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Enhanced Resolution, Imaging, and Interpretability: Dual-Sensor Towed Streamer Data Examples from around the World

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Summary

Every reflection wavelet recorded by a marine streamer is accompanied by a 'ghost' reflection from the sea surface. If both the seismic pressure wavefield and the vertical component of the particle velocity can be acquired using co-located pressure and velocity sensors, it is then possible to combine these datasets to produce a seismic image with the receiver ghost removed. The dual-sensor streamer has been developed to record both of these desired seismic wavefields and enable extraction of the up-going and down-going pressure and velocity wavefields. The up-going pressure wavefield represents the de-ghosted pressure result. The dual-sensor streamer architecture uses densely sampled co-located pressure and velocity sensors housed in a low-noise ruggedized solid streamer to deliver de-ghosted data in one pass, using one streamer depth. Deep streamer towing facilitated by the dual-sensor technology increases the operational weather window (and therefore improves operational efficiency), reduces noise, and increases signal penetration. The de-ghosted seismic data exhibit a greater frequency bandwidth and a greater signal-to-noise ratio than can be obtained using conventional streamers. The new dual-sensor streamer technology enhances resolution and imaging of the subsurface and through more responsive data processing and improved seismic inversion, contributes to a better understanding and interpretability of any asset.

Introduction

When upward-travelling seismic reflection energy arrives at a towed streamer, the resultant pressure variations are sensed by the hydrophones in the streamer. The up-going seismic wave continues propagating beyond the streamer until it reaches the sea surface, where it is totally reflected back downwards. This down-going pressure wavefield is also detected by the hydrophones in the streamer. Thus, every reflection event recorded using a marine streamer is accompanied by a 'ghost' reflection from the sea surface. The effect of this ghost is to elongate the seismic reflection wavelet, reducing temporal resolution and introducing a series of peaks and notches into the frequency spectrum of the seismic data (Figure 1(a)).

In order to work around the receiver-ghost notch, conventional streamer surveys are either conducted at shallow depths to acquire high-frequency energy (but at the risk of greater noise and at the expense of low-frequency information), or conducted at greater depths to achieve better penetration and acquire low-frequency energy (but at the expense of high-frequency information). It has long been understood that if seismic energy could be acquired using co-located hydrophones and velocity sensors, then by properly combining their signals, ghost reflections could be cancelled. This would create new ways to optimise the design of streamer surveys and provide opportunity for enhancing seismic resolution while, at the same time, maximising signal penetration. To date, more than 80,000 line kilometers of 2D and 8,500 sq km of 3D data has been acquired with the GeoStreamer™, the industry's first successful implementation of dual-sensor streamer technology. Data examples from different geological settings around the world highlight the geophysical advantages and the improvement in data quality and interpretability.

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Dual-Sensor Streamer Theory, Acquisition and Processing

The underlying principle of the dual-sensor streamer relies on the fact that pressure and velocity sensors record the down-going receiver-ghost wavefield with opposite polarity. The down-going pressure wavefield recorded by a hydrophone will have the opposite polarity to the up-going pressure wavefield. As illustrated in Figure 1(a), for vertical incidence, the associated ghost notches for a pressure sensor will exist at 0 Hz and integer multiples of $V_w/2d$, where V_w is the velocity of sound in water and d is the receiver depth. In contrast to pressure sensors, velocity sensors are directional. Consequently, the down-going wavefield detected by a velocity sensor will have the same polarity as the up-going velocity wavefield. Figure 1(b) shows that the resultant receiver-ghost notches for the velocity sensors are also separated in the frequency domain by integer multiples of $V_w/2d$, but are offset by $V_w/4d$ from the pressure sensor notches. This offset means that the peaks and notches in the frequency-amplitude spectrum for the pressure data are complementary to those of the velocity data. Appropriate combination of the measured pressure and velocity data will enable complete cancellation of the ghost event trailing each primary event such that no receiver-ghost notches will exist in the amplitude spectra of the resultant data.

