An efficient 4D processing flow for variable-depth streamer data

Erik Hicks, Henning Hoeber, and Gordon Poole, CGG
Ben King, Statoil

Abstract

Variable-depth streamer acquisition is now widely used, achieving a bandwidth of more than 6 octaves (2.5 to 200 Hz) and excellent lateral resolution and providing improved impedance and reservoir analysis. This acquisition and processing method is based on towing the streamer deep, using a variable-depth profile optimized to ensure receiver notch diversity at the imaging stage and a deghosting method that takes advantage of the notch diversity. For 4D processing of monitors now acquired with variable-depth cables and with a baseline consisting of a flat towed streamer, we must deal with two processing issues. First, raypaths of traces acquired at the same surface locations differ; second, receiver ghosts lead to different wavelets. A 4D coprocessing flow is introduced that codatums 4D vintages to a common datum early in the sequence. Furthermore, a new deghosting technique is applied to variable-depth and conventional data. This processing flow gives excellent repeatability with 4D noise of less than 10% on a zero-time repeatability test with North Sea data from 2013.

Introduction

Broadband seismic data offer the promise of imaging the earth with much higher resolution than previously thought possible. Many recent case histories highlight the benefits of broadband data over conventional narrow-band reflection seismic for data interpretation and inversion (e.g., Duval, 2012), although examples of repeat broadband time-lapse applications are still lacking.

The broadband deghosting solution (Soubaras, 2010) applied in this case study, called BroadSeis™, uses a combination of new acquisition technology and new processing methods to mitigate the effect of receiver ghosts and to broaden the spectrum. On the acquisition side, the largest part of the solid streamer is towed deeper than it would be conventionally to increase the signal-to-noise ratio at frequencies down to about 2 to 3 Hz. In addition, the variability of the streamer depth provides notch diversity across all offsets and allows the removal of the receiver-side ghost, thus shaping the wavelet closer to a spike than is possible with conventional towed-streamer acquisition.

Soubaras (2010) shows that with this new acquisition configuration, a joint deconvolution using migration and mirror migration is a good solution to perform amplitude-preserving 3D deghosting. This is also true for repeat 4D BroadSeis acquisitions. However, today we find ourselves in a position in which a new BroadSeis monitor data set first needs to be 4D-coprocessed to previous monitors and the baseline, all of which generally have been acquired with flat streamer configurations. In this article, we show how this is done.

We present a new processing algorithm to codatum two or more streamer data sets acquired with different cable shapes to a common depth. This method is applied early in the processing sequence so that standard 4D coprocessing, such as 4D QC and 4D binning, can be performed easily. We also show how we can match the spectra of a legacy baseline with flat tow and monitor data acquired with variable streamer depth so that they both have minimal ghost content. We find that the 4D difference on maximally deghosted data is better than when BroadSeis data is downgraded to legacy data.

This deghosting technique, which we call ghost wavefield elimination (GWE), can be used to remove as much of the ghost in legacy data as is achievable, depending on the signal-to-noise ratio of the legacy data in and around ghost notches. A North Sea data example from early 2013 is used to demonstrate these ideas. We achieve excellent 4D repeatability with about 10% background noise (NRMS).

4D processing with variable-depth streamer data

From the very early days of 4D processing, it has been understood that the only way to obtain clean seismic 4D difference images is to maximize data repeatability during acquisition (an early example is Ross and Altan, 1997). There are many aspects to this (e.g., Johnston, 2013), but we focus here on repeatability of source and receiver locations.

Techniques such as steerable sources and receivers, feather repeat, and oversampling through the use of extra cables are all designed to maximize the probability of acquiring, on the monitor, traces in the same surface locations as on the baseline. Once time-lapse data are acquired with optimal acquisition repeatability, the data are coprocessed to increase signal similarity as much as possible (e.g., Campbell et al., 2011; Helgerud et al., 2012).

One of the key steps in this procedure is 4D binning, whereby a local trace-selection criterion is applied to remove poor traces which fall outside a predefined acquisition-quality criterion, such as the sum of their source and receiver distances measured at sea level. Exactly what is meant by *poor* in this context (at a given offset) depends on geology (complexity of the overburden, dips), on the reservoir context (how large the 4D signal is), and on the acquisition context (for example, we might have to work with less well-repeated traces around obstructions).

In some instances, leaving bins empty and using interpolation techniques can be the best option to keep 4D noise down. Four-dimensional binning can and generally does remove a large amount of the data acquired for 4D. Only the very best traces with maximum ray similarity are kept for further processing.

The careful reader will have noted that the acquisition criterion of source and receiver repeatability, as defined above, does not include source or receiver depth variations. In 4D towed-streamer acquisitions, those variations are generally small and can be dealt with in other processing steps. However, our intention now is to create low-frequency and ghost-free 4D data by using the BroadSeis acquisition method. In that technique, streamer cables are towed with variable depth to create notch diversity in the spectrum.

