Towards a method for ghost-free marine acquisition

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Abstract

A dual sensor streamer effectively removes the receiver ghost from seismic data through dual sensor summation. The source ghost can be attenuated by spreading out the ghost contribution in time by towing the gun arrays in a multilevel arrangement. The combination of the two dramatically increases the bandwidth of marine seismic data. In particular, the low frequencies are significantly enhanced, which provides better penetration and improved Q estimation. The multi-level source will be biased towards low frequencies and have an anisotropic radiation pattern.

Introduction

The ghost in marine seismic recording is the result of an almost perfect reflection of the acoustic wave-field from the sea surface. Up-going waves are reflected back as down-going waves with a reversed polarity, and interfere constructively for certain frequencies and destructively for other frequencies. This phenomenon occurs both on the source side and on the receiver side. The affected frequencies depend solely on source and receiver depths. Marine seismic acquisition therefore involves a trade-off between the various frequency ranges. To record high frequencies, sources and receivers have to be towed shallow, which strongly attenuates low frequencies. Conversely, a deep tow favors low frequencies at the expense of high frequencies.

Methods to attenuate the ghost and thereby increase the seismic bandwidth have been the subject of considerable research effort. Early attempts involved over-under receivers (Brink and Svendsen, 1987) and a similar approach on the source side (Moldoveanu, 2000). With ocean-bottom receivers the receiver ghost can be effectively eliminated using dual-sensor recordings (Barr and Sanders, 1989. Recently a dual-sensor streamer has been developed that effectively removes the receiver ghost while maintaining the efficiency of towed streamer acquisition (Carlson et al., 2007).

The over-under source approach requires a flip-flop shooting schedule that ultimately halves the number of shot points in the survey. Alternatively, the source ghost can be attenuated using a beam steering technique originally developed some 60 years ago for dynamite land acquisition (Shock, 1950). The principle is to detonate charges at various depths in a sequence that constructively builds the down-going wave at the expense of the up-going wave. The multi-level source technique adapts this beam steering approach to air-gun arrays in the marine environment. In its simplest form it is straightforward to implement and requires only minor modifications of the existing gun arrays.

Receiver ghost effects

A pressure sensor records the up-going wave and, after a delay called the ghost period, its mirror image reflected at the sea-surface. The ghost period τ is a function of sensor depth *d*, acoustic velocity of water *V* and incidence angle θ:

$$\tau = \frac{2d}{V\cos\theta} \qquad (1)$$

The impulse response of the hydrophone ghost can therefore be expressed in the Fourier domain as:

$$H_g = 2\,|\sin(\pi\tau f)| \qquad (2)$$

Frequencies that are multiple integers of $1/\tau$ are effectively zeroed by the ghost, while the frequencies in-between these notches have their amplitude multiplied by two. Thus the ghost is detrimental for some frequencies but beneficial for others.

The depth of a hydrophone-only streamer is therefore critical to determine the recorded frequency range. A shallow deployment favors high frequencies at the expense of low frequencies, and a deep deployment results in the exact opposite (Figure 1). If we could remove the receiver ghost (blue curve in Figure 1), the useful bandwidth would dramatically increase on both ends of the spectrum and would only be limited by the source ghost. The idea of a dual-sensor streamer that combines pressure and velocity sensors for ghost removal is as old as the marine streamer itself. The difficulty arises with recording a meaningful particle velocity in a moving object: the amplitude of streamer motions far exceeds that of the expected reflections.

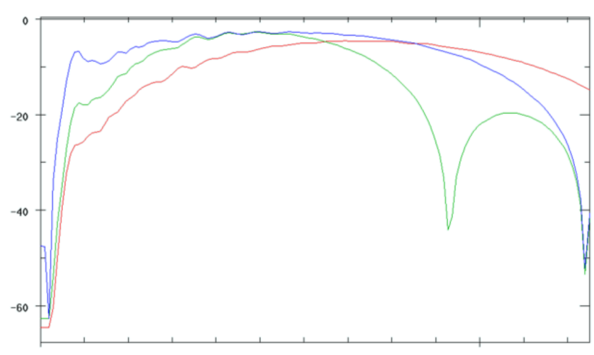

***Figure 1**: Amplitude spectra in dB for various marine configurations. Red: 4m source, 5m streamer. Green: 6m source, 8m streamer. Blue: 6m source, no receiver ghost*.

