Benefits of multi-sensor streamers for broadband acquisition

Jo Firth[1]*, Gordon Poole[1], Federico Buriola[1], Steve McDonald[1], Paul Fallon[1], Steve Hollingworth[1], James Cooper[1] and Gaetan Mellier[2] present a case study from the North Sea where the monitor survey was recorded using multi-sensor streamers towed deeper than the baseline survey and redatumed to deliver the full broadband benefits and wider weather window of deeper-towed multi-sensor streamers.

Introduction

Broadband towed-streamer data has extended the usable seismic bandwidth at both ends of the frequency spectrum. As well as enriching the overall seismic image, improved low frequencies have delivered more reliable full-waveform inversion results and more quantitative elastic inversion, while improved high frequencies enable better interpretation of thin-layered structures. Various strategies have been developed to acquire broadband data, ranging from processing-only approaches using horizontal-tow hydrophone-only streamers, to combined acquisition and processing schemes using multi-level streamers (Posthumus, 1993), variable-depth streamers (Soubaras, 2010) or multi-sensor streamers (Carlson et al., 2007).

The desire to extend all the benefits of broadband 3D data to 4D time-lapse surveys has been constrained by the requirement for repeatability between successive surveys. The use of deep-towed multi-sensor streamers in time-lapse acquisition creates challenges, as the existing baseline surveys will often have been acquired using a shallow-tow streamer. For optimal 4D repeatability, subsequent monitor acquisitions would traditionally be acquired using the same streamer depth as the earlier surveys. Using a case study from the North Sea, we tested recording monitor data at a deeper streamer depth than the baseline survey using multi-sensor streamers, and then redatuming to simulate data recorded at the shallow streamer depth. Based on the successful outcome of this trial, we successfully acquired two 4D monitor surveys during the recent summer season using this method.

Multi-sensor streamer deghosting

Broadband seismic data can be achieved by removing the ghost notches in the amplitude spectrum. These notches are caused by interference between the upgoing primary wavefield and downgoing ghost waves reflected from the sea surface. The polarity of the downgoing wavefield is reversed by reflection from the sea surface, but in the case of particle velocity data there is an additional reversal owing to its sensitivity to the propagation direction. The opposite polarities of the hydrophone and particle velocity ghost wavefields mean that there is destructive interference between the primary and ghost wavefields of one data type, at the same frequency as there is constructive interference of the other data type (Figure 1).

Multi-sensor streamers use co-located hydrophones and accelerometers so that the particle velocity data (obtained by integration of the particle acceleration data) provides a complemen-

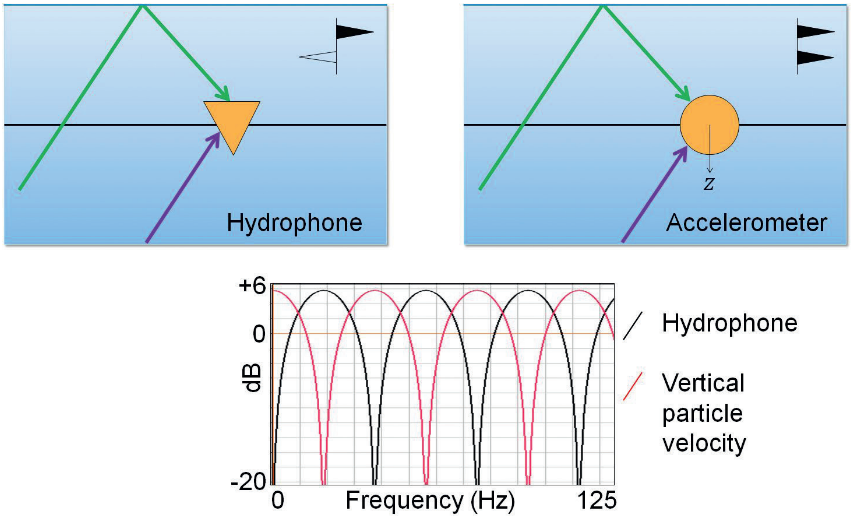

Figure 1 The hydrophone records the primary and its ghost with opposite polarity while the vertical particle velocity primary and ghost are recorded with the same polarity to provide complementary information in the hydrophone notch.