Before discussing the impact of depth variability, consider the idealized ghost spectrum with conventional flat towed-streamer data and with BroadSeis data for a single reflector in a shot gather for a horizontal streamer and a variable-depth streamer, as shown in Figure 1.

In these noise-free synthetics, we assume perfect cancellation (at the specific frequencies, determined by receiver depth and water velocity) of the up- and downgoing waves so that the notches are deep. In reality, we generally observe some signal in the notches too, unlike in our idealized synthetic example. Just above DC (2 to 10 Hz), we are in a frequency zone in which the signal-to-noise ratio is often not good enough to extract reliable signal. By using solid streamers, towed to a large extent at greater depths than in conventional towed-streamer acquisition, it is possible to significantly reduce noise in that part of the spectrum.

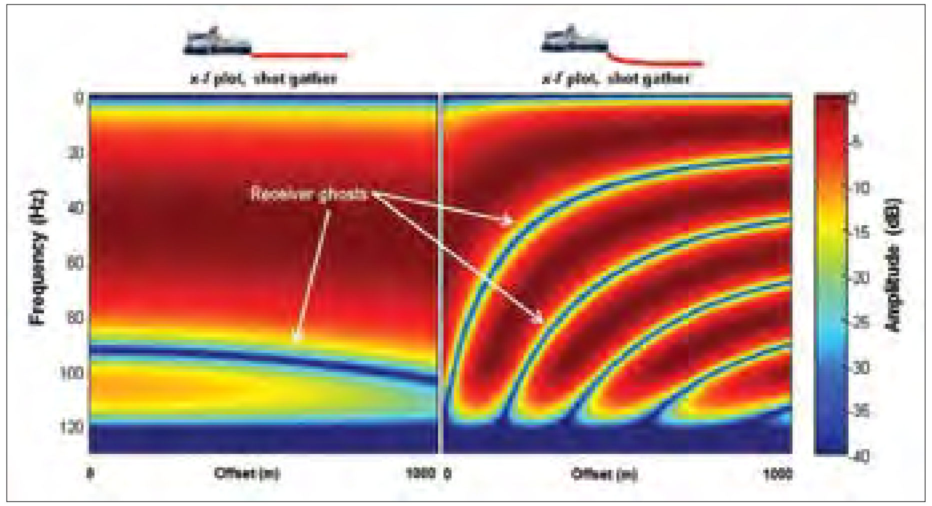

Figure 1. Idealized receiver ghost notch attenuation versus offset for conventional (8-m deep) and variable-depth (6.2- to 36.6-m deep) configurations (before NMO). The improved receiver notch diversity of BroadSeis is visible.

Figure 2 shows typical shot gathers acquired in January 2013 in the North Sea, using solid streamers towed flat at 9-m depth, and the corresponding shot (same location, shot within one week) with variable-depth streamer acquisition. The improved signal-to-noise ratio achieved with the variable-depth streamer, towed much deeper on average, is obvious.

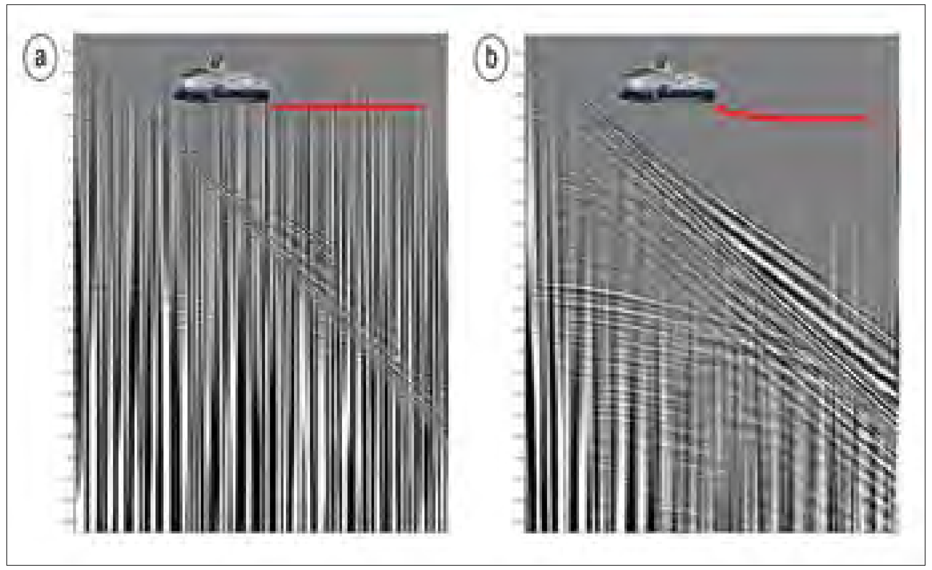

Figure 2. (a) Flat and (b) variable-depth streamer raw shot gathers (shown with t^2 gain).