Decomposition of the seismic data into the up-going and down-going pressure and velocity wavefields follows the work of Barr and Sanders (1989), Fokkema and van den Berg (1993), and Amundsen (1993) (amongst others), and inherently incorporates all angle-dependent effects. Furthermore, the shape of the sea surface is irrelevant, and the streamer depth is not constrained. After separation into up-going and down-going components, both pressure data and velocity data can be extrapolated to any desired recording depth. This enables matching to any legacy seismic data that might exist, and makes GeoStreamer™ data suitable for 4D seismic applications.

Our ability to remove the receiver-ghost notch provides significantly increased flexibility in streamer towing depth. It is attractive to tow as deep as possible to reduce weather and operational noise, and increase signal penetration of the low-frequency energy. This does not penalize recovery of the high-frequency energy because, as discussed above, dual-sensor summation will remove the impact of the receiver-ghost notch and enable recovery of the full-bandwidth seismic signal. The GeoStreamer™ architecture uses densely sampled co-located pressure and velocity sensors housed in a quiet solid-fill streamer with distributed electronics and Ethernet telemetry. Acquisition of the pressure and velocity wavefields is achieved in one pass at one streamer depth, and use of conventional streamer deployment, towing and retrieval systems means the GeoStreamer™ can be efficiently deployed on conventional seismic vessels. In practice, the GeoStreamer™ towing depth is in the range of 15-25 m – at this depth recording can continue in rough seas, and the pressure and velocity data are better behaved than would be the case for shallower towing. This greater towing depth, together with dual-sensor processing, ensures GeoStreamer™ data will have increased bandwidth, deeper penetration, and a better signal-to-noise ratio than conventional streamer data.

Pre-processing of the dual-sensor data to recover the de-ghosted pressure wavefield is relatively straightforward. First, the impulse response of the velocity sensor (which has a non-flat spectrum) is matched to the flat zero-phase hydrophone spectrum. This step takes into account the difference in the sensitivities between the two sensor types. Signal conditioning is then applied to the velocity sensor data over the range 0 – 20 Hz, constrained by the pressure sensor data using an exact mathematical formulation (Fokkema and van den Berg, 1993). This is desirable because velocity sensors record strong low-frequency mechanical noise. The conditioning of the low-frequency data is mathematically robust for scattered wavefields (the direct arrivals are removed), and since seismic wavelengths are of the order of 75m or larger for frequencies below 20Hz, small variations in streamer depth or the sea surface will have little impact on the conditioning process. After being separated into up-going and down-going wavefields both the pressure data and velocity data can be extrapolated to any desired depth. The up-going pressure wavefield represents the de-ghosted pressure result, and is completely free of the receiver-side ghost. Both the low and high frequency content of the de-ghosted data is significantly boosted compared to the input data. Thereafter, the data are passed on to a 'conventional' processing flow, modified of course to exploit and preserve the improved frequency content and signal-to-noise ratio of the data.

Enhancing Resolution, Imaging, and Interpretability

Figure 2 demonstrates the improvement in clarity of the seismic image from a dataset in the North Sea that is obtained by combining the recorded pressure and velocity wavefields to produce the up-going (de-ghosted) pressure wavefield. The total event set is effectively halved with the removal of the receiver-side ghost, simplifying interpretation of the seismic section considerably. The frequency amplitude spectrum of the de-ghosted data does not contain the notches observed in the pressure and velocity data, and the up-going wavefield exhibits improved temporal resolution.

The example shown in Figure 3 is from the North West Shelf of Australia, in an area known for its seismic 'dead zone', caused by penetration problems, i.e., the inability to see seismic energy reflected from the subsurface. In this case the seismic energy is attenuated by a thick carbonate layer in the overburden. The left panel of Figure 3 illustrates the lack of deep penetration of regular seismic data due to the carbonate layer. The extended bandwidth provided by GeoStreamer readily offers a better image of the deep section (Figure 3, right panel) while preserving and even enhancing the shallow resolution.

