How to combine single hydrophone streamers with multi-component streamers in a 4D context: An offshore West Africa case study

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Summary

In this paper, we demonstrate how conventional single-hydrophone streamer data can be combined with dual-sensor acquisition data to support the reservoir monitoring of a producing field in offshore West Africa. We describe innovative processing techniques for increasing the 4D resolution, and use case study examples to illustrate the methodology. The chosen processing approach intends to extend the signal bandwidth in a 3D and 4D sense. Improving the resolution of the 4D signal is essential for understanding the production of this complex reservoir, which is composed of turbiditic stacked channels.

Introduction

For the last ten years the seismic industry has been offering marine broadband 3D seismic solutions. Broadband acquisition and processing technologies are attractive for 4D time-lapse surveys in order to increase the resolution and consequently the understanding of the fluid movement due to the reservoir production. Therefore, multi-sensor technologies for towed streamers are being integrated into reservoir 4D acquisition cycles. Deeper tow depths deliver useful low frequency and improved signal-to-noise ratio. Importantly, multi-sensor recording provides receiver ghost-free data, insensitive to the sea state.

In the case of time-lapse studies which have a conventional baseline dataset (hydrophone only), various processing strategies can be used for introducing a new broadband monitor dataset into the reservoir monitoring cycle. One option is to re-datum and re-ghost the multi-sensor data after wavefield separation, thereby performing 4D band-limited imaging with the conventional hydrophone data (backward compatibility) (Day et al., 2010).

An alternative is to extend the 4D signal bandwidth by combining the de-ghosted legacy (baseline) hydrophone data and the ghost-free (monitor) up-going wavefield data intrinsically produced by the multi-component sensors. This paper illustrates this alternative option using a 4D case study located in offshore West Africa. The processing approach intends to extend the bandwidth of the 4D signal and consequently to improve the 4D image resolution.

The field case study

The field was discovered in 2010 by an exploration well and was delineated in the following couple of years by two appraisal wells. The reservoir consists of a Tertiary turbiditic weakly confined channel complex characterized by several stacked channels lying over a horst structure. The channel complex is over 200m thick with a typical fining-upward sequence formed by 1) wide, thick amalgamated channels at the base of the system, and 2) small, narrower channels toward the younger part of the reservoir complex. The reservoir (high-porosity and high-permeability sandstones) has excellent reservoir properties, leading to improved well production.

The imaging of the target is challenging due to the presence of 1) thick overburden characterized by the presence of faults that generate shadow effects, and 2) hydrocarbon-related amplitude anomalies affecting velocity modelling. These elements negatively influence the seismic energy penetration and can affect the amplitude preservation.

Production started in early 2017 and the pressure support is maintained by water and gas injection. The monitor survey was acquired in 2018 after more than a year of production.

The 4D acquisition geometry

The baseline survey was acquired using 10 streamers on a 6 streamer pre-plot, whilst the monitor survey repeated the baseline sail lines using 14 streamers on a 12 streamer pre-plot. 4D seismic modelling was used to assess and to find a compromise between monitor survey acquisition cost and geometry repeatability.

Monitor shot positions were repeated for 1:2 baseline saillines using steerable sources. For the streamers the cable separations were respected but their depth was different. The baseline data was acquired with conventional shallow hydrophone-only streamer depth (8 m) and the monitor data was recorded using deep-towed dual-sensor streamers at 20 m depth. Multi-component streamers combine pressure sensors and vertical velocity sensors to perform accurate separation of the up-going and down-going wavefields (where the down-going wavefield represents the receiver ghost). Due to the deep tow the ghost-free up-going wavefield contains clean low frequency signal and high frequencies not affected by the sea surface. Consequently, the up-going wavefield is considered as the most consistent broadband signal for this 4D experiment. The up-going wavefield is backward propagated to be re-datumed at the depth of the baseline streamers.

The 4D broadband processing strategy

For both 4D processing sequences, the fast-track and the full integrity sequences, the option of broadening the signal was preferred. That means the data recorded with the conventional shallow streamer was de-ghosted with a deterministic operator using the nominal source and receiver depth. The de-ghosting is applied in the Laplace domain (complex frequencies – wavenumber domain). This process assumes flat sea surface, accurate depths for the sources and receivers, and consistent sea surface reflectivity. The effects of these parameter variations are mitigated later on in the processing workflow.