One of the questions we must address when processing broadband data with high signal-to-noise everywhere, down to very low frequencies, is how best to coprocess frequency ranges in which conventional data have a much worse signal-to-noise ratio. A common choice in those scenarios is to downgrade the better of the two vintages. That means removing part of the available signal spectrum from the broadband data for the 4D analysis because of its nonrepeatability with legacy data. That choice is clearly not appealing because the low frequencies contain 4D signal and are of importance for inversion applications.

A 4D processing solution is needed as a form of compromise which maximizes signal repeatability over the complete spectrum without completely downgrading the wider-frequency-content broadband data. Rather than reintroduce ghosts into the BroadSeis data, we prefer to fill the notches in the conventional data as much as possible, given the signal-to-noise of the specific acquisition.

Both spectra in Figure 1 display a common source ghost. A single receiver ghost notch in the flat tow streamer, slowly varying as a result of the offset, is replaced by a diverse set of notches at all offsets when the streamer is towed at variable depth. As we will see, for variable-depth streamer data, this notch diversity can be used to effectively model and hence remove receiver ghosts. The discussion shows that application of this technique to the conventional data is desirable in the 4D context. We would like to maximally boost signal in the notches of the conventional data, even though it has less notch diversity than broadband data. Equally, we would like to minimally downgrade the broadband data after having performed ghost wavefield elimination.

Returning now to the discussion on 4D binning, it is clear that whenever 4D repeat acquisitions are acquired with an identical streamer shape as on previous vintages, conventional or variable depth, we can perform 4D binning as discussed. However, as we move from one or more vintages of legacy 4D data acquired with conventional tow data to monitor surveys with variable-depth streamer acquisition, we must find a way to coprocess 4D vintages with different streamer shape and depth.

Our first solution to this problem (Charrier et al., 2012) used migration to solve this issue. That is a perfectly good solution, and the 4D subtraction worked well. However, in the 4D context, it means that we have to compromise at the 4D binning stage because the data premigration is not comparable by the surface locations of source and receiver alone. That also prevents us from using all offsets for 4D comparisons and QC.

In summary, the two key processing issues are related to imaging (different reflection points relative to surface position) and wavelet differences (receiver ghosts). Although both issues can be handled by using known methods and tools, they require a significant workload. They also introduce potential uncertainties in the 4D sense because processing will not be identical between vintages. Clearly then, to simplify the workflow and to perform trace selection prior to regularization and migration, we need a processing solution that can redatum all vintages to a common datum and modify the receiver ghosts to a common level at an early stage during the 4D processing flow.

Preimage deghosting and codatuming for 4D coprocessing

Poole (2013) shows how variable-depth streamer data can be separated into upgoing and downgoing wavefields using a linear Radon model. Assuming 2D wavefield propagation, the separation can be used to align the up- and downgoing events and to generate a receiver ghost model. Simple subtraction of the resulting ghost model from the input data creates a deghosted data set.

We apply those techniques of ghost wavefield estimation and ghost wavefield elimination (GWE) on shot gathers early in the sequence. The same method is used to output the data, either up- and downgoing wavefield separately or as a combination, on a new datum. This allows us to create shot gathers with or without receiver ghosts that have been codatumed to constant-depth streamer shape and to continue to process the data in a conventional 4D coprocessing manner, using standard 4D binning and 4D QC methods (Table 1).

Codatuming on its own, without subsequent receiver deghosting, delivers base and monitor data that can be processed with standard 4D coprocessing workflows. To maximize 4D signal at all frequencies, we can now attempt the additional application of GWE. Because of the notch diversity of the variable-depth streamer acquisition, we expect good separation of the upgoing and downgoing components (Poole, 2013).

However, given the limited notch diversity of the conventional data and its potentially lower signal-to-noise content at low frequencies, we might run into trouble with a full GWE of the conventional data. Thus, depending on the quality of the conventional data, we will consider residual matching of the codatumed and deghosted 4D data so as to find the optimal common wavelet.