Dual-sensor streamer

In 2007 Tenghamn et al. introduced a dual-sensor streamer design that manages to confine the motion noise in the very low frequency range (0-20Hz). Therefore, above 20Hz the dual-sensor streamer can be used as effectively as an ocean-bottom cable (OBC) to remove the receiver ghost. Below 20Hz, the authors propose a spectral replacement technique that uses the low frequencies of the hydrophones. This technique implicitly assumes a flat sea-surface with -1 reflection coefficient within the replacement bandwidth. This is a fair assumption at these low frequencies because the Fresnel zone exceeds typical swell wavelengths. Since the low frequency content solely comes from the hydrophone, the dual-sensor streamer must be towed deep to maximize low frequency energy (as explained in the previous section). The hydrophone notch-frequencies associated with the deep tow (between 15 and 25m) are compensated by the velocity data which have maximum energy there.

Towing deep is actually beneficial because the recording environment is quieter, and the sensors are not subject to swell noise. Thus the low frequencies doubly benefit from increased signal amplitude and decreased noise level. High frequencies are also enhanced, as illustrated by the example in Figure 2, but this benefit decreases with depth due to earth attenuation. Figure 3 shows an example were the low frequency content of the deep-towed dual-sensor streamer data has clearly improved deep penetration compared to a standard acquisition.

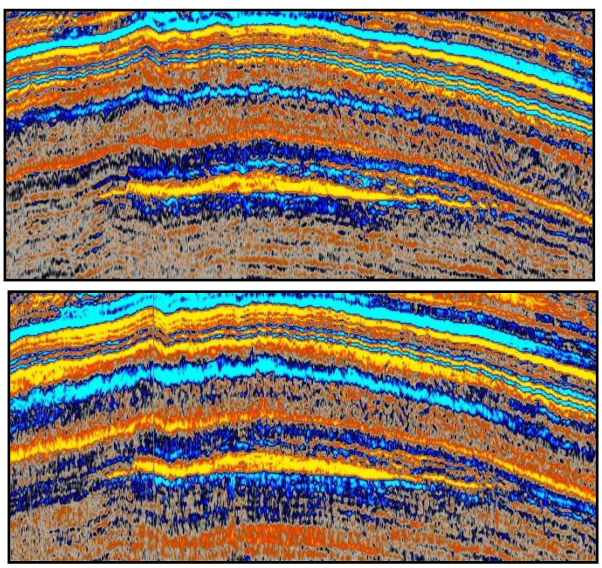

Figure 2: Relative impedance sections (no low frequency input from a well) for a standard acquisition (top) and a dual-sensor streamer acquisition (bottom). The latter shows enhanced bandwidth with a better defined reservoir (above the flat spot) and layer-like structures.

Earth attenuation (Q factor) further emphasizes this low frequency effect (Figure 4). The bandwidth of standard surface seismic data is deemed too narrow to accurately extract Q values (White, 1992) but, as Figure 4 suggests, the enhanced bandwidth from dual-sensor data might prove sufficient.

These examples are only focusing on the de-ghosted up-going wave, which is only half of what dual-sensors provide. The down-going wave can be further used to improve signal-to-noise ratio, multiple attenuation and imaging. Indeed, the down-going wave can alternatively be seen as a direct measurement of multiple energy or as an up-going wave recorded (with reversed polarity) at the mirror image of the streamer.

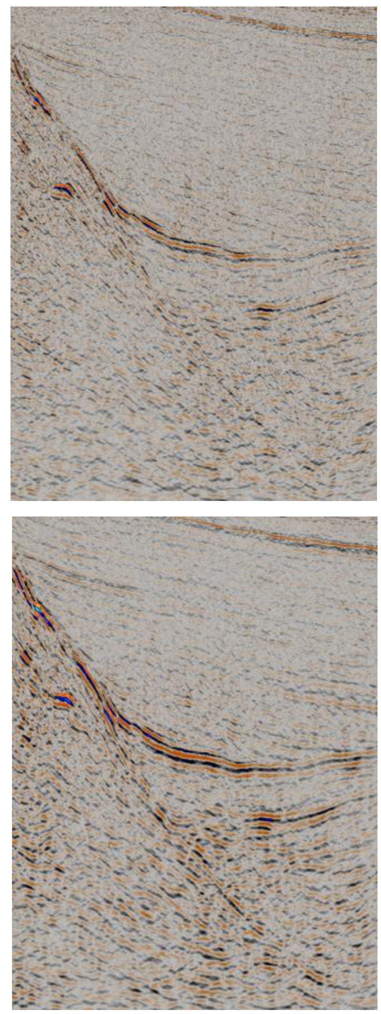

Figure 3: Deep imaging (3-9s) for standard (left) and dual-sensor (right) streamer acquisitions. The low frequency content of the latter improves penetration and imaging.

