Overcoming 4D repeatability challenges from mixed acquisition systems

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Summary

Time-lapse (4D) surveys have traditionally been reliant on baseline (base) surveys being well repeated by the monitor to decrease 4D noise. In this case study the monitor was acquired independently from the 3D narrow-azimuth, towed-streamer, hydrophone-only base, and "mixes" two different types of acquisition: a multi-sensor, towed-streamer acquisition for prime coverage and a multi-sensor towed-streamer infill. We describe technologies used to overcome the limitations in 4D repeatability and intra-monitor consistency. 3D Ghost Wavefield Elimination and a novel blind signature inversion method were crucial to create a seamless monitor across the target and to reconcile the signature and ghost differences between the base and monitor. Inconsistent azimuth content between base and monitors introduced complexities for the demultiple process; nevertheless, multiples were successfully attenuated using wave equation deconvolution with joint base and monitor reflectivity imaging. Residual non-repeated 4D noise was attenuated using a curvelet domain 4D co-operative denoise workflow.

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Introduction

Time-lapse (4D) seismic surveys are a crucial tool for monitoring fluid movement and subsidence in subsurface reservoirs. The ability to accurately repeat the acquisition set-ups for 4D surveys is usually critical for capturing changes in the subsurface, particularly where the 4D signal is weak relative to 4D noise. Increasingly, inconsistent acquisition setups are being used for monitoring 4D targets, due to the cost of 4D survey design and the desire to produce improved 3D images using upgraded acquisition systems such as additional streamers or multi-sensor broadband acquisition. However, the use of different acquisition systems poses a number of challenges that may impact the 4D signal-to-noise ratio (S/N). In this paper, we present a case study in which we utilized several processing technologies to overcome these challenges. These included the use of source-receiver deghosting to mitigate variable ghost energies from different acquisition systems, the integration of source wavelets derived from blind deconvolution to normalize the difference in source signature, the adoption of a jointly derived reflectivity for consistent demultiple of base and monitor, and the use of a curvelet domain 4D co-operative denoise algorithm to reduce non-repeated 4D noise. Our results demonstrate the effectiveness of these approaches in overcoming the challenges of repeatability for inconsistently acquired 4D surveys.

Our case study data consisted of a 1995 3D narrow-azimuth towed streamer (NATS) hydrophone acquisition as a base, and a monitor with a “mix” of two different surveys: a 2019 NATS multi-sensor acquisition for prime coverage and a 2021 NATS multi-sensor infill over a rig hole. The areas covered by the base and monitor are shown in Figure 1. The prime monitor was acquired fully independently of the base survey and as such the source/receiver array, spread, tow depths and coordinates (hence intra-sailline azimuths) differed significantly. The infill was acquired specifically with the aim of aligning saillines with the base survey; however, it did not repeat the source set-up or the shot/receiver locations due to additional streamers. The discrepancy in source and receiver depths between the three surveys (6 m, 7 m and 7 m for the base, monitor prime and monitor infill source and 7 m, 12 m and 18 m for the base, monitor prime and monitor infill receivers, respectively) caused significant variations in the source signatures and ghost energy, while differences in azimuth content created non-repeated multiples.

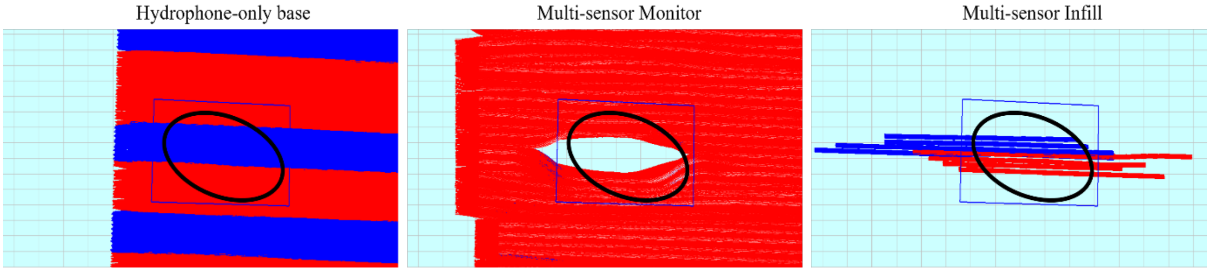

***Figure 1** Outline of base and monitor acquisitions, with processing area outlined in blue. Colour indicates shooting direction. East to West in red, West to East in blue. Field outline indicated in black.*