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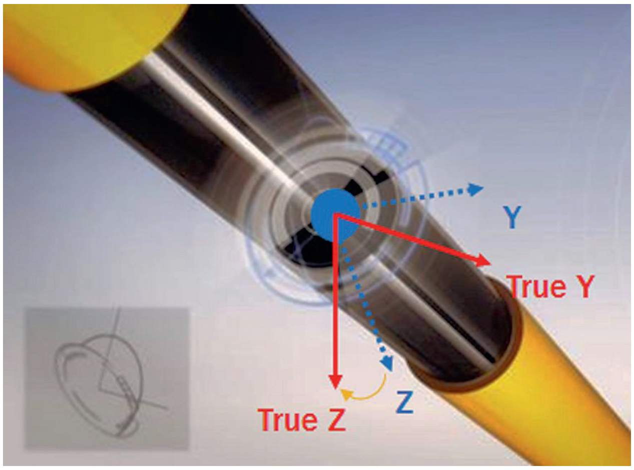

Figure 2 Sentinel MS three-component streamer (Image courtesy of Sercel).

tary signal for deghosting the hydrophone receiver-ghost notch. In theory, this can be achieved by summing the two recorded data sets so that the ghosts cancel each other out, and then dividing by two (P-Z summation).

Hydrophone-only deghosting for flat-towed streamers may only partially compensate for the receiver ghost notch, especially if the signal-to-noise ratio is low. This is a key challenge for deghosting algorithms, which can theoretically be overcome by P-Z summation. However, in many cases, the high noise levels from transverse vibrations recorded on the accelerometer data can cause practical issues, especially at low frequencies where these tend to be aliased. In addition, higher-frequency noise may be present, generated from equipment mounted on the cable (Elboth and Sanchis, 2014). Noise attenuation routines can be designed to address these challenges, but are time-consuming and can risk signal damage.

Inversion-based multi-sensor receiver deghosting

The inversion-based approach to multi-sensor receiver deghosting derives a surface-datum model of the upgoing wavefield that is constrained by the time-space hydrophone data and previously wavefield-separated data. The wavefield-separated data may be either upgoing (derived from P-Z summation) or downgoing (from P-Z subtraction). It provides data with high signal-to-noise ratio to the inversion at some frequencies and offsets, while at others it may be contaminated by noise. In order to mitigate this noise contamination, data-domain sparseness weights can be used to condition the inversion (Poole and Cooper, 2018). These weights may be a function of time, space and frequency, and can be obtained via comparison of the measured particle velocity data with particle velocity data reconstructed from the measured hydrophone data (Peng et al., 2014). Such techniques enable the inversion to rely less on the prior wavefield-separated data at frequencies and offsets where it is contaminated by noise. The inversion can be further constrained by the use of model-domain sparseness weights (Poole, 2013). Once the inversion has found the upgoing wavefield model, the deghosted data may be obtained by subtracting the corresponding ghost model from the input hydrophone data.

This approach is similar to the multi-sensor deghosting techniques of Poole (2014) and Wang et al. (2014), but is less reliant on a ghost model, since it includes the additional constraint of the previously wavefield-separated data. It is also less sensitive to recording noise, owing to the sparseness weights. Wave-height