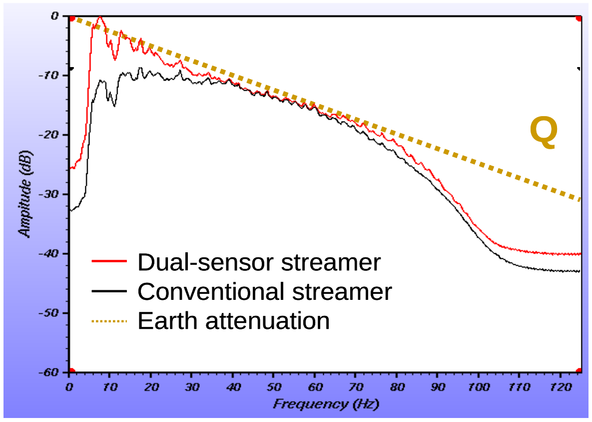

Figure 4: Spectral comparison of dual-sensor streamer (red) with conventional streamer (black) for deep data. The effect of Q (dashed line) tilts the spectra toward the low end of the spectrum which explains the overwhelming presence of low frequencies in dual-sensor data.

Multi-level source

A conventional air-gun array is made up of several sub-arrays, each containing a number of guns or clusters of guns. All guns are at the same depth and fire at the same time. This provides constructive down-going energy as well as constructive up-going energy (Figure 5). The ghost has the same energy as the direct wave. The multi-level source puts guns, clusters or sub-arrays at different depths and fires them sequentially so that only the down-going waves builds up constructively and the ghost effects are reduced. Figure 6 shows the ghost spectra for the two schematic sources represented in Figure 5. The multi-level source amplitude spectrum is flatter than for a conventional source: more extended towards the high and low frequencies, but trimmed in the mid-frequency range. This is what to expect from de-ghosting: the notched frequencies are filled, but the boosted frequencies are no longer multiplied by two. This effect is not observed on the receiver side because the two sensors add constructively and double signal strength.

An important issue to consider with the multi-level source is the radiation pattern. The geometry used in Figure 5 clearly shows that directions other than down-going also benefit from the beam steering. This constructive energy could be eliminated by changing the gun pattern: switching the depth and firing time of the two first guns for example. However, this would simply displace the problem as yet another direction will be favored by the new beam steering geometry. Although conventional source arrays also have a radiation pattern, and are far from being isotropic, this issue is more pronounced with the multi-level source. Array modeling is required to ensure the spectral benefits are not offset by unintended consequences.

The multi-level source was tested in the Browse Basin, Australia, where the presence of a strong carbonate reflector prevents, at places, seismic wave penetration. To try and resolve this problem, a 2D seismic line was acquired three times in a spatially-coincident manner. The first acquisition was with a conventional source and a conventional solid streamer, the second with a conventional source and a dual-sensor streamer and the third with a multi-level source and a dual-sensor streamer. The conventional source used in the survey consisted of four sub-arrays towed at 6m, totaling 2980cu.in. The multi-level source was achieved by simply lowering two sub-arrays at 12m and the remaining two at 18m, with a firing time delay of 4ms.

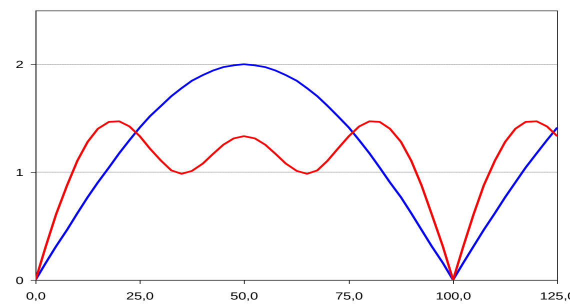

Figure 6: Ghost spectra for the standard (blue) and multi-level (red) sources of Figure 5. The multi-level spectrum shows more energy in the high and low frequencies, but less in the mid-frequency range.

