Time domain versus frequency domain CSEM in shallow water.

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Summary

The marine CSEM method is being applied to the problem of detecting and characterizing hydrocarbons in a variety of settings. Until recently its use was confined to deep water (water depths greater than approximately 300m), because of the interaction of signals with the atmosphere in shallower water depths. This interaction is often described as an airwave: a signal free of information about the earth, which contaminates the signal. Based on this interpretation and inspired by the land electro-magnetic surveys case, a possible solution is going from the classic frequency domain CSEM to the time domain one in order to decouple the earth from the air. The purpose of this presentation is to compare frequency and time domain methods in the marine case.

Introduction

The marine controlled source electromagnetic (CSEM) method is now largely used as an exploration tool for detecting and delineating hydrocarbon reservoirs. Whereas seismic surveys can detect the structures that may contain hydrocarbons with great accuracy, distinguishing hydrocarbon fluids from water within these structures is more problematic. Originally developed in the late 70s (Young and Cox, 1981), the CSEM method uses a high powered horizontal electric dipole (HED) to transmit a low frequency electromagnetic signal through the seafloor to an array of multi-component electromagnetic receivers (figure 1). By studying the received signal as the source is towed through the array, the bulk electrical resistivity of the seafloor can be determined at scales of a few tens of metres to depths of several kilometers. Transmission frequencies are typically between 0.01Hz and 10Hz. At such low frequency, the behavior of electromagnetic fields in the earth is governed by the diffusion equation rather than the wave equation which governs seismic method.

Early applications of the CSEM method in hydrocarbon exploration concentrated on targets lying in deep water (300m and greater) (Johansen et al., 2005; Ellingsrud et al., 2002). This is because in shallower water signals that have interacted with the air dominate the response. These signals have been dubbed the airwave because they were initially identified, using seismic parallel, as a refracted wave through the highly resistive atmosphere. Several approaches to mitigate the effect of the airwave have been proposed, based on the wave-like description of the airwave feature: up and down going signals separation (Amundsen et al., 2006), time domain approaches (Constable and Weiss, 2006; Ziolkowski et al., 2006).

After a characterization of the airwave signature in frequency and time domain data set, we will describe it analytically. Understanding the physics behind CSEM in shallow water we will compare sensitivity to the earth in deep and shallow water for both methods.

Airwave signature

- Frequency domain:

We consider a simple 1D model composed of a sea water column H metres thick followed by an infinite uniform earth of 1Ωm resistivity. The source dipole is above the receivers which are positioned at the sea bed. They are aligned along the dipole axis. Figure 2 shows the amplitude and phase of the corresponding horizontal electric field for various water depths using a representative frequency of 0.25Hz. When the water depth is infinite we can see the amplitude (with a logarithmic scale) and phase (with a linear scale), have a close to linear behavior especially at large offsets. This is characteristic of the electric field propagation in the simple uniform earth considered here. As we decrease the water depth the amplitude of the measured electric field increases. There is an abrupt change in the slope of the amplitude curve occurring at shorter and shorter offset as the water depth is reduced.
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Similarly in the phase response the effect of reducing the water depth is to flatten the phase at progressively shorter offsets. At face value these signatures can be explained by a simple coupling with the atmosphere via a refracted wave at the sea surface propagating in the air (Constable and Weiss, 2006). As the air is infinitively resistive the skin depth tends to infinity corresponding to a decay factor of 1: no attenuation, and a flat phase symbolizing an infinite phase velocity. The decay after the abrupt change in the slope of the amplitude could be explained by the spherical divergence term as the waves are not plane waves.

Nevertheless a closer look at the curves shows that the effect of signal interaction with the air can be seen at all ranges and even beyond the onset of the airwave signature the measured signals depend on seafloor structure: amplitude decay can not only be explained by a spherical divergence term and phase gradient is not reduced to zero.

- Time domain:

The same exercise is now done in time domain for a representative source-receiver separation: 5km.
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A simple airwave explanation can not fully explain the airwave signature in the data sets. The physics of CSEM in shallow water is more complex.