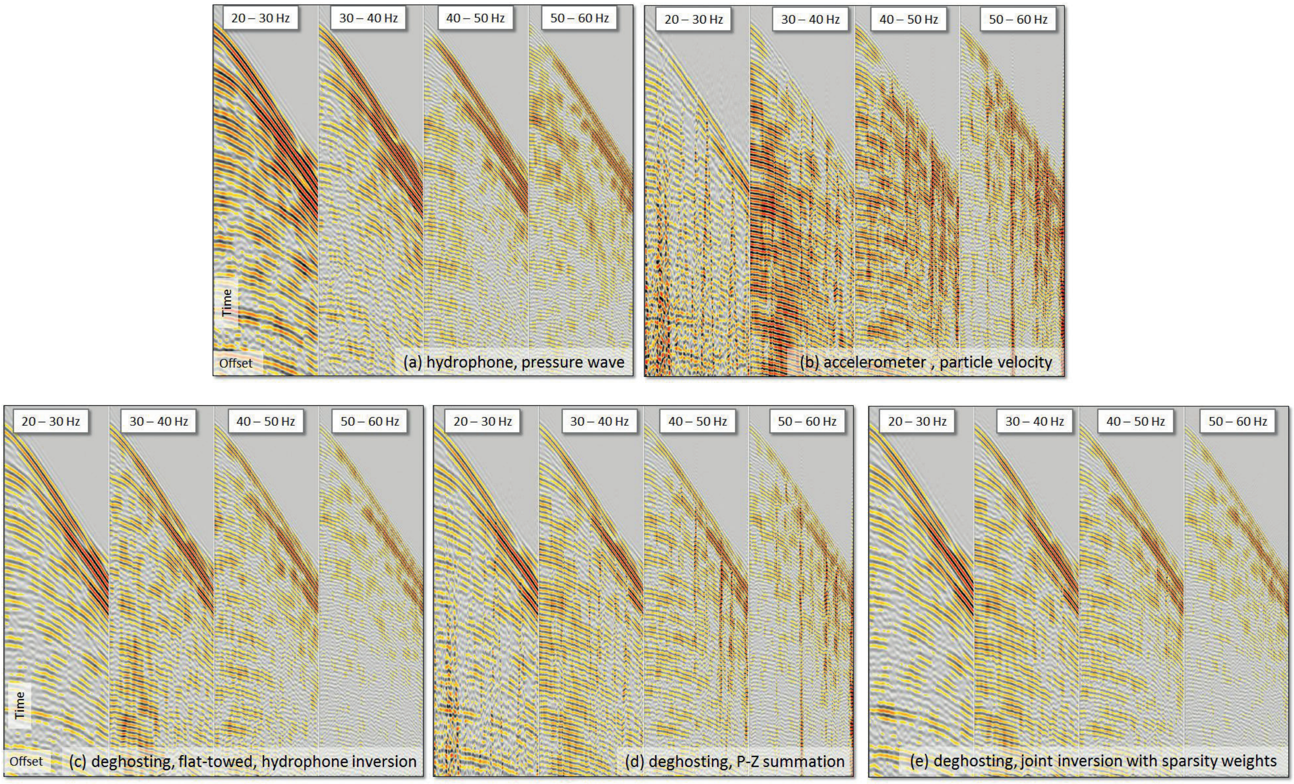

Figure 3 Shot gather frequency panels: (a) raw hydrophone data, (b) vertical particle velocity data, (c) hydrophone-only deghosting, (d) P-Z summation deghosting multi-sensor deghosting (e) multi-sensor deghosting by joint inversion with sparsity weights (Images courtesy of CGG Multi-Client & New Ventures).

