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# 4D Broadband Towed-Streamer Assessment, West Africa Deep Water Case Study

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## Summary

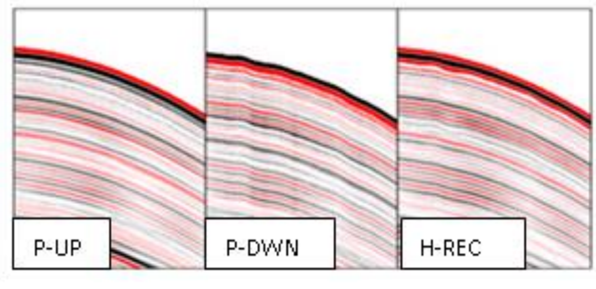
A 4D broadband assessment has been performed in a deep offshore West Africa environment using repeated dual-sensor streamer acquisitions. Three sail lines have been re-acquired only a few weeks after the original acquisition with standard 4D acquisition consideration. The study has compared the data repeatability metric NRMS along the processing sequences using, on one side, a reconstructed band limited 4D data corresponding to a single hydrophone and on the other side an extended bandwidth 4D data using the up-going wavefield only. Because the datasets have been recorded using the same acquisition, the main differences come from the bandwidth discrepancy and the variable sea-state. The 4D “Up-going on Up-going” preserves, for all processing steps, around 1% NRMS benefit against the 4D hydrophone-only. Because the NRMS comparison is biased by the dominant frequency discrepancy, the 1% gain does not fully reflect the detectability advantage of the 4D broadband. The NRMS analysis on the low frequency part has demonstrated the clear improvement on 4D broadband and a qualitative evaluation on the 4D differences has highlighted the negative effect of the sea-state on the hydrophone-only 4D results.

## Introduction

4D towed-streamer represents the most cost-effective acquisition for seismic reservoir monitoring and can cover large areas in an efficient way. However, it provides data with a lower 4D Signal-to-Noise when comparing to OBS (Ocean Bottom Seismic) and PRM (Permanent Reservoir Monitoring) 4D datasets. The repeatability metric NRMS is routinely used as a quality criterion for time-lapse data. Several investigations have been published relating the sensitivity of the NRMS value to the acquisition geometry repeatability, for example, Kragh and Christie (2002), and Eiken et al. (2003). As opposed to seabed recorded data, single hydrophone streamer data contain swell noise and a variable receiver ghost due to sea surface conditions. Per nature, these features are not repeatable between two acquisitions and affect the 4D signal bandwidth.
For the last ten years, the seismic industry has been offering higher resolution standards with an extended bandwidth for 3D imaging using multi-sensor streamer data. These broadband acquisition and processing technologies look most appealing for 4D time-lapse surveys.

## Deep-towed Multi-Sensor Streamers for reservoir monitoring

Multi-sensor streamer systems should offer an optimum platform for acquiring 4D broadband data. Deeper tow depths give a better signal-to-noise ratio as well as allowing an improved acquisition weather window. In addition multi-sensor recording provides ghost-free data insensitive to the sea state. The resulting 4D signal bandwidth should be improved and not contaminated by the sea-state variability (Laws and Kragh, 2002). Multi-sensor technologies have begun to be integrated into some reservoir 4D acquisition cycles. For example, Deplante (2012) described the use of a dual-sensor streamer Monitor survey for a 3D/4D study. In this case, the deep towed dual-sensor monitor data was re-datumed and re-ghosted for performing the 4D band-limited imaging with the legacy conventional hydrophone data. The pressure sensor is combined with the vertical velocity sensor for performing an accurate up-going and down-going wavefield separation (representing the receiver ghost), denoted P-UP and P-DWN. The two wavefields are propagated forward and backward to reconstruct a shallow hydrophone record, H-REC (Figure 1a). In a 4D broadband context, the data repeatability has to be optimized along the extended signal bandwidth and the most consistent of the separated wavefields may be preferred. The potential benefit of using only the up-going pressure field is illustrated in Figure 1b. Repeated shot gathers recorded with a dual-sensor towed streamer at the same location are displayed. In this preliminary 4D acquisition trial offshore South-America, three sail-lines have been shot and re-shot with a short interval in-between, to mimic 'baseline' and 'monitor' surveys and to help evaluate repeatability issues. Observations made in the field show these sail-lines were acquired with around 4 m swell.