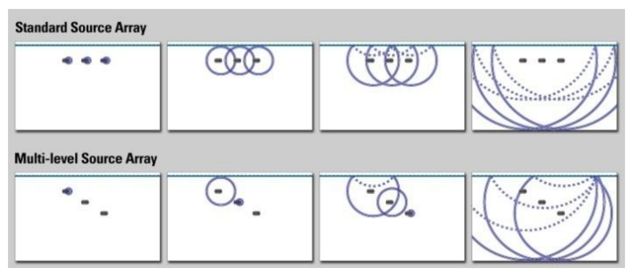

Figure 5: A conventional source array (upper) fires all guns simultaneously generating constructive down-going wave (solid) and ghost (dashed). The sequential firing of the multi-level source (lower) builds a constructive down-going wave but not a constructive ghost. Note however the constructive energy on the upper-right corner of the last panel.

Figure 7 shows the modeled source signature. It exhibits a significant energy uplift in the low frequencies and an energy loss in the mid-frequency range, as expected from Figure 6. Note that the array separation was identical to the conventional source depth, which explains why both source signatures exhibit a notch at 125Hz. Figure 8 shows a comparison between the conventional acquisition (standard source and streamer) and the multi-level source and dual-sensor streamer acquisition. Previously weak, incoherent and impossible to interpret events now appear clearly with improved spatial coherency and interpretability. The improved penetration and deep resolution experienced with the new acquisition is due to both the multi-level source and the dual-sensor recording.

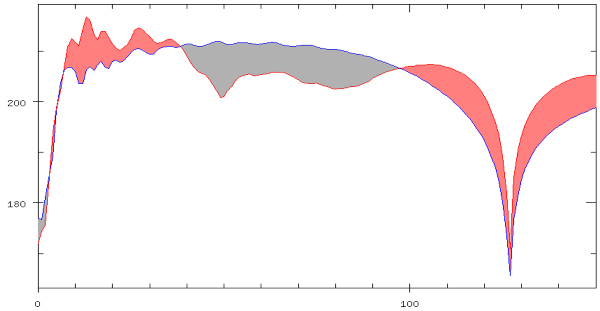

Figure 7: Multi-level source spectrum (red) compared to conventional 6m tow (blue).

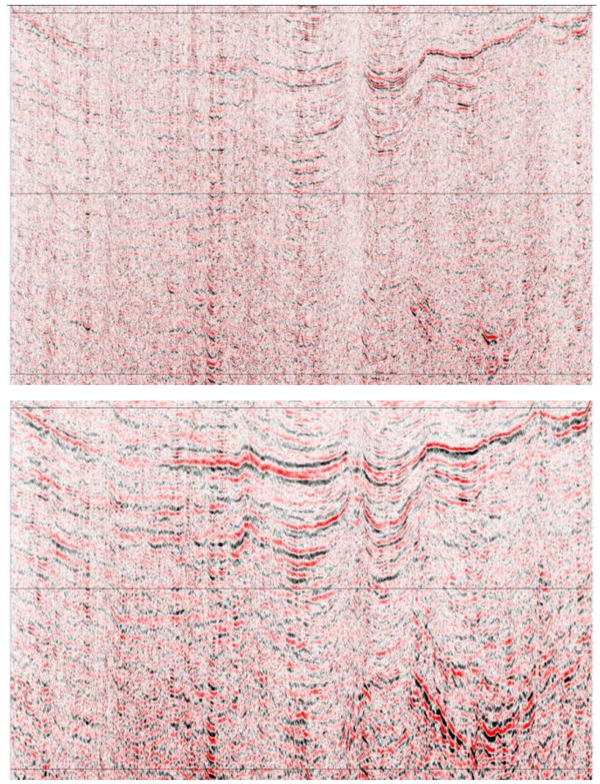

Figure 8: Comparison of the test lines in the target time window of 2–4s. When the effects of both the receiver and source ghost are present on conventional data (top) the target events are weak, incoherent and impossible to interpret. In contrast, the dual-sensor streamer and multi-level source result (bottom) demonstrates a profound improvement in event strength, spatial coherency and interpretability.

Conclusions

The combination of dual-sensor streamer and multi-level source is ideal for seismic penetration because it enhances low frequencies. Previously impossible to interpret events below highly reflective layers (e.g. carbonates) are now clearly visible with improved spatial coherency. The dual-sensor streamer effectively removes the receiver ghost and the multi-level source strongly attenuates the source ghost. However, the multi-level source loses the benefit of the ghost boosting effect in the mid frequency range, and has an anisotropic radiation pattern. Its use must be focused on resolving deep penetration issues. The dual-sensor streamer on the other hand has no limitations in its use and increases useful bandwidth under any circumstances.

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