The improvement in bandwidth gained via the dual-sensor system is illustrated in the frequency panels shown in Figure 4. The figure compares the frequency content of conventional hydrophone-only recording versus GeoStreamer de-ghosted data in the North West Shelf of Australia. We see a significant boost in the low frequencies, but also a gain in the higher frequencies, since the amplitude spectrum is now effectively flattened and free of notches. The figure confirms a gain of more than 20Hz bandwidth with GeoStreamer in this example.

Figure 5 is a detail section of a gas reservoir, also from the North West Shelf of Australia. The reservoir is known to be complex with the presence of multiple sand bodies. The de-ghosted GeoStreamer section shows an improved seismic flat-spot and amplitude response. Importantly, improved resolution in the GeoStreamer data makes it possible to identify the individual layers of stacked sands.

In offshore Cyprus, a different geological regime also presents penetration problems. The left panel of Figure 6 shows a 2006 conventional streamer line, and the right panel shows the same profile re-acquired using GeoStreamer in 2008. The improvement is dramatic and illustrates the importance of full bandwidth from the dual-sensor system, and the positive impact this can have on data processing and imaging. In this example the attenuating layer is anhydrite, but a similar problem exists on much of India's west coast, with basalt.

Conclusion

Seismic data acquired using the dual-sensor streamer will exhibit greater frequency bandwidth and a greater signal-to-noise ratio than can be obtained using conventional streamers. The geophysical advantages of dual-sensor streamer technology are seismic images with greater temporal resolution, stronger and more coherent deep reflectors, increased low-frequency content and simplified event representation that will all contribute to new opportunities for enhanced geological characterisation of the sub-surface.

Examples from different geological settings from around the world show that the GeoStreamer dual-sensor system will always change the interpretability of an asset for the better. In geological domains where an attenuating overburden, such as carbonates or basalts, inhibits the seismic response, the dual-sensor technology provides significant improvement in the deeper section.

References

1. Amundsen, L., 1993. Wave-number-based filtering of marine point source data. Geophysics, 58, 1335-1348.
2. Barr, F.J., and Sanders, J.I., 1989. Attenuation of water-column reverberations using pressure and velocity detectors in water-bottom cable. Annual Meeting Expanded Abstracts, SEG, 653-656.
3. Fokkema, J.T., and van den Berg, P.M., 1993, Seismic applications of acoustic reciprocity. Elsevier, Amsterdam, 350pp.

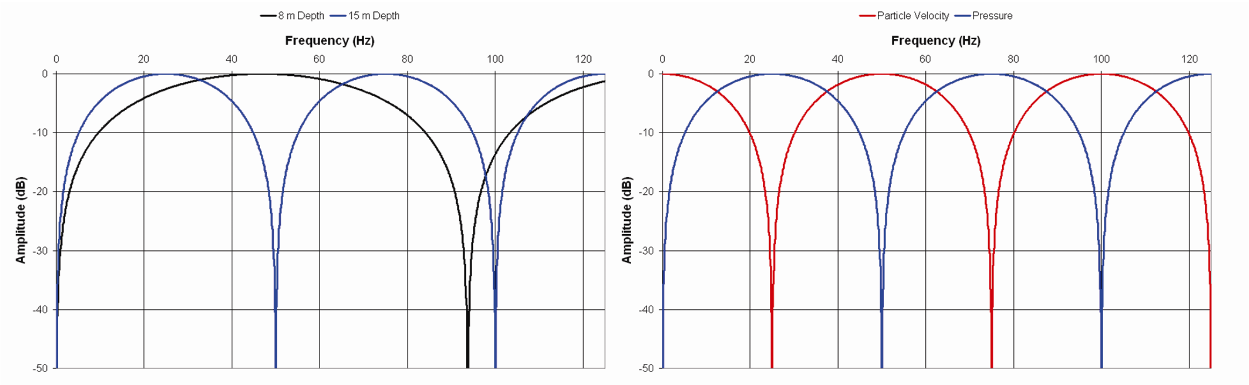

Figure 1: (a) Frequency amplitude spectra for a pressure sensor towed at a depth of 8 m (black) and 15 m (blue). The wavefield is assumed to have vertical propagation (i.e. zero angle of incidence). (b) Frequency amplitude spectra for a pressure (blue) and velocity (red) sensor towed at 15 m.