Source signature and ghost repeatability – a novel blind signature inversion solution

To deghost and debubble we applied joint source/receiver 3D Ghost Wavefield Elimination (GWE) and designature using input source signatures (Poole, 2013; Wang et al. 2014; Poole et al., 2015). A numerically modelled Vertical Far-field (VFF) wavelet was used for de-signature of the base, while near-field hydrophone (NFH) data were available for the prime monitor survey. As residual bubble energy was present in the 4D difference, a data-driven blind deconvolution approach (Yang et al., 2015) was employed. The goal of the approach was to derive a representative source signature to minimize bubble-related 4D noise by improving the designature for the base and monitor. In the first step of the blind deconvolution approach, we picked a sparse representation of coherent data that is free of signature effects (i.e. the bubble in the data). Then we solved a least-squares problem to find a VFF such that when convolved with the sparse representation of data we obtain the input data, which has bubble included. The inverted VFF can be used to designature the data and the process can be iterated to generate a more accurate far field. The methodology can also be used for a residual designature, or in another approach, a hybrid signature can be derived by combining the signature from blind deconvolution with a modelled or NFH-derived signature. In this case, the improved sailline-based source signatures derived from blind deconvolution were used for the debubble and zerophasing. Figure 2 shows the impact of the blind deconvolution wavelet on the pre-migration monitor, base and 4D stacks compared to the VFF wavelet. We observe that with the source wavelet from blind deconvolution, the monitor is more consistent with the base, with a reduction in low frequency residual bubble energy in the 4D difference highlighted by the arrows.