By extending the signal bandwidth of the conventional baseline dataset we could create a direct comparison with the ghost-free up-going wavefield data produced by the dual-sensor monitor survey. This methodology can potentially enhance the resolution of the resulting 4D signal if the conventional hydrophone has good signal-to-noise ratio. For example, the presence of strong environmental noise may moderate the signal broadening uplift.

It should be noted that the challenging de-ghosting processing of the baseline data is performed prior to the monitor data delivery, and consequently does not affect the turnaround time of the 4D fast-track delivery. For multi-component streamers, the production of the broadband up-going wavefield does not require extra-time and is directly available after the last shot of the monitor survey.

A conservative strategy would be to re-create for the monitor survey a band-limited hydrophone dataset from the deep-towed multi-sensor streamers by re-datuming the up-going and down-going wavefields, and re-ghosting the data. This approach would provide a band-limited 4D signal and does not require de-ghosting of the baseline hydrophone data. However, it implies extra-processes for reconstructing the monitor hydrophone data, and furthermore, the down-going wavefield reintroduced into the data may introduce some non-repeatable sea state effects.

According to the 4D objectives with reservoir targets composed by turbiditic weakly-confined channel complexes, the preference for this case study was to broaden the baseline data as much as the frequency signal-to-noise spectrum would allow, and to be combined with the monitor broadband up-going wavefield data.

The 4D processing sequences

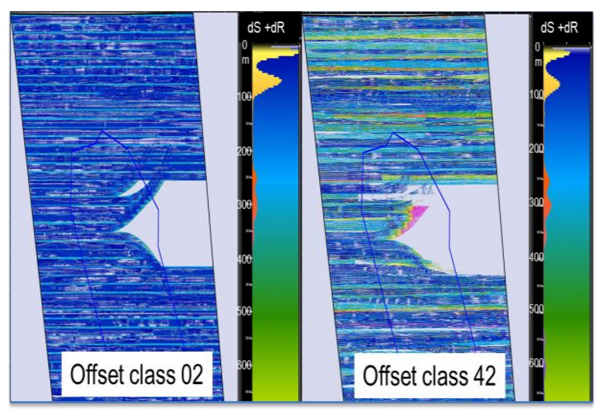
The most significant challenges during 4D processing came from the differences in acquisition geometry between the baseline and the monitor surveys. In this paper we illustrate some innovative techniques that have been tested and validated for this case study. Three key processing steps have been reviewed and adjusted in order to optimize the 4D imaging:

- 4D Binning, 4D Matching and 4D Denoise

4D Binning

Because the acquisition geometries were partially repeated, the 4D binning parametrization was a crucial process for collecting traces-pairs in an optimum way. The goal of 4D binning is to ensure maximum source-receiver geometry consistency between of the baseline and monitor data without compromising the density of traces necessary for the interpolation/regularization procedures.

The summation of the source location pair distance and receiver location pair distance (noted dS+dR) is commonly used as a geometrical threshold for rejecting the non-repeatable traces pairs. Figure 1 (top) shows the dS+dR attributes mapped for a near offset class (Offset class 02, ~395 m) and far offset class (Offset class 42, ~4395 m). It can be noted that most of the trace pairs are included below the maximum desired limit of 100 m for the near offset class, while for the far offset class the statistical distribution is larger. By plotting trace density associated to the 4D dS+dR attribute for each offset class we define an adjustable limit with offset (white curve in the bottom of Figure1) in order to maintain good repeatability without compromising the trace-pair coverage for each offset class. Large areas with missing repeated traces are then limited which facilitated the signal regularization/interpolation before the data migration.



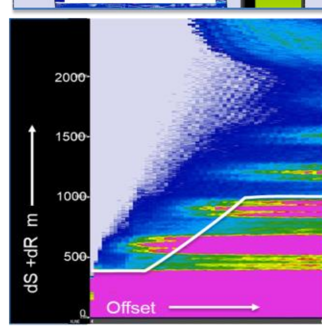


Figure 1. (Top) dS+dR maps for near offset (OFC02,~395m) and far offset (OFC42,~4395m) classes.
(Left) Trace density plot dS+dR versus offset. The white line corresponds to the offset-dependent dS+dR threshold.

