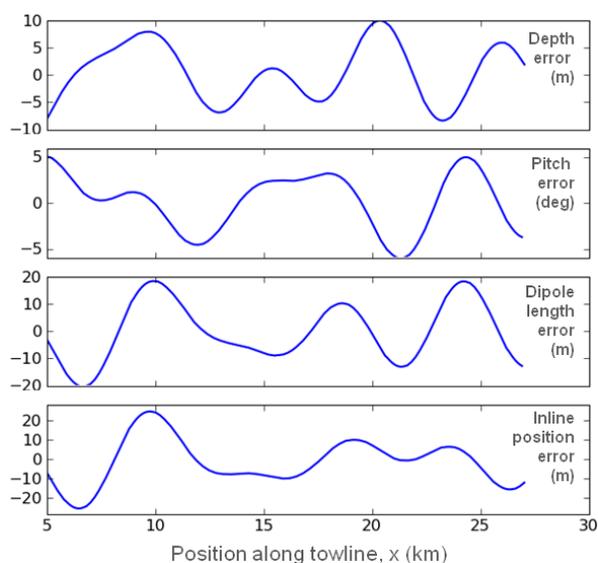
Figure 5: Synthetic noise introduced into source navigation data that is given to the inversion.

between 100 and 700 m are shown in Figure 4.

The inversion results confirm the main trend that we observed in the sensitivity study. At deeper waters, 500 and 700 m, inversion of the deep towing data was able to find all the targets and place them at the correct depth as well as reproduce the background resistivity with very good detail. Inversion of surface towing data was much less successful: only 2 out of 4 targets show up clearly at the final inverted model. At the same time, in shallower water depths of 100 and 200 m, the resistivity distribution obtained from the deep-towing and the surface-towing data do not differ much and it is difficult to say which one is closer to the true model. Based on these results, the threshold water depth below which one may safely use the surface towing for the given model is within ∼ 250 m.

Inversion with noise in navigation

The inversion results presented so far were based on the "perfect" synthetic data. This approach disregards all measurement errors inherent to data acquisition. As discussed above, measurement errors in the source navigation are expected to be larger for deep-towed systems than for surface-towed. In order to evaluate what effect it will have on inversion results, we ran inversion on the deep towing data with artificially corrupted navigation. Namely, we introduced noise into four key source parameters: inline position, dipole length, depth and pitch. The corresponding rms errors are 10, 10 and 6 m and 3 degrees respectively, while the typical wavelength of the navigation noise is 5 km, see Figure 5.

Inversion results obtained from data with correct navigation and from data with noisy navigation are presented in Figure 6. In both cases we assume the deep towing scenario and a 300 m water depth. It is clear that inverting data with noisy navigation gave poorer results, in particular, a significant mismatch in depth for the two deepest targets. We did not aim here at

reproducing realistic navigation errors for the commercially available deep-towed and surface-towed systems. The rms values we used are probably larger than the typical navigation errors expected for a source towed ~ 300 m below the surface. Nevertheless, our results clearly indicate that an improved accuracy in the source navigation should lead to more accurate inverted resistivity distributions. It further extends the range of water depth favorable for use of surface-towed systems with well-controlled electrode positioning. An additional argument in favor of surface towing is the possibility to cover larger areas during the same acquisition time due to faster towing speeds.

Inversion of upgoing field

In the range of water depths favorable for the use of surface towing, the air-wave represents a significant part of the recorded EM signal and often dominates the response coming from the subsurface. An efficient method to mitigate the air-wave effect is decomposition of the measured signal into up-going and down-going components (Amundsen et al., 2006). The down-going field is of little interest since it is almost fully determined by the primary air-wave, while the upgoing field is mostly determined by resistivities of the subsurface. Use of the upgoing field in the CSEM data attributes makes the anomalies due to resistive targets much stronger when the water depth is below a few hundred meters.

