Quantifying the effect of the water layer in shallow marine active source EM
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Summary

The water layer above the source and receiver in active source marine EM surveying is known to affect the measured response with a significant amount of energy travelling from the source to the receiver through the air. This has the effect of reducing the sensitivity to resistivity variations in the subsurface. This is especially true in shallow water. The use of a transient source waveform allows for a degree of temporal separation of the water layer and subsurface responses; this separation increases for decreasing water depth and decreasing subsurface resistivity. In the frequency domain no such separation exists and the airwave is only suppressed by increasing water depth.

Introduction

The use of active source electromagnetic methods for hydrocarbon exploration has grown quickly over the past eight years with success in de-risking deep water exploration wells (Hesthammer et al., 2010).

The technique currently used in deep water employs a continuous signal in which the scattered field is measured in the presence of the incident (source) field. In shallow water the signal from the source can arrive at the receiver through two paths: one path is through the earth (our signal), the other path is through the air (unwanted signal). Energy arriving at the receivers through the air can be extremely high in amplitude in shallow water relative to the signal that travels through the conductive earth. With a continuous signal this energy is arriving at the receivers all the time with the result that the sensitivity to earth resistivity contrasts is greatly reduced.

An alternative to using a continuous signal is to use a transient signal. For a transient system the current is on for a given time and is then switched off. In shallow water there is a degree of temporal separation between the water layer response and the subsurface response and so the reduction in subsurface sensitivity is reduced (Weiss, 2007).

The nature of the water layer response, however, is complex and can contain important information about the earth (Andreis and MacGregor, 2008). This work decomposes the total response into the earth response and three water layer components for different water depths, subsurface resistivities and offsets in order to illustrate the effectiveness of a transient system in shallow water.

Components of the water layer response

The water layer response in a double half-space of air and water can be considered in terms of two components. The ‘primary airwave’ (Figure 1) travels up from the source, through the air at the speed of light with attenuation of the signal proportional to $1/r^3$ and down through the water column to the receiver where $h$ is the depth of water above the source and receiver, $\delta$ is the skin depth and $r$ is the source-receiver offset.

Figure 1: Schematic of the propagation path of the ‘primary airwave’.

This is what is commonly referred to as the ‘airwave’ in active source EM (Constable and Srnka, 2007). In the field of subsea communications it is known as the lateral wave (Bannister, 1984; King et al., 1992).

The primary airwave has several important properties:

- It is independent of water depth and sea floor conductivity;
- It depends only on the depth of the source and receiver, offset and seawater conductivity;
- It propagates diffusively up and down in the water between source and receiver;
- It propagates as a wave through the air at the speed of light with $1/r^3$ amplitude decay.

The second component of the airwave is known as the direct wave or water wave and involves propagation through the water layer. Chen and Alumbaugh (2009) illustrated using the analytic expression for a double half-space of air and water (Bannister, 1984) that there is a source image term associated with this direct wave as illustrated in Figure 2.
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The key properties of the ‘water wave’ are:
- Propagation is in the water layer only;
- It is significant only at short offsets;
- Signal is rapidly attenuated by the conductive sea water;
- The response is similar to that of a whole-space of water, with differences introduced by the modified image term when the source is near the sea surface.

A third component of the water layer response is introduced when we consider models with three or more layers. Consider for example the introduction of the sea floor. Each time the electric field travels vertically upwards from the source it induces a new airwave component at the sea surface and sets up a rapidly damped sequence of reverberations. Similarly, the component travelling vertically downwards from the source sets up a reflection and associated reverberation sequence which induces a new airwave component with progressively less strength at the sea surface (Norskag and Amundsen, 2007). A similar series of reverberations is set up at the receiver. The water layer reverberations are shown schematically in Figure 3 where $z_S$, $z_R$ and $z_B$ denote the source depth, receiver depth and water depth respectively.

The magnitude of the reverberations depends on the water depth and the sea floor resistivity. The energy which travels through the air is a purely TE phenomenon (Weidelt, 2007) and the sea floor reflection coefficient for a vertically travelling plane wave in the TE mode is given by (Norskag and Amundsen (2007)).

$$R \left( \frac{\sqrt{\sigma_1} - \sqrt{\sigma_2}}{\sqrt{\sigma_1} + \sqrt{\sigma_2}} \right)$$

where $\sigma_1$ is the sea water conductivity and $\sigma_2$ is the sea floor conductivity. It can be seen from equation (1) that the reverberations are a function of the sea floor resistivity and so are a function of the earth resistivity structure. Furthermore the reverberation sequence is not only present in the water layer but is present within every layer in the subsurface. Andreis and MacGregor (2008) show that the coupling between the earth and the air can be expressed as an infinite series of multiple reflections between the sea surface and all resistivity boundaries within the subsurface just as with seismic data. Because of the skin depth effect, the number of reverberations which actually contribute to the sequence is generally very small. However, in shallow water and with a large seafloor resistivity the total contribution of the reverberations can be as large as, or even larger than, that of the primary airwave. Because reflections and reverberations are set up at every resistivity boundary the reverberation response can be significantly modified by large resistivity contrasts in the first few hundred metres of the sea floor. It is therefore not always the case that the reverberation response is unwanted if for example the near surface resistivity structure is complex.