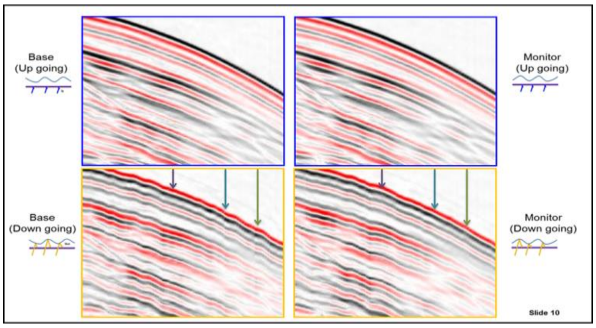




***Figure 1a (Right)*** *Shot domain example of the dual-sensor outputs: Up-going wavefield (P-UP), down-going wavefield (P-DWN) receiver ghost and hydrophone reconstructed (H-REC).*
***Figure 1b (Left)***: *Repeated shot gathers for the up-going wavefield (top) and for the down-going (bottom) wavefields. These examples have been taken from a different dataset, with a less benign sea-state.*

In this example, the use of the up-going wavefield for 4D not only recovers the frequencies in the receiver ghost notches but also preserves the most repeatable part of the seismic signal. The down-going wavefield, corresponding to the receiver ghost, is clearly modified by the sea-state in a different way between the baseline and monitor surveys and may degrade the repeatability of the 4D broadband signal.

## Full scale 4D broadband acquisition and processing test

A deep water survey was carried out by BP in offshore West Africa using dual-sensor streamer technology. Three sail lines were re-acquired only few weeks after the original acquisition. Source and receiver positions were repeated as closely as possible. By re-acquiring data over the baseline with a time lag of only a few weeks, it gave us the opportunity to assess the detectability potential of 4D broadband and to evaluate the contribution of the sea surface condition variability on the 4D noise along the processing sequence. The sea state was considered mild averaging ~1.7 m. Due to the very short time-lapse (maximum 76 days) and location on the edge of the reservoir, no production related 4D signal was expected. The 4D compliance was optimum as the vessel and acquisition parameters were almost perfectly repeated. Reconstructed hydrophone (H-REC) and broadband up-going wavefield (P-UP) data were both derived via wavefield separation, re-datumed at 4m cable depth and processed using a 4D workflow.

## Repeatability comparison along the 4D processing sequences

NRMS was computed for both components, P-UP on P-UP and H-REC on H-REC, and analyzed at each processing step (Figure 2). The main steps are displayed: Static correction (water column variation), Q phase correction + scaling, 4D binning + regularization, PSDM migration, post stack HF recovery (Q amplitude compensation) and 4D global matching.

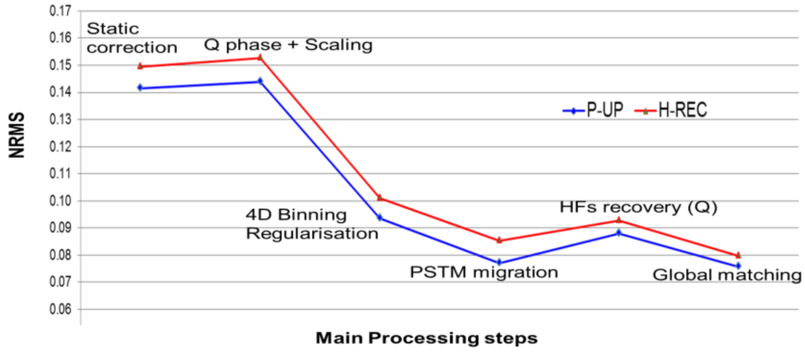



***Figure 2****: Evolution on the NRMS along the 4D processing sequences for the Up-going wavefield, P-UP on P-UP (blue) and the reconstructed hydrophone, H-REC on H-REC (red).*