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4D Matching

In addition to conventional pre-migration global matching steps, a specific matching procedure was designed for cross-equalizing the baseline and monitor signal spectra in the angle domain.

For the baseline data, the objective of the deterministic receiver-side de-ghosting was to upgrade the hydrophone signal (band-limited data) as close as possible to the broader bandwidth of the monitor up-going wavefield data. Assuming a flat sea surface, the deterministic operator uses the nominal receiver depth. Inaccuracy in the cable depth measurement and/or high swell conditions can produce some undesirable artefacts, seen as residual ghost mismatches that can affect the repeatability of the 4D data. In a previous case (Webb et al., 2018), joint matching operators were designed for each set of angle-traces to mitigate the residual effects on the baseline dataset. These joint operators are constrained by the signal-to-noise ratio and use an adaptive time window (ATW), i.e. the operator is estimated using different window lengths according to the given frequency band. In other words, the operator length will be larger for the low frequencies of the signal, and reduced for the high frequency part of the signal. The joint matching operators cross-equalize both signals on the common signal amplitude spectrum and correct the residual phase difference between the de-ghosted hydrophone streamer data and the broadband up-going wavefield data produced by the multi-component streamer (Figure 2).

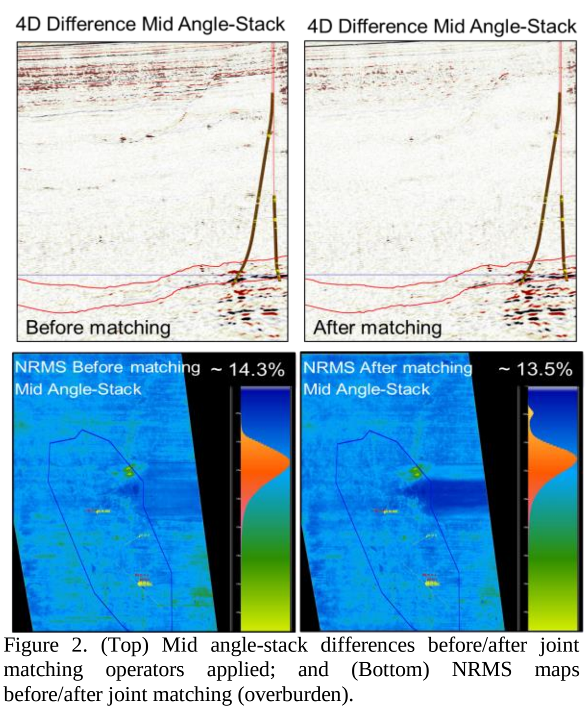

Figure 2. (Top) Mid angle-stack differences before/after joint matching operators applied; and (Bottom) NRMS maps before/after joint matching (overburden).

4D Denoise

If any difference in recording systems can be handled by the joint matching operators, the 4D noise due to the discrepancy in streamer geometry has to be minimized in a different manner. It is well known that 4D Kirchhoff PSDM images are very sensitive to acquisition geometry differences. In our case, because of the dissimilar spread as well as strong feathering issues, the 4D binning threshold has been relaxed for the long offsets (c.f. 4D Binning). Consequently, various source-receiver azimuths have been migrated for both datasets, creating specific non-repeatable interferences after migration. Using the frequency-dependent character and the pattern of the artefacts, we generated different '4D noise models' with the data itself and tested the model subtraction on the data. Figure 3 shows 4D differences before/after the denoise application for two models. The first noise model handles residual high frequency 'smiles' due to source-receiver azimuth inconsistency. These residual interferences are principally visible in the cross-line direction. The second noise model focuses on the low frequency phase variability visible along sublines.