Base Conventional	Monitor BroadSeis
• Shot domain de-noise	• Shot domain de-noise
• Wavelet processing (zero-phase, partial source side notch handling)	• Zero-phasing de-signature filter (with source ghost only)
• Co-datum	• Co-datum
• Maximally de-ghost/match to BroadSeis	• De-ghost & match to conventional
• SWD & SRME	• SWD & SRME
• 4D coprocessing & binning	• 4D coprocessing & binning
• Data regularization	• Data regularization
• Velocity analysis	• Velocity analysis
• Migration	• Migration
• RMO	• RMO
• Stack	• Stack

Table 1. *4D coprocessing flow between conventional (flat) streamer baseline and variable-depth monitor survey. Codatum and ghost wavefield elimination (red text) synchronize the 4D flow and allow for 4D QC and 4D binning as in conventional 4D coprocessing. 4D coprocessing steps are highlighted in green (QC and 4D analysis is omitted).*

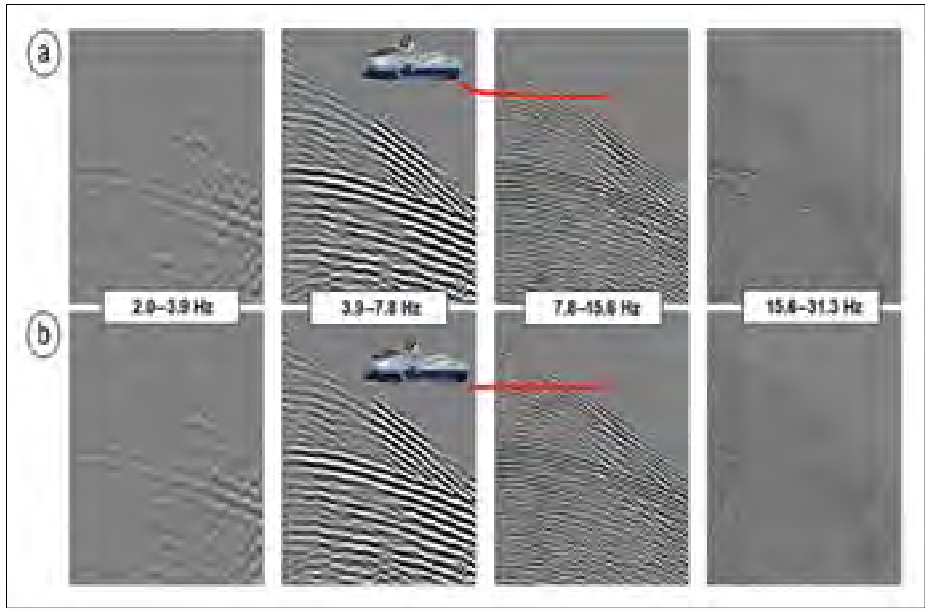

Figure 3. *Frequency panels of as much as 30 Hz for (a) BroadSeis and (b) conventional tow. Both data sets have undergone denoise processing.*

Table 1 summarizes the proposed 4D coprocessing between conventional and variable-depth streamer data. For 4D data, in which we are in coprocessing mode, we apply both techniques, redatuming and ghost wavefield elimination, to the conventional base and the variable-depth streamer data.

Application to North Sea data

A field trial was acquired in January 2013 over the Sleipner CO_2 sequestration field. Sleipner consists of several gas and condensate fields in Blocks 15/6 and 15/9 in the Norwegian North Sea. Since 1996, approximately 13 million tons of CO_2 have been captured for gas production at Sleipner and injected into the shallow (800- to 1000-m) Utsira Formation. Eight previous seismic acquisitions exist over this area, the earliest in 1994, although they generally were not acquired with 4D as a priority. Typical reservoir targets in this area, from early Paleocene to Middle Jurassic, are at depths of about 2 to 2.5 km.

Base and monitor surveys were acquired in 2013 using identical acquisition specifications, with the exception of the streamer depth variation. One of the data sets was acquired with a conventional horizontal streamer configuration and the other with a variable-depth cable profile. Eight cables, with 5100 m of active cable length and 100 m of cable separation, were deployed. Cable depth for the BroadSeis acquisition varied between 9 and 50 m; 9 m is also the depth of the conventional data acquisition. Two sources at 7-m depth were shot in flip-flop mode with a 12.5-m interval. A full fold of 102 was achieved over a 24-km^2 area.

The surveys were acquired within 10 days, providing us with a “zero-time repeatability test” (Ross and Altan, 1997). Because of the short calendar time elapsed between vintages, no production effects will be visible on 4D comparisons. Processing should yield difference sections of “zero,” and any remaining noise and geologic signal leakage are indicators of acquisition and/or processing issues.

Data quality is good, considering the winter acquisition slot. The acquisition was done without matching of tidal conditions and feather repeat. Figure 3 shows frequency panels of conventional and BroadSeis data of as much as 30 Hz after the initial denoise. We achieved very good signal-to-noise