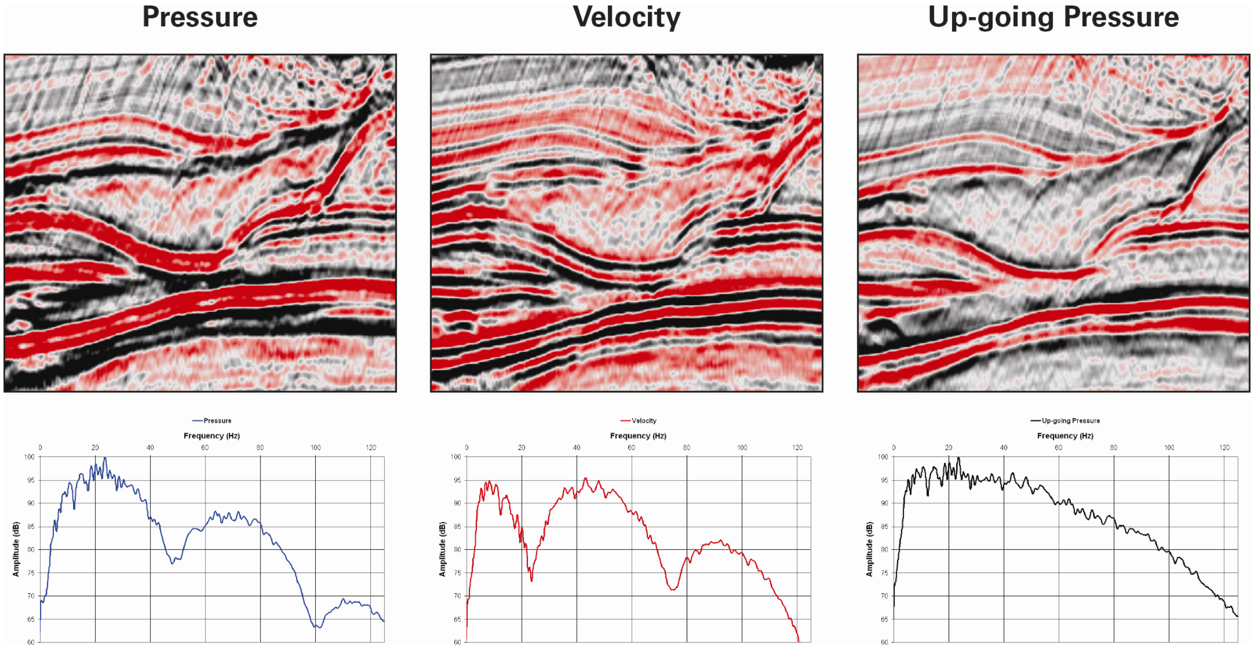

Figure 2: An un-migrated stack comparison showing (from left to right) the pressure-only section, the velocity-only section, the up-going pressure wavefield derived from summation of the pressure and velocity wavefields; and their respective frequency amplitude spectrum.

