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Broadband towed marine seismic acquisition via total system de-ghosting

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Summary

Conventional towed streamer seismic acquisition suffers from the ghost recording at the receiver as a direct consequence of towing the streamer beneath the sea surface. Energy reflected from the earth"s subsurface is recorded in the streamer sensors first as an up-going wave-front, then secondly as a down- going reflection from the sea surface. This reflection from the sea surface is referred to as the „ghost" recording. The ghost adversely affects the seismic record, introducing notches in the frequency spectrum.

Similarly, since the seismic source is also towed beneath the sea surface, a source ghost is also generated. In this case the ghost is the source energy reflected from the sea surface; it interferes with and degrades the principal source energy directed to the subsurface.

A dual-sensor streamer utilizes co-located hydrophones and vertical velocity sensors to eliminate the ghost on the receiver side. The two sensors record their respective ghosts with different polarity, allowing wave-field separation to retain the up-going wave- field, which is free of the receiver ghost. De-ghosted data via the dual-sensor system exhibits broadband quality rich in both low and high frequencies, which leads to greater resolution of events, and greater penetration in the deep section.

An innovative approach now addresses the ghost on the source side. The source array is divided into sub- sources, with each sub-source being fired with specific fire time delays and deployed at specific depths. The fire time distribution allows separation of the wave- fields from the sub-sources, and the depth distribution allows those wave-fields to be recombined such that the source ghost is removed.

The implementation of the time and depth distributed source in conjunction with the dual-sensor streamer yields a total ghost-free recording system for towed marine seismic. Acquisition aberrations associated with conventional towed streamer are removed to reveal the earth's response with high resolution and large seismic bandwidth.

***Key Words**: broadband, ghost, dual-sensor, source, resolution, penetration.*

Introduction

Figure 1 illustrates how ghost recordings in towed marine seismic are inevitable since both the marine seismic source and the streamer cable are towed beneath the sea surface. The ghost recordings introduce notches in the frequency spectrum of the recorded data, with the notch frequencies directly dependent on the depth of the streamer and the depth of the source. As an example, Figure 2 shows the frequency notches which result for a streamer towed at 15m with source depth 6m.

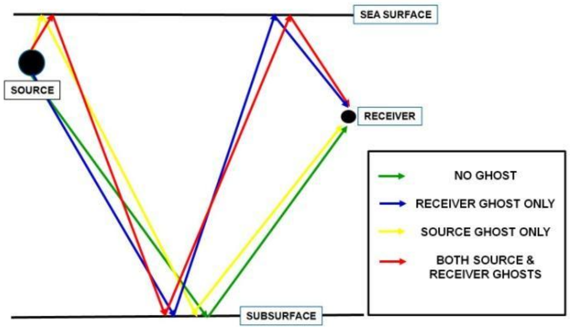

Figure 1. Raypaths showing source and receiver ghosts in towed marine seismic.

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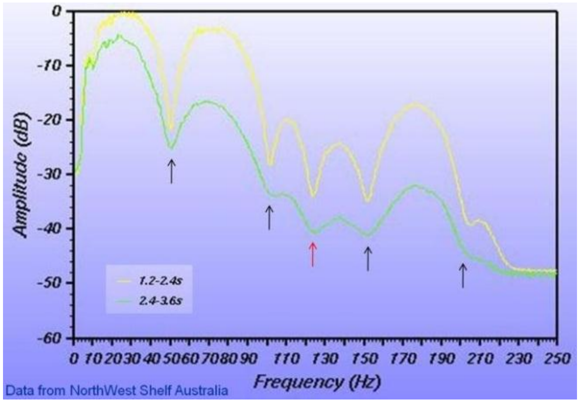

Figure 2. Receiver ghost notches (black arrows) and source notch (red) for streamer at 15m tow depth.

As a consequence the tow depths used in marine seismic acquisition have historically been configured to give the optimum range of frequencies achievable for a particular target depth or objective. A shallow streamer tow was used for high frequency recording, at the expense of the low frequencies, whereas a deep tow was used if lower frequency, or deeper penetration, was required. Furthermore, the reduced bandwidth in the recorded data adversely affects both the resolution of seismic events, and the penetration of signal deep in the section. In 2007, Tenghamn et al introduced the dual-sensor streamer as a means of delivering towed marine seismic data which is free of the receiver ghost, and soon thereafter production data recorded with the dual-sensor method confirmed that the precise elimination of the receiver ghost resulted in improved resolution and penetration in the recorded data (Carlson et al, 2007).