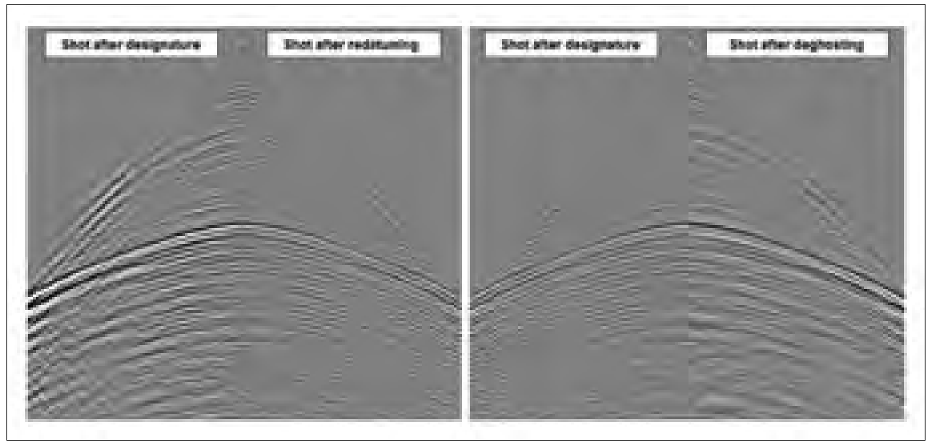

Figure 4. *A single BroadSeis shot gather and its progression as it is redatumed and deghosted.*

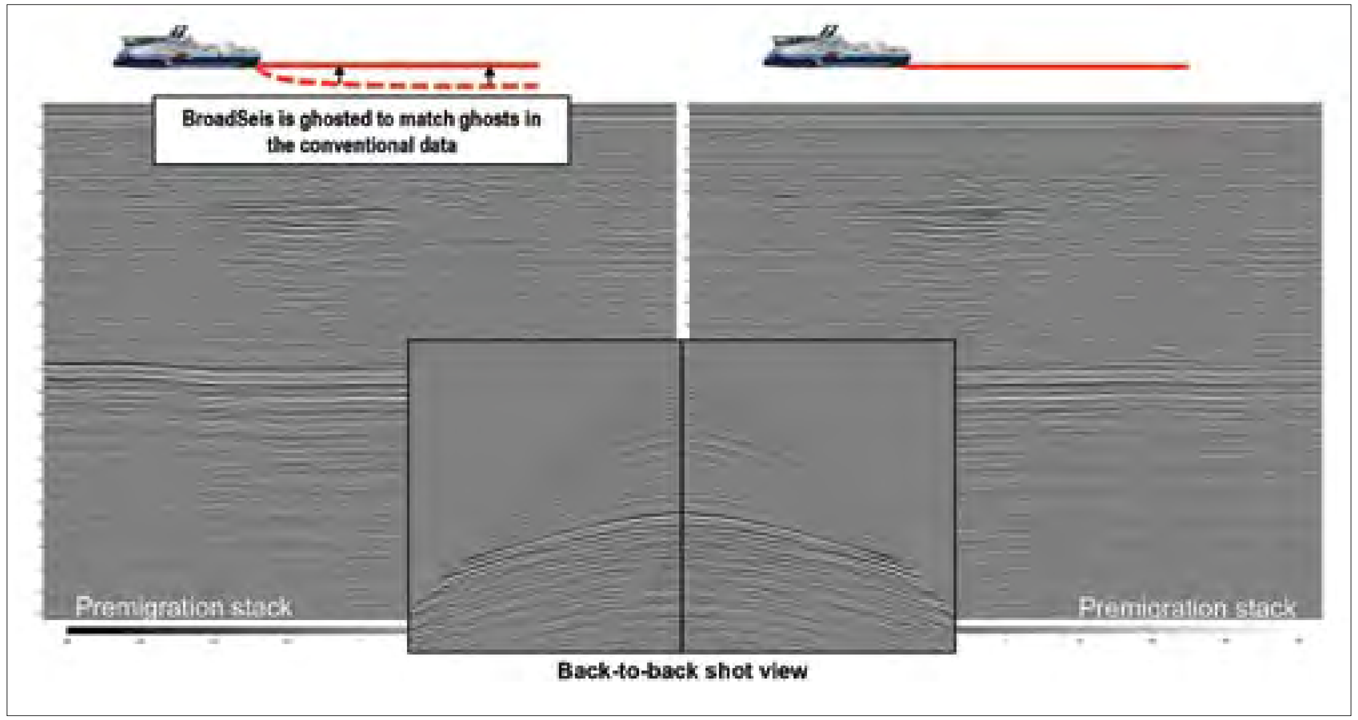

Figure 5. *Shot gathers and premigration stacks after codatuming of both data sets to a common depth of 9 m.*

ratio on both sets of data, but the BroadSeis panels show higher signal content, as expected, in all the low-frequency parts of the spectrum. The shot gathers also show significant differences in the tuning of upgoing and downgoing components at mid- and far offsets.

Surface repeatability, quantified as the sum of source and receiver position differences ($\delta S + \delta R$), are as expected for a modern 4D repeat acquisition. Near offsets have a median surface nonrepeatability of 10 m, increasing to 30 m for mid- and far offsets.