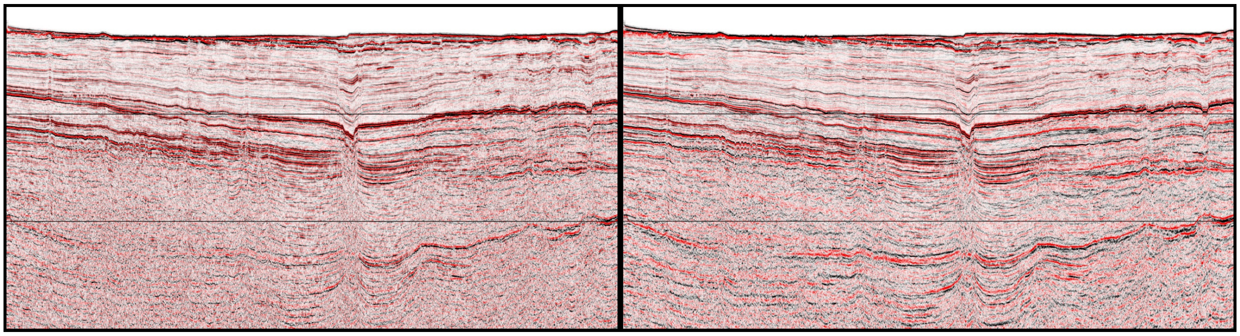

Figure 3: Final migration of Line 34 for Phase I hydrophone (top) and Phase II up-going wave (bottom). Note the improved penetration in the deep "dead-zone."

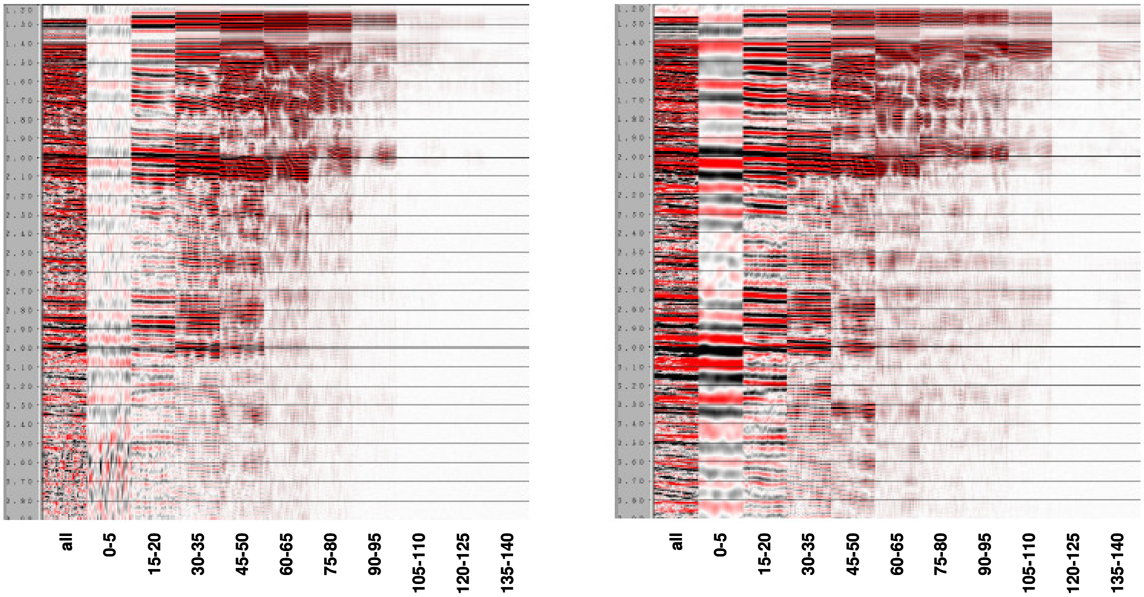

Figure 4: Filter panels for conventional streamer (left) and de-ghosted GeoStreamer data (right). Frequency band in Hz is given at bottom.