Whilst the dual-sensor streamer yields greater broadband data rich in both low and high frequencies, there remained the ghost recording introduced on the source side. An innovative approach in the configuration of the marine source now addresses the source-side ghost (Parkes et al, 2011). The source array is divided into sub-sources, with each sub-source being fired with a specific fire-time delay, and deployed at a specific depth. The combined time and depth distribution of the unit sub-arrays that make up the source configuration allow de-ghosting of the source-side ghost.

The combination of the dual-sensor streamer and the time-and-depth distributed source yields towed marine seismic data which is truly broadband and free of ghost frequency notches. These seismic benefits translate to significant value for the hydrocarbon exploration and production effort. Broadband, ghost- free data has better resolution of seismic events, greater penetration of signal in the deeper section, and is easier to interpret. Data processing is more responsive and the results of inversion work or Quantitative Interpretation (QI) are more accurate.

Eliminating the Receiver Ghost

A dual-sensor towed streamer is used to eliminate the receiver ghost. Co-located hydrophones and velocity sensors (which record vertical particle velocity) contained in a single solid streamer record their ghosts respectively with different polarity. The hydrophone which records pressure and is insensitive to direction, records its ghost with reversed polarity. The velocity sensor records its ghost with unchanged polarity. This facilitates the separation of the total recorded wavefield into its component up-going and down-going parts, for each of the sensors, irrespective of the depth of tow. The up-going wavefield is then, by definition, free of the receiver ghost.

The left panel in Figure 3 shows the pressure wavefield recorded by the hydrophone, for a sample window of stacked data, from the dual-sensor streamer towed at 15m. This is of course exactly equivalent to a conventional hydrophone-only streamer. The centre panel of Figure 3 shows the equivalent stack from the velocity sensor, and the right panel shows the de- ghosted hydrophone data which results from the dual- sensor system. The amplitude spectrum beneath each panel shows the range of frequencies recorded with the associated notches for the component hydrophone and velocity sensors, and the notch-free de-ghosted data.

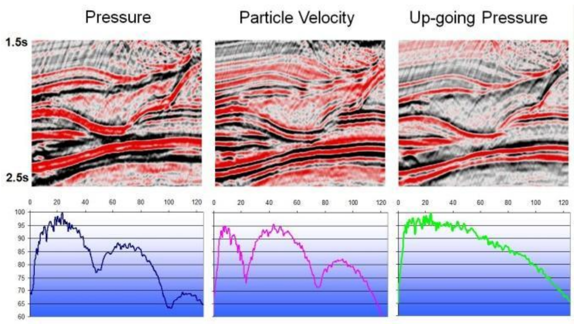

Figure 3. Hydrophone, Velocity sensor, and resulting amplitude spectra for dual-sensor streamer at 15m tow depth. (Frequency range is 0-120Hz.)

A significant operational advantage of the dual- sensor towed system is that the streamer can be towed at a depth of

15 – 25m, in a much quieter environment away from swell and mechanical noise. Moreover, recording of seismic interference noise is attenuated by the velocity sensor, which records the vertical particle motion only.

Significant benefits are observed when the receiver ghost is eliminated. Ghost free data is clearer, easier to interpret, and more closely ties earth"s reflectivity. Physically eliminating the ghost recording from the recorded data is expressed in the frequency domain by the elimination of the frequency notches introduced by the ghost, resulting in broadband data. The value of broadband data is evident from (a) improved resolution of seismic events (which requires both low and high frequencies) and (b) greater penetration of seismic signal in the deeper section (resulting mainly from the increased low frequency content).

Broadband data is more responsive to data processing routines; for example, velocity analysis proceeds with greater accuracy and confidence of picking. Sophisticated demultiple applications such as 3D Surface Related Multiple Elimination (3D-SRME) can be enhanced to utilize the down-going velocity wavefield (one of the products of the dual-sensor system) so that assumptions about the sea state during data acquisition become redundant. But most importantly, it is at the level of reservoir investigation where the benefit of broadband data is fully realized, in inversion and reservoir characterization studies.