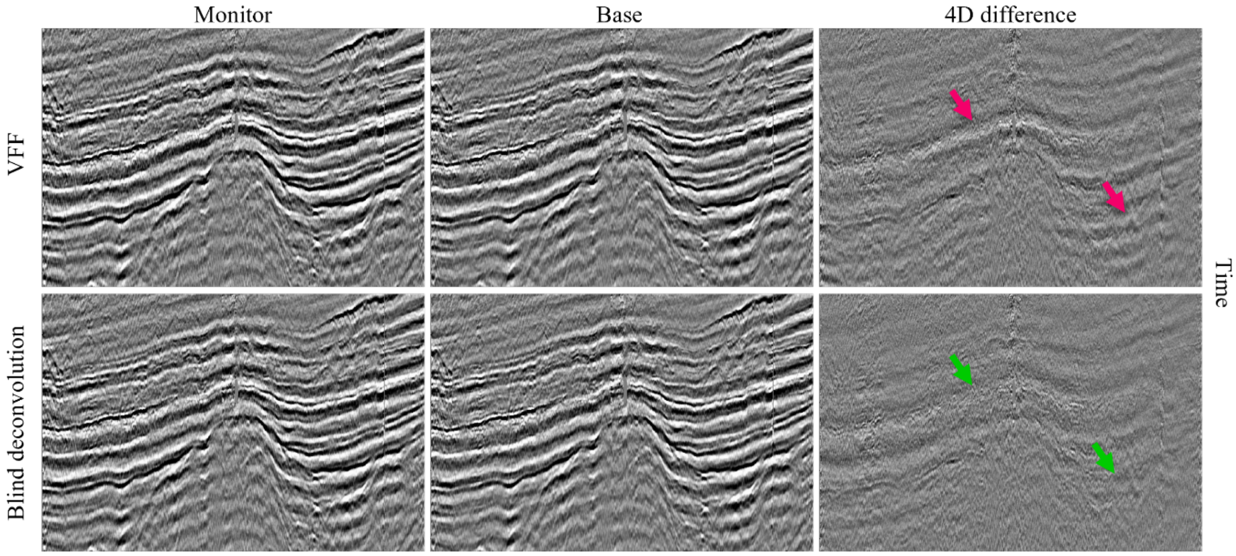

Figure 2 *Blind deconvolution effect on 4D difference of pre-migration stack in time. Top row: Vertical Far-field used for GWE and zerophasing. Bottom row: Blind deconvolution wavelet used for GWE and zerophasing.*

In addition to the significant differences in the ghost and bubble energy between the base and monitor, there were challenges in the consistency of the signature and ghost energy within the mixed monitor, which lead to a 4D noise imprint. Figure 3 shows the 4D difference of the migrated stacks in time as a 3D view, a timeslice, and a shallow time window repeatability metric (NRMS) map before deghosting and from the final output. The boundary of the infill is indicated with arrows on the 3D view and an outline on the timeslice and NRMS map. The successful deghosting, debubble and zerophasing were key to reducing 4D noise, and to providing a seamless monitor across the target. This can be seen in Figure 3 where the amplitudes on the seismic section and NRMS maps become spatially continuous across the infill boundary, and the NRMS decreases.

Inconsistent multiples and residual non-repeated noise

Multiples were inconsistent between the base and monitor surveys due to variations in azimuth content resulting from the difference in cable separation. The change in travel time between source and receiver is multiplied by each order of multiple leading to significant differences for higher order multiples. To attenuate the short-period multiples, Wave Equation Deconvolution (WEDecon) was applied using a near surface reflectivity derived using multi-sailline 3D least-squares inversion (Poole, 2019). To improve the accuracy and stability of the modelling a joint reflectivity was derived using both base and monitor datasets. Figure 4 shows the 4D difference of migrated stacks in time for base-only derived WEDecon reflectivity (left) and jointly derived WEDecon reflectivity (right). Using both surveys for the joint reflectivity provided improved 3D multiple modelling accuracy and the demultiple from the improved joint reflectivity thus reduced the 4D multiple imprint and provided a cleaner 4D difference.

To further attenuate non-repeated 4D noise, a curvelet domain 4D co-operative denoise (co-denoise) workflow, adjusted from the method proposed by Huang et al. (2014), was implemented. Base and monitor data are transformed to the 3D curvelet domain where if the amplitude ratio for a curvelet domain 'scale' is below a defined threshold, the energy of the scale will be reduced. To protect coherent 4D time shift signal the monitor and base are warped to each other in the data domain. Additionally, amplitude signal is protected by creating clean dummy 4D differences which are used as guides for the denoise. Figure 5 compares 4D difference migrated stacks at target with and without 4D co-denoise. The residual non-repeated 4D noise is separated from primaries in the curvelet domain and hence the noise can be attenuated without damaging 4D signal. The workflow was safely used in several passes throughout the processing flow, both pre- and post-migration for maximum effect.