We therefore ran a new set of inversions in 100 and 200 m of water, now using only the upgoing field, and obtained much more accurate imaging of the subsurface resistivity. This improvement is illustrated by Figure 7 for the surface towing case, 100 m of water. In the conventional inversion based on E_x and H_y fields the two resistive targets on the right are completely misplaced in depth and look like one extended resistor (top panel). When inverting only the upgoing electric field, all the four resistive targets are imaged correctly (bottom panel). Importantly, the degree of improvement for deep-towing and surface-towing data was approximately the same. Hence, even very efficient air-wave mitigation methods do not affect the choice between deep and surface towing.

Conclusions

We have compared the sensitivities of the marine CSEM method to thin hydrocarbon-filled layers for the deep towing and for the surface towing of a HED source. The advantage of the deep towing is that very little EM energy is lost while propagating through the sea water, therefore it is preferred at larger water depths. We however demonstrate that in water depths of 250 m or less surface towing is likely to become the standard operation. At these depths, surface towing gives equally good results in terms of sensitivity and inversion as deep towing, while at the same time allowing a superior operational efficiency. Reduction in navigation uncertainties, faster towing speeds and potential for using a more powerful EM source extend the water depth range for surface towing beyond 250 m. From a target sensitivity point of view, we have shown that the water depth threshold for surface towing can be as large as 700 m. The exact water depth threshold will depend on the specific target depth and geologic setting, and must be established through modeling and inversion during survey planning.
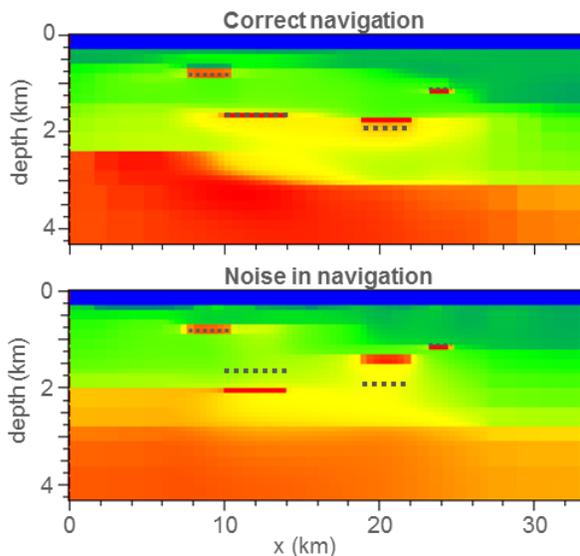
Figure 6: Resistivity models obtained by inverting deep-towing CSEM data which has correct navigation (top) or navigation contaminated with noise (bottom). The true target locations are marked by dotted black lines. Water depth is 300 m, the color coding is the same as in Figure 3.
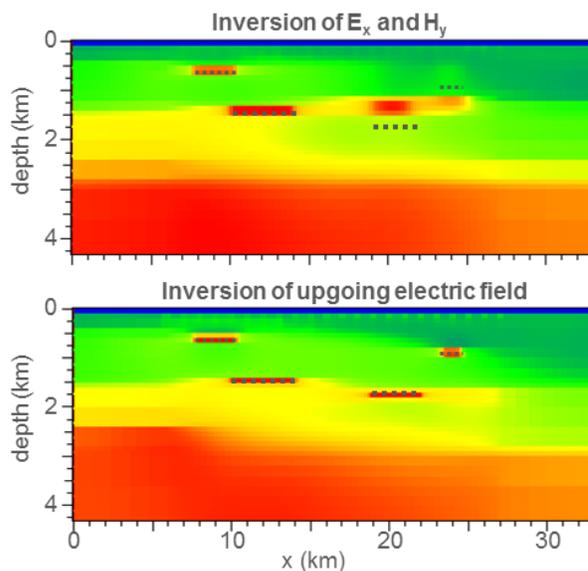
Figure 7: Resistivity models obtained by inverting surface-towing CSEM data using the total E and H fields (top) and only the upgoing E field (bottom). The true target locations are marked by dotted black lines. Water depth is 100 m, color coding is the same as in Figure 3.

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