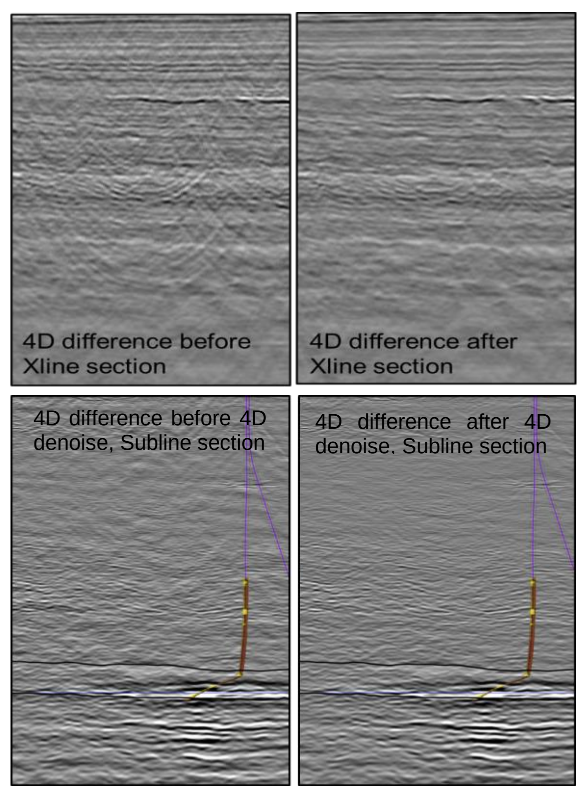

Figure 3: (Top) 4D denoise for residual high frequency 'smiles' in Xlines. (Bottom) 4D denoise for low frequencies in Sublines.

Further considerations

The processing objectives presented here are an attempt to extend the signal bandwidth in a 3D and 4D sense. It is important to mention other essential processing steps (not illustrated here) used to support the spectral broadening challenge.

Careful attention to de-bubbling and shot-by-shot de-signature process is key for improving the low frequency signal repeatability. Similarly, shot-by-shot statics (Barnes et al., 2017), water column corrections and 4D statics are also crucial to enhance the repeatability of high frequencies.

The goal of this processing sequence was to deliver an optimum seismic product for the quantitative interpretation (QI) team who will convert the 4D migrated pre-stack seismic data into acoustic and elastic delta-impedance, and finally, into fluid saturation and pressure changes at the reservoir level. Broadening the 4D signal is principally beneficial for reservoir production attributes resolution. It is therefore important that the processing QC is fully aligned with the overall objectives of the 4D project. For this reason we used the 4D intercept and the 4D gradient for assessing the post-migration pre-stack processing parametrization. Figure 4 illustrates the QCs using such 4D AVO/AVA attributes before and after application of the warping process.

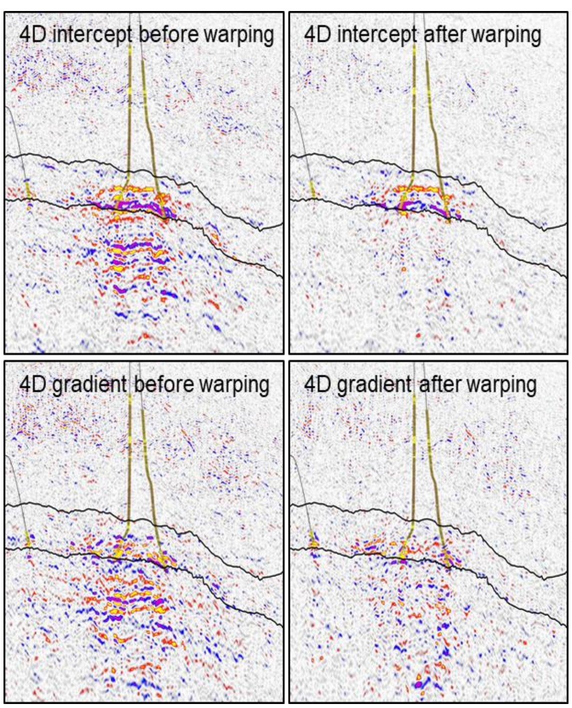

Figure 4. QCs for warping application. (Top) 4D Intercept before/after warping; and (Bottom) 4D Gradient before/after warping.

Conclusions

This offshore West-Africa 4D case study has combined shallow-towed conventional hydrophone-only streamer baseline data with deep-towed multi-component monitor streamer data. Through specific 3D and 4D processing processes we have demonstrated that it is possible to upgrade, to a certain extent, the signal bandwidth of the single hydrophone data to be compared with calibrated ghost-free broadband signal provided by the dual-sensor streamer data. Improving the resolution of the 4D signal for every angle stack is essential for characterizing the production of this complex reservoir composed of turbiditic stacked channels.

This time-lapse experiment is a step forward for future repeated multi-component streamer surveys that provide an ultimate platform for 4D broadband imaging. The 4D broadband ambition is to achieve a better understanding of fluid movements and fault behaviors in the field with the aim of identifying new business opportunities.

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