Figure 4 illustrates the uplift in resolution and penetration of de-ghosted dual-sensor data compared to conventional streamer data, whilst Figure 5 shows improved inversion results because of the increased bandwidth in the data.

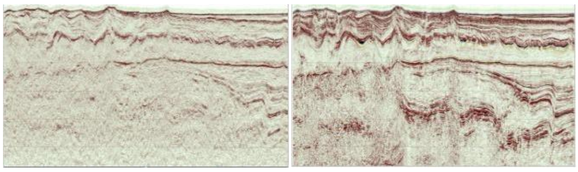

Figure 4. De-ghosted dual-sensor data from offshore Cyprus (right) shows improved resolution and penetration compared to conventional streamer data (left)

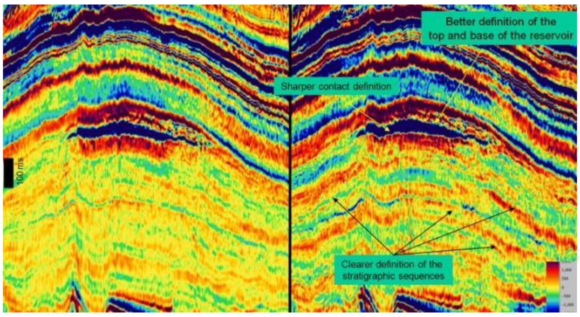

Figure 5. A relative inversion exercise over a large gas reservoir from the NWS Australia. Conventional streamer data (left), and de-ghosted dual-sensor data (right).

Eliminating the Source Ghost

The source ghost is addressed in an innovative approach to source array design, which utilizes sub- arrays which are (a) deployed at different depths and (b) fired with a fire-time delay. For example, in a typical configuration using a total of three sub-arrays, two of the sub-arrays on either side of a central sub- array are deployed at 9m depth, and the central sub- array is deployed at a shallower depth of 5m. The outside sub-arrays (at 9m depth) are fired at time zero (i.e., no fire-time delay), and the shallower sub-array (at 5m depth) is fired with a delay ranging from 250ms to 1000ms. The fire-time delay is randomized for subsequent shots, keeping within the range 250-1000ms.

The source design is thus both a time and depth distributed source. The time-distribution aspect of the source introduced by the randomized fire-time delays of the sub-sources allows the separation of the wavefields from the sub-sources. The depth distribution of the sub-sources allows for the removal of the source ghosts according to a method based on the redatuming, correlation, and summation of the source ghost functions. (Posthumus 1993) as illustrated in the conceptual schematic in Figure 6.

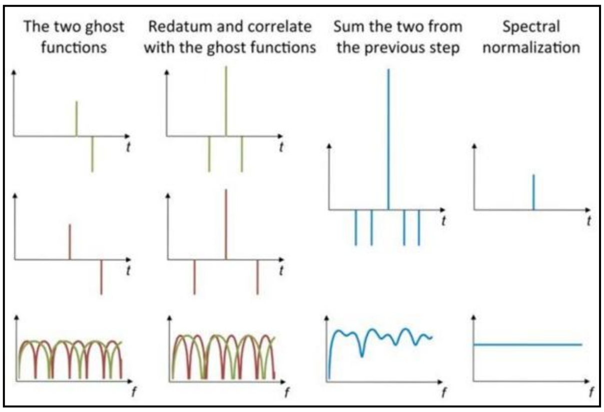

Figure 6. The de-ghosting method described by Posthumus, 1993.

Figure 7 shows a shot record which results from the time and depth distributed source described earlier. On the left the data from the 5m and 9m sub-sources is seen superimposed, as recorded by the recording system. The middle record is after de-ghosting, and the record on the right is after separation of the sources.

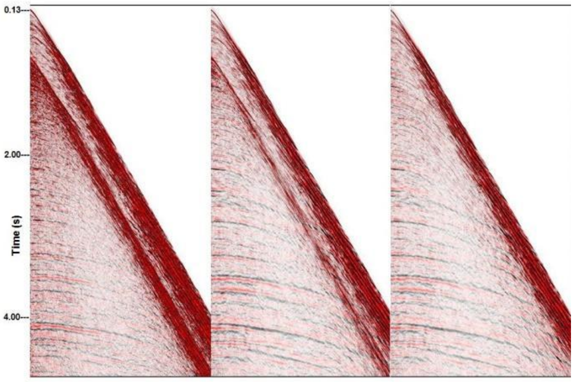

Figure7. Shot record from depth & time distributed source. Left: as recorded, Centre: After de-ghosting Right: after de-ghosting and source separation.