Figure 4 shows a single shot from the variable-depth streamer acquisition after denoise and source designature. Back-to-back shot displays show the progressive changes as the shot is taken through redatuming to a constant depth of 9 m and subsequently through ghost wavefield elimination. We see most changes toward mid- and far offsets, in which tuning between upgoing and downgoing components is modified as the variable depth of the streamer is removed. Removing the downgoing component from the data also suppresses some of the ringing character, corresponding to reduced side lobes in the wavelet.

We now focus on the 4D suitability of the codatum and GWE technology. We assess those algorithms first visually, on shots and stacks, and then by using NRMS to measure 4D residual noise. Considering that the data were acquired with the same equipment and within 10 days (in similar weather conditions), we expect minimal 4D noise everywhere, if the proposed algorithms can match the primary and ghost content of the two acquisitions.

Figure 5 shows the data after application of the codatum step to both vintages. In the spirit of 4D coprocessing, the conventional towed data were also redatumed with the same technique to a 9-m horizon. At this stage of processing, both data sets are contaminated by ghosts, but given their common datum, they are now already suitable for coprocessing with a standard 4D sequence.

Moreover, because both vintages are acquired with the same equipment and within such a short time frame as to not have significant variability in water temperature or salinity, one would expect very little global bulk time, phase, or amplitude difference in the two data sets after redatum. Indeed, no global matching whatsoever was required on the data sets after codatum. That is a strong indication of the robustness of the GWE algorithm.

In a first attempt to assess 4D repeatability, we leave receiver ghosts in the data and coprocess the two vintages with the 4D flow (omitting deghosting) shown in Table 1. On migrated stacks, with no global matching, cross-equalization, or trace-by-trace matching, we find residual 4D noise on the order of 13.2% (Figure 6). This compares favorably with recent state-of-the-art North Sea 4D data processing (e.g., Campbell et al, 2011; Helgerud et al., 2012).

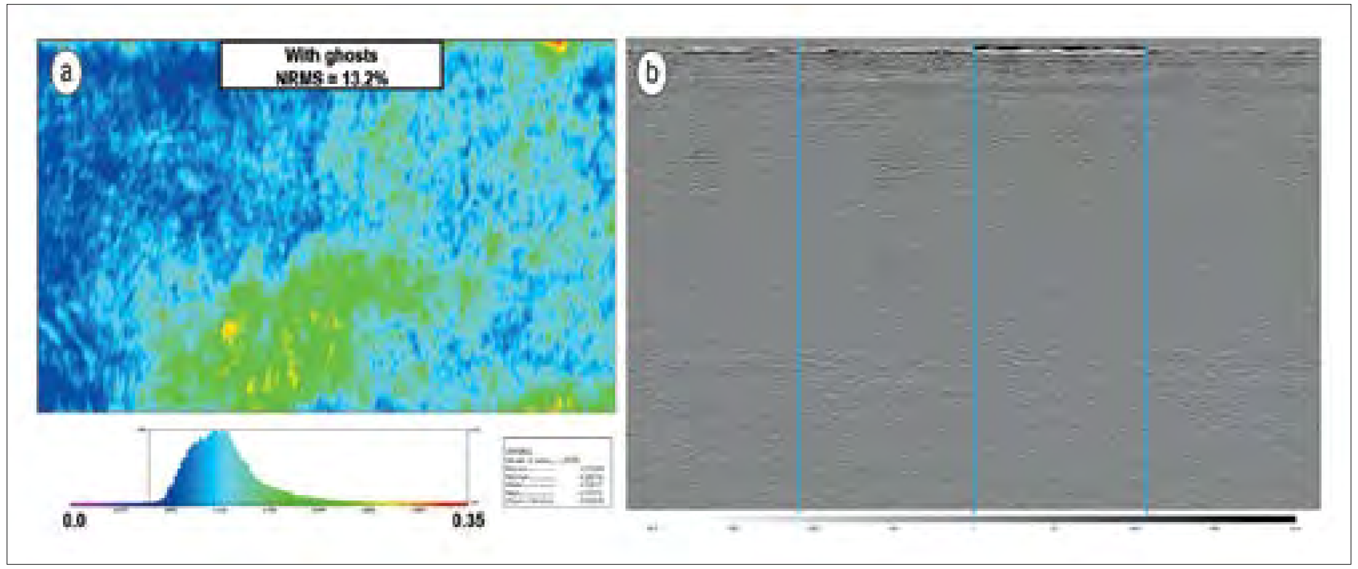

Figure 6. *(a) Postmigration repeatability analysis of conventional towed and variable-depth streamer data after application of codatuming to a reference datum of 9 m. The BroadSeis data were reghosted at that depth. There is no 4D effect because the two acquisitions were acquired at the same calendar time. (b) The seismic section shows four inlines.*