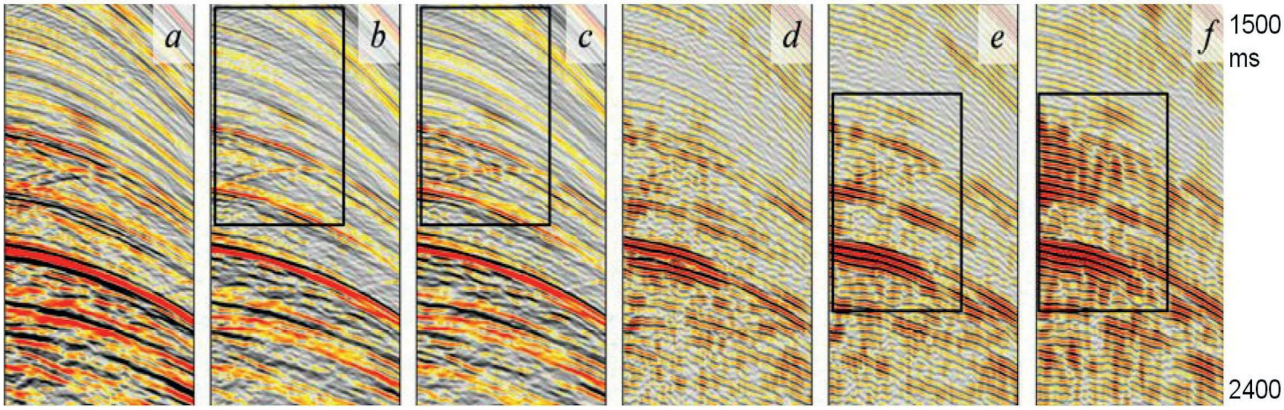

Figure 4 Shot gather data: (a) raw hydrophone data, (b) hydrophone-only receiver deghosting, (c) multi-sensor inversion method with sparseness weights. Corresponding band-limited displays around the hydrophone notch (56-64 Hz) are shown in (d), (e) and (f) respectively (Image courtesy of CGG Multi-Client & New Ventures).

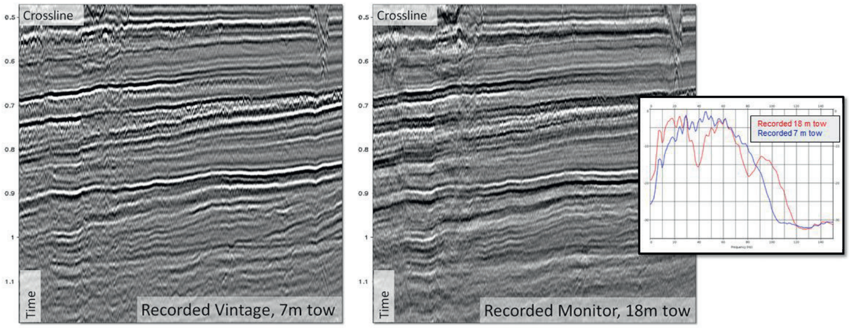

Figure 5 Raw time stack data comparison, and their respective amplitude spectra (Image courtesy of CGG Multi-Client & New Ventures).

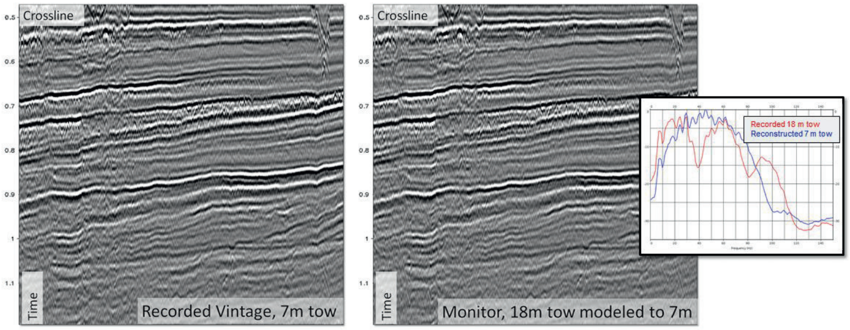

Figure 6 Raw stack of 7 m-tow vintage data and 18m-tow data reconstructed to 7 m-tow. The amplitude spectra of the 18 m data and its reconstruction of 7 m data is shown in the right-hand box (Image courtesy of CGG Multi-Client & New Ventures).

variations can be incorporated, if required, by modifying the deghosting operator (King and Poole, 2015).

The latest generation of multi-sensor streamers also record the y-component of the velocity particle data in addition to the z-component. Where this additional information has been recorded with a good signal-to-noise ratio, the described deghosting approach can be extended using the observations of Robertsson et al. (2008), to make use of its de-aliasing properties to reconstruct the pressure wavefield in the crossline direction for obtaining a potentially better deghosting result at shallow aliased structures. In most cases, this has been found to have limited effect on the final deghosted result, but where there is a significant crossline component of the recorded wavefield (as in wide-azimuth acquisition or shallow complex geology), slightly improved deghosting results are achieved.

Examples

The use of multi-sensor receiver deghosting has been validated on synthetic shots and real data examples. Seismic data was recorded in the Norwegian North Sea, deploying 12 multi-sensor streamers towed at 20 m, each separated by 75 m. The Sercel Sentinel *MS* streamers deployed are solid, to minimize noise, and contain two orthogonal particle motion channels and one hydrophone channel at each sensor location (Mellier et al., 2014). The tilt is dynamically measured and the group design and length are tuned to minimize cable vibration (Figure 2).