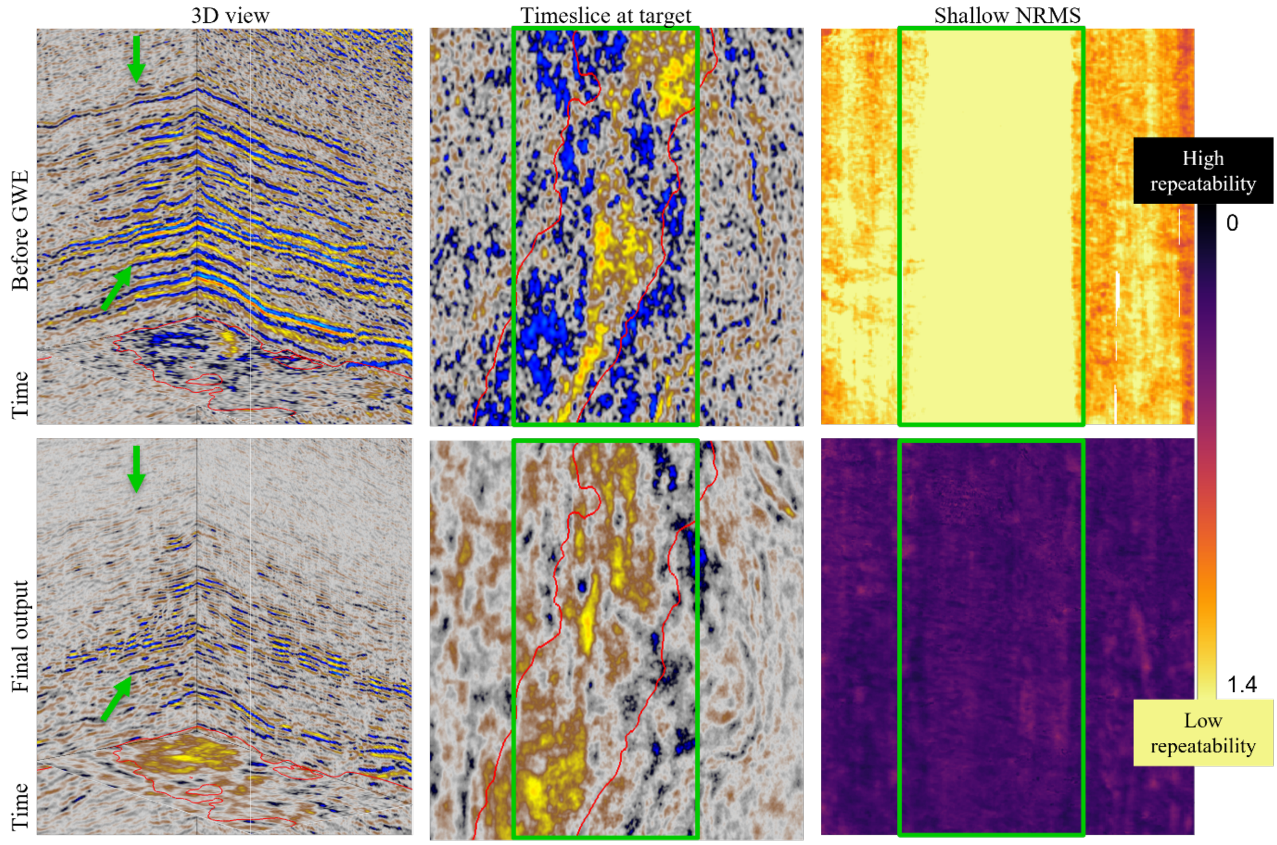

Figure 3 *4D seismic responses to de-signature of inconsistently acquired monitor infill. Top row: before deghosting. Bottom row: final output. Reservoir outlined in red, and the infill outline is shown in green, with arrows highlighting the infill boundary in the 3D view.*