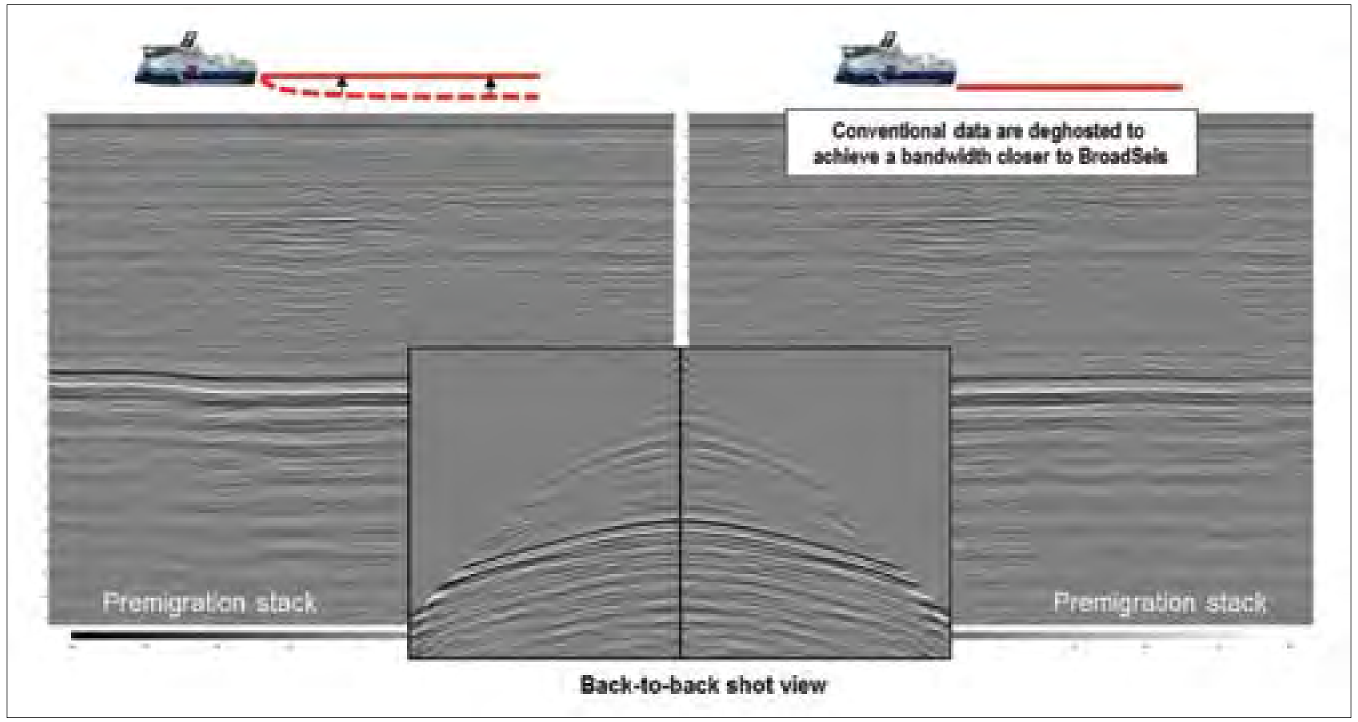

Figure 7. *Shot gather and stack after codatuming and maximal ghost wavefield elimination applied to both sets of data.*

We now investigate whether this repeatability can be improved by removing receiver ghosts and performing residual wavelet matching. Figure 7 shows the equivalent of Figure 5, with both vintages not just codatumed but also maximally deghosted and matched. In this instance, the excellent signal-to-noise ratio in these data allows us to perform a very effective deghosting of the conventional data and match it and the BroadSeis data with nearly full ghost removal.

The back-to-back shot gathers show that the data are perfectly aligned and very well matched. This is backed up by the indistinguishable stacks before migration and by the 4D QC postmigration (Figure 8). NRMS is now down to 9.6%, which is a good improvement compared with the 4D difference with ghosts (Figure 6), in which we found nonrepeatable noise of 13.2%. Once again, following codatum and ghost wavefield elimination, a standard 4D coprocessing sequence, with 4D binning and 4D QC as usual, has been applied (Table 1).