The example in Figure 3 shows data from this acquisition. The data is shown in 10 Hz frequency panels for (a) hydrophone input, (b) vertical particle velocity input, (c) receiver deghosting using hydrophone-only data, (d) deghosting by P-Z summation and (e) receiver deghosting from multi-sensor data using the inversion approach with sparseness weights.

In the hydrophone-only example, the signal is weaker at the receiver-ghost notch of ~38 Hz, where there is strong signal from the vertical particle velocity data, amplified by the ghost peak. Although there is noise on the particle velocity data (and therefore the P-Z summation), mainly relating to equipment attached to the streamer, using the sparseness weights prevents it from contaminating the deghosted data. This method also results in stronger signal around the hydrophone notch than using just the hydrophones in the deghosting.

Figure 4 shows a second example from the Porcupine Basin, offshore Western Ireland. This was acquired using 14 streamers towed at 12 m depth, each separated by 100 m. The full bandwidth displays are shown for (a) the hydrophone data, (b) the hydrophone-only deghosted data, and (c) the deghosted data from multi-sensor data inversion with sparseness weights. The corresponding displays, band-limited around the hydrophone notch, are shown in (d), (e) and (f) respectively. The data resolution is considerably improved by the inversion method and there is less residual ghost than in the hydrophone-only solution. This is especially obvious in the band-limited displays where the particle velocity data provides increased signal strength at the hydrophone notch.

Multi-sensor streamers in 4D

Deghosting via the multi-sensor, wavefield-separation approach using sparseness weights overcomes the challenges caused by the noise on the accelerometer data to deliver clean broadband data. The next step for multi-sensor acquisition was to assess its use in 4D when towed at a different depth than in the baseline survey.

The use of deep-towed streamers improves operational efficiency by widening the weather window, and increases signal-to-noise ratios at low frequencies. Better-quality low-frequency data reduces cycle-skipping in Full-Waveform Inversion and reduces the reliance on a low-frequency model from well data for elastic inversion. However, for optimum 4D repeatability, monitor surveys are typically performed using the same streamer depths as the earlier surveys. In order to assess the feasibility of acquiring monitor data sets with a deeper cable depth than the baseline, a field trial was conducted in early summer 2018 in the Central North Sea (Buriola et al., 2018). A swathe of three sail-lines was acquired with a receiver depth of 7 m and then repeated with a receiver depth of 18 m (Figure 5). Ten streamers were deployed with a cable separation of 100 m, a channel spacing of 12.5 m and a maximum offset of 8000 m.

Using the joint inversion with model-domain sparseness weights technique described earlier, the 18 m data was separated into upgoing and downgoing data sets, redatumed and recombined to simulate data acquired at 7 m (Figure 6). Once at a common datum, with common ghost energy, the data could be processed using standard time-lapse techniques to compare the differences.

The comparison of multi-sensor deghosting constrained by sparseness weights, with conventional deghosting of hydrophone-only data, shows a clear 4D repeatability benefit for the multi-sensor approach (Figure 7). The difference section shows much less energy overall, and in particular much less ringing energy corresponding to the receiver-notch frequency. Even without full 4D processing to spatially match the data sets, the energy in the difference section was sufficiently low, when using the multi-sensor inversion with sparsity weights, to validate the technique for commercial 4D monitor acquisition with different streamer depths from the baseline survey.

Commercial multi-sensor streamer 4D surveys

Three 4D surveys were acquired using Sentinel *MS* streamers in the summer season of 2018, two in the North Sea and one West of Shetland. Two of these were acquired with a different streamer depth than the baseline, and all three were acquired with very little weather downtime, owing to the deeper tow enabled by use of multi-sensor streamers. Technical downtime was 1% or less. As a result, the surveys were completed ahead of schedule, below budget and with a high degree of client satisfaction.