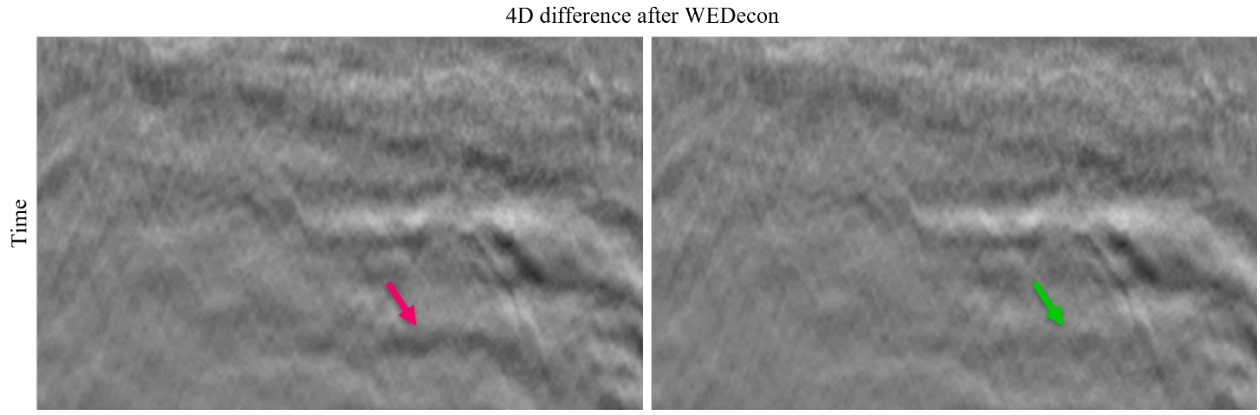

Figure 4 *Left: 4D difference from base-only WEDecon reflectivity inversion. Right: 4D difference from joint WEDecon reflectivity inversion.*

Conclusions

We have shown that careful processing with regard to the de-ghosting, designature, demultiple, and denoise can achieve a good 4D S/N, even in the case of poorly repeated monitor acquisitions. 3D GWE and blind deconvolution were instrumental to achieve a seamless combined monitor despite the mixed monitor acquisitions involving both an independent multi-sensor survey and a non-dedicated multi-sensor infill. The deghosting and designature were also key to reconcile the significant source differences between the hydrophone base and the mixed acquisition multi-sensor monitors. Inconsistent azimuth content made the demultiple process more complex. Nevertheless, multiples were consistently attenuated using WEDecon with a joint base and monitor reflectivity. Residual non-repeated noise was supressed, without evident 4D signal leakage, using a curvelet domain 4D co-operative denoise workflow. These data processing technologies overcame repeatability challenges inherent in the inconsistent acquisition datasets, resulting in a clear and interpretable reservoir response.

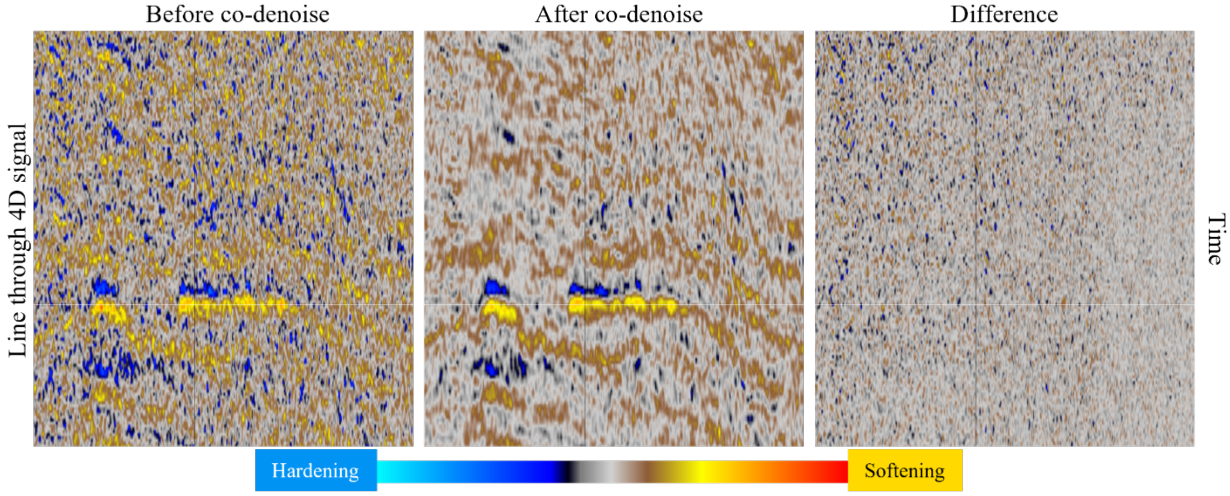

Figure 5 *4D differences before (left) and after (centre) co-denoise, with noise removed on the right.*

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