Quantifying the water layer contributions

The ‘primary airwave’ can be calculated simply from the response within a half-space of water at very long offset. Reverberations can be calculated from the response at very long offset over the model in question, this allows for almost complete temporal separation of the earth response from energy which has travelled through the air between source and receiver. The primary airwave can be subtracted from the long offset water layer response to give the reverberation response. Scaling by $1/r^3$ then gives the primary airwave and reverberation response at the required offset $r$.

There is no way of isolating the ‘water wave’ response but it can be approximated from the water half-space response with the primary airwave removed.

Figure 4 shows the response at an offset of 6km in 100m of water over a 1 ohm m halfspace. The top plot shows the contribution of the different components in the time domain while the bottom plot shows the real component of the
frequency response. The vertical scale on the time domain plot does not show the full extent of the airwave response. At early times, it is about 40 times that of the peak earth response amplitude. The horizontal axis is dimensionless time with the time of the peak of the earth response ($t_{peak}$) equal to one. It is clear from this plot that in shallow water the primary airwave has almost complete temporal separation from the earth response. Reverberations from the sea floor are more of an issue, but, by the peak time of the earth response, contribute only about 15% of the amplitude. In the frequency domain (Figure 4 bottom) the high amplitude airwave response is spread across all frequencies. At 0.1Hz the earth response comprises about 25% of the total response and there is no frequency at which the earth response makes up over 50% of the response.

To gain a better understanding of how the water layer response interacts with the earth response as a function of time, frequency, offset, water depth and resistivity, synthetic data were generated over three simple models for offsets of 2-9km and decomposed in the same way as the data shown in Figure 4. Figure 5 shows the time domain response and Figure 6 the real component of the frequency response for a 1 ohm m half-space in 100m of water. In both figures the primary airwave is shown in the top left. It only affects the response at very early times but in the frequency domain is significant over a wide frequency range. The reverberations are shown in the top right. The effect in the time domain is significant up to about 0.5 $t_{peak}$; in the frequency domain the response contributes significantly to the total amplitude in the same bandwidth as the signal. The water wave shown in the bottom left is small in both the time and frequency domains. It is most noticeable in the time domain beyond about three $t_{peak}$. This is because the other components have decayed significantly beyond this time. The response after removing the water layer components is shown in the bottom right. The time domain response is dominated by the earth response beyond 0.5 $t_{peak}$ where it makes up 70-95% of the response. In contrast, the frequency domain response has a significant negative response while the airwave and reverberations have a much larger positive response in the same frequency range. This clearly illustrates the advantage of operating in the time domain in shallow water.

Figure 4: Decomposition of the impulse response into water layer and subsurface components. Top: Time domain. Bottom: Real component of the frequency response.

Figure 5: The time domain response showing the percentage contribution of different components. Colour scale range -100 to +100%. Vertical scale is dimensionless time from 0-5 $t_{peak}$, horizontal axis is offset from 2-9km. Top left: Primary airwave. Top right: Reverberations. Bottom left: Water wave. Bottom right: Water layer response removed.

Figure 6: The real component of the frequency response showing the percentage contribution of different components. Vertical scale is frequency from 0-1Hz, horizontal axis is offset from 2-9km. Top left: Primary airwave. Top right: Reverberations. Bottom left: Water wave. Bottom right: Water layer response removed.
Figures 7 and 8 are the same as Figures 5 and 6 but for a half-space resistivity of 2 ohm m in 100m of water. The effect of the increase in subsurface resistivity is that the amplitude of the reverberation response is larger due to the larger seafloor reflection coefficient. The increased resistivity also increases the amplitude of the subsurface response but the arrival time is earlier which results in less temporal separation, the primary airwave is now even less significant in the time domain. In the frequency domain the primary airwave still has a significant effect up to 5km offset, however, the reverberation response is significant at all offsets right across the signal bandwidth. The water wave is small.

However, beyond 7km offset the primary airwave is significant.

Conclusions

Decomposition of the earth impulse response into water layer and subsurface contributions provides a useful insight into how the water layer response interacts with the subsurface response as a function of water depth and resistivity.

The water layer response is not independent of the earth but is strongly coupled to it, especially the sea floor where there is a large resistivity contrast. In 100m of water the time domain signal has a significant separation of the water layer response from the subsurface response. In the frequency domain there is significant overlap of the two responses. Inversion of the time domain response in the time domain for times greater than 0.5 \( t_{peak} \) eliminates most of the water layer response. In the frequency domain the total water layer response must be included. In 500m of water the temporal separation in the time domain is less and the airwave in the frequency domain is reduced making the distinction between the two techniques less. In very deep water where there is no airwave the results would be the same.

Figure 7: The same as Figure 5 but for a 2 ohm m half-space in 100m of water.

Figure 8: The same as Figure 6 but for a 2 ohm m half-space in 100m of water.

Figure 9: The same as Figure 5 but for a 1 ohm m half-space in 500m of water.

Figure 10: The same as Figure 6 but for a 1 ohm m half-space in 500m of water.
EDITED REFERENCES
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REFERENCES