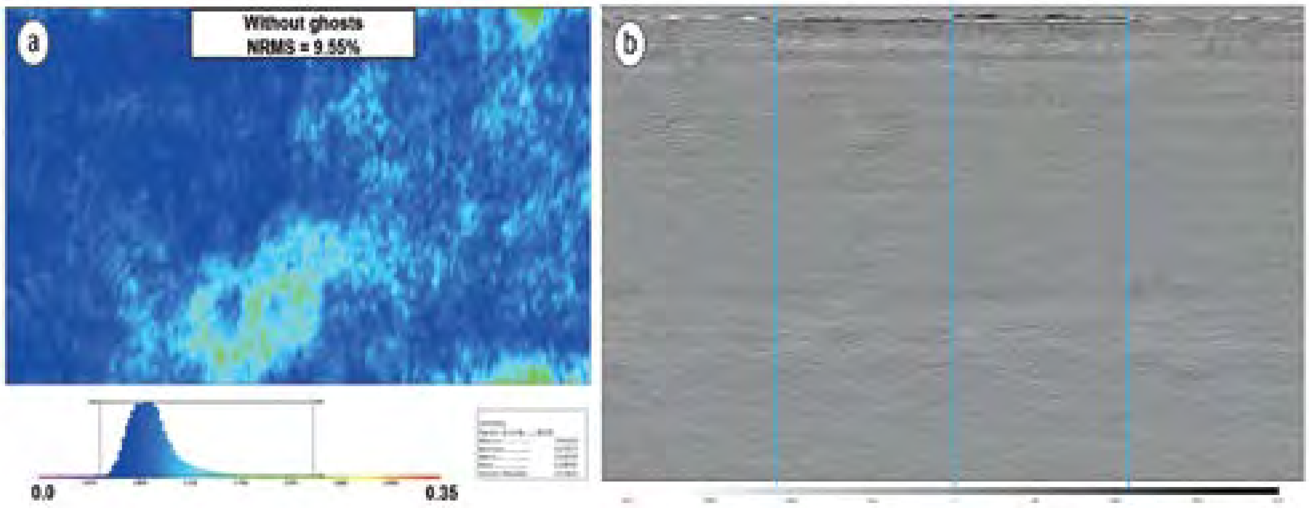

Figure 8. *(a) Postmigration repeatability analysis of conventional towed and variable-depth streamer data after application of codatuming and to a reference datum of 9 m followed by ghost wavefield elimination. There is no 4D effect because the data are acquired within a few days. The residual noise of 9.6% is less than that found with codatuming only (NRMS of 13.2%). (b) The seismic section shows four inlines.*

Conclusions

We have shown how to efficiently 4D-coprocess a conventional flat streamer base data and a variable-depth streamer broadband monitor. We developed a 4D coprocessing flow that codatums the 4D vintages to a common datum early in the sequence so that 4D QC and conventional 4D coprocessing methods such as 4D binning can be applied. We demonstrated an application of those ideas to recently acquired North Sea data and obtained a well-matched 4D difference with residual noise (NRMS) of 13.2%.

In addition, we demonstrated a new deghosting technology, ghost wavefield elimination, which was applied to variable-depth and conventional data. We used this method to model and remove the downgoing wavefield, thus creating a 4D difference uncontaminated by receiver ghosts and with a larger bandwidth than in conventional 4D. In our case study, the 4D coprocessing of codatumed and receiver-deghosted 4D data further reduces the 4D noise to less than 10%. TLE

References

Campbell, S., C. Lacombe, R. Brooymans, H. Hoeber, and S. White, 2011, Foinaven: 4D processing comes up trumps: The Leading Edge, **30**, no. 9, 1034–1040, http://dx.doi.org/10.1190/1.3640527.

Charrier, P., Z. Yu, and T. Rebert, 2012, 4D processing between variable-depth and conventional streamer data: 74th Conference and Exhibition, EAGE, Extended Abstracts, E013.

Duval, G., 2012, How broadband can unlock the remaining hydrocarbon potential of the North Sea: First Break, **30**, no 12, 85–91.

Helgerud, M. B., U. K. Tiwari, S. G. Woods, P. Homonko, A. K. Bucki, B. P. Laugier, E. Hicks, H. Hoeber, and J. Khan, 2012, 4D case study at Ringhorne, Ringhorne East, Balder and Forseti — Integrating OBC with streamer data: 74th Conference and Exhibition, EAGE, Extended Abstracts, E014.

Johnston, D. H., 2013, Practical applications of time-lapse seismic data: SEG Distinguished Instructor Series No. 16.

Poole, G., 2013, Pre-migration receiver de-ghosting and re-datuming for variable depth streamer data: 83rd Annual International Meeting, SEG, Expanded Abstracts, 4216–4220, http://dx.doi.org/10.1190/segam2013-0541.1.

Ross, C. P., and M. S. Altan, 1997, Time-lapse seismic monitoring: Some shortcomings in nonuniform processing: The Leading Edge, **16**, no. 6, 931–937, http://dx.doi.org/ 10.1190/1.1437701.

Soubaras, R., 2010, Deghosting by joint deconvolution of a migration and a mirror migration: 80th Annual International Meeting, SEG, Expanded Abstracts, 3406–3410, http://dx.doi.org/10.1190/1.351355.

Acknowledgments: We are grateful to CGG and Statoil for funding this research. We thank Statoil, ExxonMobil E&P, Total E&P Norge, and CGG for permission to publish this work. Henning Hoeber thanks Vetle Vinje for his support in creating this article.

Corresponding author: henning.hoeber@cgg.com