1D integral equation analysis

- Frequency domain:

Starting from the Maxwell’s equations we end up with a parabolic partial derivative equation characteristic of diffusive phenomena. Solving it using a Green’s function technique (Chave and Cox, 1982) leads to equation 1 for the horizontal electric field at the sea floor due to a HED above the receiver in a 1D earth. $E_{TM}$ and $E_{TE}$ are described in equation 2. TM means Transverse Magnetic and TE Transverse Electric mode.

\[
E_{TM} = \frac{P_{ccw} \theta}{4\pi\sigma_0} \int_0^\infty \beta_0 \left( J_2(Kr) - \frac{J_1(Kr)}{r} \right) e^{-\beta_0(z'-z)} \frac{1}{1 - R_{air}^T R_{TM}^T} \left( e^{-\beta_0(z'-z)} \right) dK
\]

\[
E_{TE} = \frac{P_{ccw} \theta}{4\pi\sigma_0} \int_0^\infty \frac{\beta_0}{r/\beta_0} \left( J_2(Kr) \right) e^{-\beta_0(z'-z)} \frac{1}{1 - R_{air}^T R_{TE}^T} \left( e^{-\beta_0(z'-z)} \right) dK
\]

K is the real horizontal wave number, $\beta_0$ the complex wave number in the sea water (pseudo wave number), r the source-receiver distance, $\theta$ the azimuth (equals to 0 in our case), z' and z respectively the source and the receiver altitude above the sea floor, $J_0$ and $J_1$ respectively the 0 and 1th order Bessel’s functions, P the dipole moment, $\sigma_0$ the sea water conductivity, $R_{air}$ the reflection coefficient with the sea surface and $R_L$ the reflection coefficient with the sea floor. $R_L$ contains all the subsurface geo-electric information: conductivity and thickness of each layer and $R_{air}$ contains sea water and atmosphere ones. Each mode is composed by 4 different signals: 1, 2, 3, 4 propagating upward or downward depending on the sign of the $\beta_0 z$ term in each exponential (positive=downward, negative=upward). Term 3 is clearly an airwave term. But it is not the only one coupled to the air: term 4 depends on $R_{air}$ too. In fact due to the factor called coupling in equation 2 they are all coupled to both air and earth. It is for this reason that simple approaches based on separating the air from the earth are ineffective.

- Time domain:

The governing equations for electromagnetic propagation are the same in time and frequency domain. To calculate the time domain response, the frequency domain equations must be integrated over an appropriate frequency spectrum: equation 3 where $F$ is the frequency domain expression of the response given by equation 1.

\[
f(t) = \int_{-\infty}^{\infty} F(f)e^{i2\pi ft} df
\]

Equation 3: Fourier’s transform

The physics of the time domain problem is therefore identical. As suggested by the data even in time domain the earth and air signals are strongly coupled in a much more complex way than just a simple airwave arriving at earlier time compare to an earthwave arriving at later time.

Sensitivity to the earth

- Frequency domain:

Figure 4 shows the dimensionless sensitivity at the seafloor as defined in equation 4 to 1D changes in the same 1Ωm uniform earth structure in deep water as a function of depth below seafloor and source-receiver separation. Frequency is still 0.25hz and the source is an HED at the sea floor aligned with the receiver.

\[
\text{sensitivity} = \frac{\partial \ln E}{\partial \ln \rho_{\text{target}}}
\]

Equation 4: dimensionless sensitivity calculation. $\rho$ is the inverse of $\sigma$.

The depth to which data are sensitive increases with source-receiver separation. Figure 5 is the equivalent of figure 4 in 100m water depth. The interaction with the atmosphere clearly decreases the overall sensitivity to the resistivity of the earth and limits depth to which data are sensitive. Note that this sensitivity is extremely model and frequency depend. The sensitivity...
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To a resistive hydrocarbon filled reservoir is orders of magnitude higher and goes deeper, than the one to the simple uniform earth presented here.

- Time domain:

The equivalent exercise is done in time domain, for the previous representative 5km source receiver separation. Figure 6 is the deep water case. Before 0.3s there is little sensitivity to the earth structure as it is the time needed for the first signals to propagate from the source to the receiver.

Figure 7 is the 100m water depth case. As in frequency domain, compared to the deep water case, there is an overall decrease in sensitivity. It is also notable that in shallow water the sensitivity to this earth structure occurs at an earlier time. This is a consequence of the coupling between earth and air. The interaction with the atmosphere, carrying information on seafloor structure, propagates faster.

Using the land electromagnetic parallel we could remove the first peak of the timeseries to remove the airwave! Comparing figure 7 with figure 3 this is equivalent to cropping figure 7 on the time axis from 0s until around 1s. Not only this does not increase the sensitivity to the earth, but more significantly removes the sensitivity to shallow earth structure.

Conclusions

We have compared frequency and time domain CSEM methods in deep and shallow water. In both cases the signal interacting with the air affects the received fields and can limit sensitivity to sub-seafloor structure. A simple separation based on wave like approximation is not possible due to the complex coupling between earth and air signals. A more successful approach based on the decomposition of the signal into TE and TM modes is described in Andréis et al. (2005, 2006). It can be used in both frequency and time domain methods.
EDITED REFERENCES
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REFERENCES