The large-scale source and receiver repeatability for the surveys was delivered by 4D operational planning, working with experts onboard to prepare and constantly update acquisition

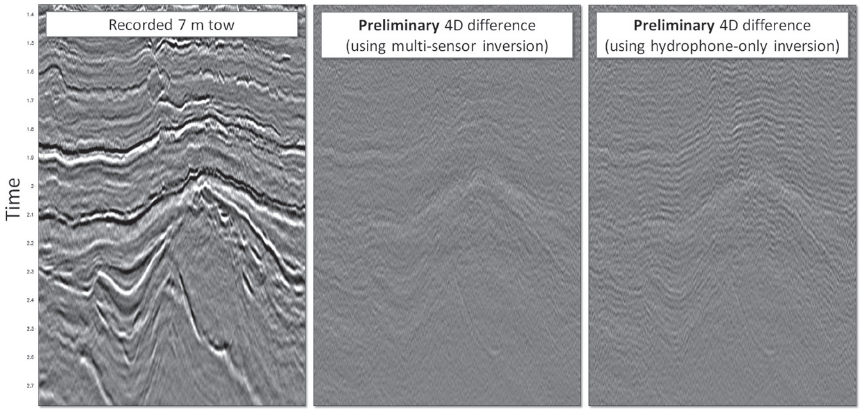

Figure 7 Preliminary 4D differences after pre-stack depth migration using multi-sensor inversion compared with using only hydrophones (Image courtesy of CGG Multi-Client & New Ventures).

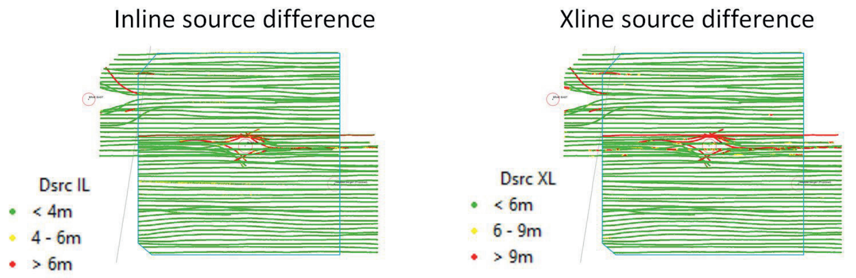

Figure 8 Inline and crossline source position differences from the pre-plot position for one of the three surveys acquired (images courtesy of Reservoir Imaging Ltd.).

Figure 9 Geo Coral and Geo Caribbean undershooting the Gudrun platform (image courtesy of Equinor).

plans, and taking environmental conditions (current, tide, etc.) into account to position the spread and optimize streamer matching (feather). The overall positioning of the system was achieved by integrated source and vessel steering, while the geometry of the spread was maintained by streamer steering units which also delivered acoustic positioning and depth control. The multi-sensor streamers were designed to be fully compatible with these devices.

Our integrated source and vessel steering system is driven by the navigation system. It consists of an automatic steering assistant to position the vessel so that the source is as close as possible to the pre-plot position, while maintaining the integrity of acquisition geometry, i.e. the source position in respect to the streamer spread. Residual crossline positioning and short-period perturbations of the source position, caused by swell and so forth, are controlled by the powerful, automatic source steering system. The system also controls the shooting strategy and triggers the source firing to respect inline positions rather than time intervals, so correcting for smaller-scale errors, such as the skew of the sources. This automatic integration of the different parts of the system has delivered considerable improvements in repeatability over source steering alone. Advanced monitoring systems and onboard QC ensure acquisition of the best possible 4D data.

In general, the source matching for all three surveys was very good, with the exception of intentional deviations around the platforms, or where lines were acquired as extra undershoot or infill passes, for which there was no 4D element, in order to gain additional coverage (Figure 8). Figure 9 shows the Geo Coral and Geo Caribbean undershooting a platform during one of these surveys.

Conclusion

The results from the initial redatuming test, using the new inversion technique with sparsity weights, were positive and three successful monitor 4D seismic surveys have been acquired this summer using Sentinel *MS* multi-sensor streamers. Redatuming enabled the monitor surveys to be recorded with deeper streamer depths to gain the full broadband benefits of multi-sensor recording and widen the weather window for acquisition. The multi-sensor streamers performed as expected, and were shown to be fully compatible with the existing steering and QC systems. Initial feedback from our clients so far has been positive and we look forward to receiving further positive feedback upon delivery of the fully processed data and also to acquiring further surveys using this technique.

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