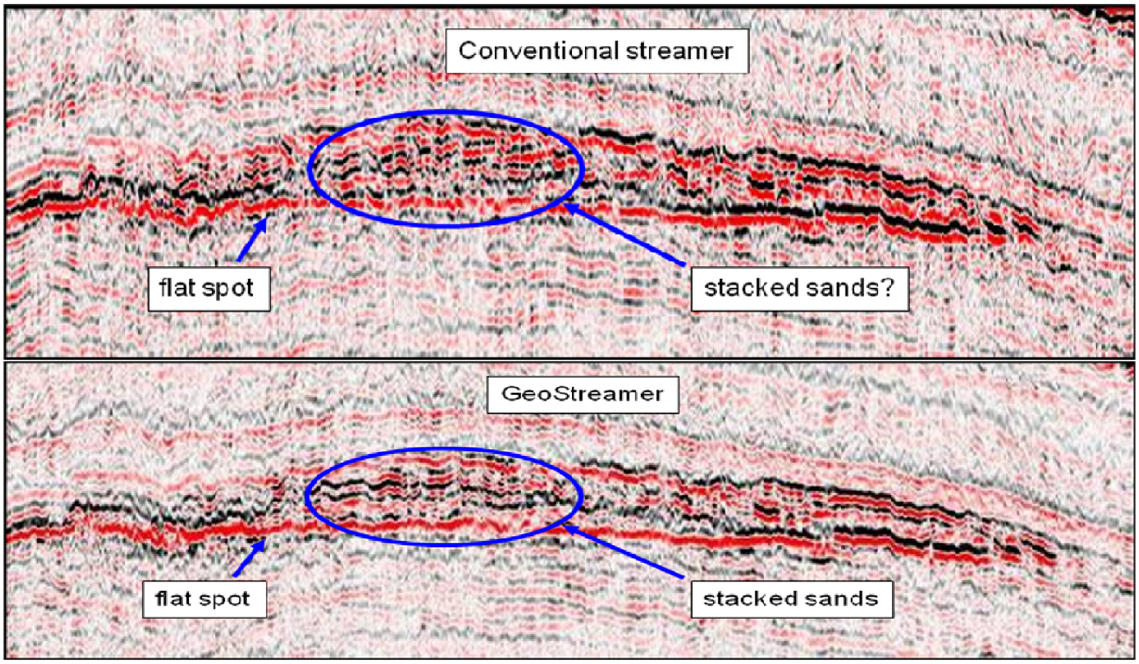

Figure 5: Improved resolution of thin beds within a reservoir. Stacked sands are more easily discernable in the GeoStreamer section, shown at the bottom.

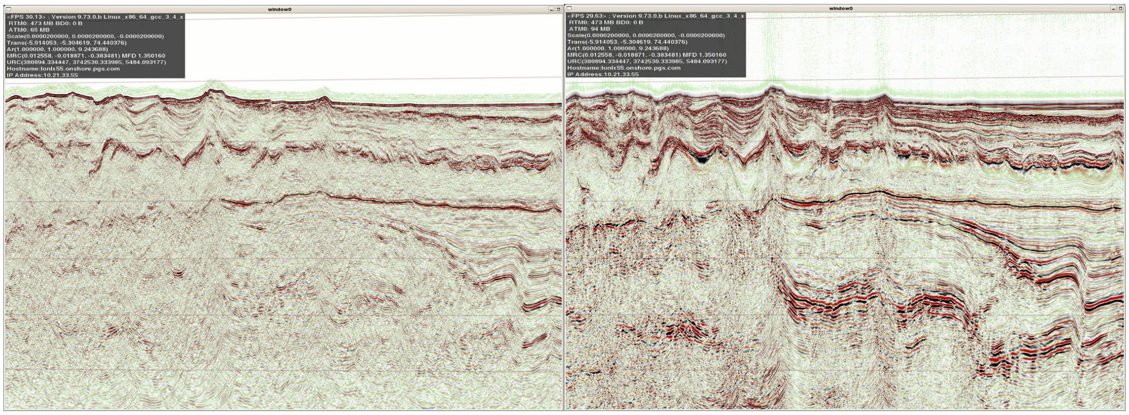

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Figure 6: Line acquired in 2006 using conventional streamer acquisition (left), compared to the same line re-acquired in 2008 using GeoStreamer, with much improved imaging deep of the deeper section, beneath an attenuating anhydrite overburden.