Revealing the True Earth Response

The seismic wavelet recorded in towed marine data acquisition is a convolution of the source response, the earth‟s filtering effect („Q‟), and the source and receiver ghosts. Removing these "aberrations" in the seismic recording method will reveal the true earth reflectivity response. The receiver and source ghosts can be eliminated using the dual- sensor streamer and the time-and-depth distributed source described earlier. The resulting broadband data allows the linear decay that is due to the earth‟s filtering effect to be measured, so that an inverse filter can be applied to the data to correct for this effect. Finally, the source signature can be removed by deconvolving with the source instrument response.

Figure 8 shows data acquired with conventional hydrophone-only streamer at 15m tow, with a conventional source at 7m depth. Source and receiver ghosts are present, and the effect of the source signature and earth‟s absorption evident. Figure 9 shows the same data using a dual-sensor streamer towed at 15m, and with the time-and-depth distributed source. Source and receiver de-ghosting has been performed, and the source signature and earth‟s absorption effects have been addressed. The true broadband earth response is revealed, free from the extraneous ghost reflections and the associated notches in the frequency spectrum.

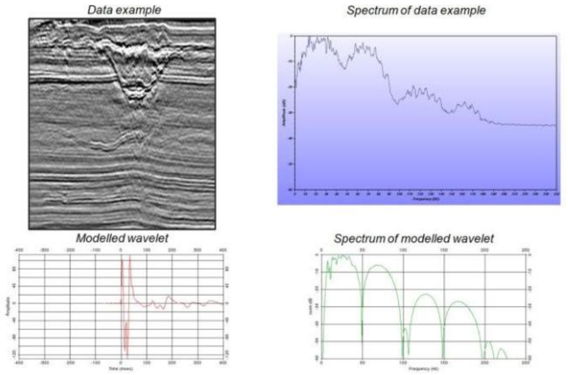

Figure 8. Data example together with wavelet and spectra, for hydrophone-only data. Source and receiver ghosts, source signature, and earth‟s absorption are all present. The frequency range shown in the amplitude spectra is 0-250Hz, vertical axis represents amplitude in dB, with zero at the top, and -10dB increments. The bottom left shows the extent of the wavelet, with the evertical axis representing amplitude, and the horizontal axis time, with 100ms increments.

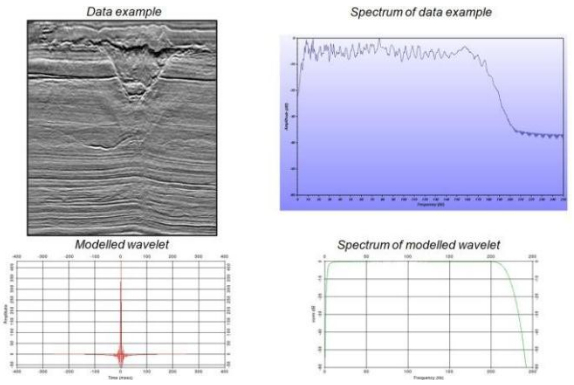

Figure 9. Same data example, after source and receiver de-ghosting, and applying source de-signature and inverse "Q" filter. Axes and scales are as for Figure 8. Note that the wavelet is now compressed and zero-phase.

Conclusions

Towed marine seismic has since its inception suffered from ghost reflections which are a result of towing the source and streamer beneath the sea surface. Other effects, such as the source signature, and the earth‟s absorption effect, "Q", also distort the true earth response.

The dual-sensor streamer technology enables de- ghosting of the receiver ghost, while a new, innovative time-and-depth distributed source enables de-ghosting of the source ghost. The de-ghosted data allows the earth‟s response, "Q", to be reliably estimated, so that an inverse filter can be applied, and the source signature can be deconvolved. When all these "aberrations" are eliminated, the true earth response is revealed.

Acknowledgements

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