Firstly, the very low NRMS values for both components should be noted. NRMS values were around 15% after water column variation correction and become less than 10% after 4D binning and regularization. As expected, 4D binning and regularization provide the main step down for all components, while the HF recovery process using Q amplitude compensation has slightly degraded the repeatability value. Indeed, the NRMS is very sensitive to the high frequency noise.
Concerning the repeatability of the different components, the broadband P-UP on P-UP introduces a 1% NRMS uplift against the band limited H-REC on H-REC. H-REC is the sum of the P-UP and P-DWN components, the latter containing effects due to the variable sea-surface condition. So, the NRMS difference can be interpreted as the effect of the sea-state variation. 1% NRMS gain seems not to be very substantial but another factor on the NRMS metric formulation has to be considered.
NRMS is dependent on seismic bandwidth (Lecerf, 2015). With a lower dominant frequency, the NRMS of the H-REC component is expected to be arithmetically reduced. The full benefit of using the P-UP component is best visualized in 4D difference section and in wavelet scales. In order to estimate qualitatively the data repeatability, the 4D residual differences, presenting less than 10% NRMS, have been displayed over-saturated in Figure 3. The 4D stack difference images are created before migration to avoid smearing of the 4D noise. The P-UP difference is significantly cleaner than the P-DWN difference which presents some lateral stripes probably due to sea-state variation effect. The remaining stripes in the P-UP difference are most likely due to acquisition geometrical repeatability issues. The H-REC difference is simply the summation of the P-UP and P-DWN differences.

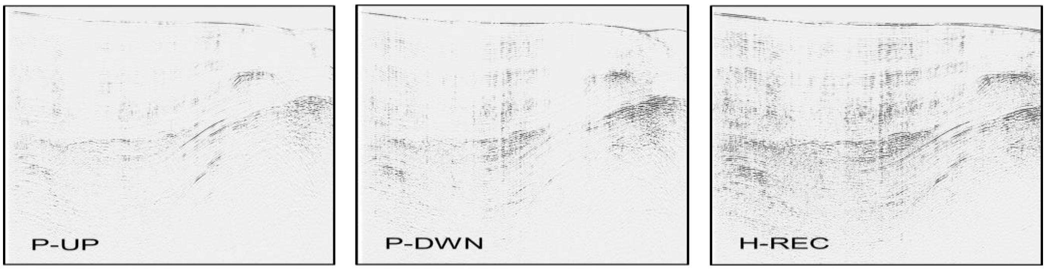
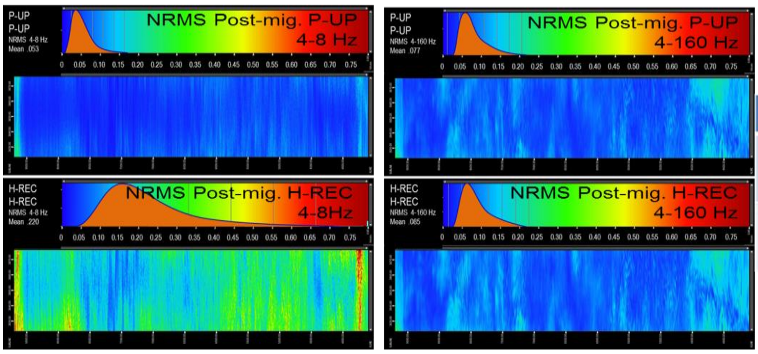



***Figure 3**: Over-saturated non-migrated 4D stack differences for each wavefield component. The reconstructed hydrophone difference, H-REC is the summation of the two P-UP and P-DWN differences.*

## Repeatability of migrated 4D images

Post-migration repeatability has been analyzed on 4D images with a global signal matching applied. The mean NRMS measurements is computed in a 1500 ms time-window below water bottom.
It is interesting to compare the repeatability value for the low frequencies for each component. The 0Hz receiver notch (present in the hydrophone only acquisition or in the reconstructed hydrophone of a dual-sensor streamer acquisition) usually limits use of the low frequencies due to a poor S/N ratio. NRMS maps along in-lines are presented in Figure 4 for a frequency band of 4-8 Hz as well as for the full bandwidth 4-160 Hz. It should be noted that below 20Hz, the geophone data is too noisy to be used. At those frequencies, the wavefield separation uses the hydrophone component only - producing ghost-free signal taking into account the emergence angle but assuming a flat sea surface. Despite this limitation, the uplift for the low frequencies is significant for the de-ghosted 4D data (5.3% for P-UP on P-UP and 22% for H-REC on H-REC), but is less significant for the total NRMS value within the full bandwidth (7.7% for P-UP on P-UP and 8.5% for H-REC on H-REC). The quality of the 4D signal in the low-end has a substantial influence for 4D impedance inversions.




| NRMS | 4-8 Hz | 4-160 Hz |
|---|---|---|
| P-UP/P-UP | Mean value 0.053<br>Std. deviation 0.027 | Mean value 0.077<br>Std. deviation 0.032 |
| H-REC/HREC | Mean value 0.220<br>Std. deviation 0.111 | Mean value 0.085<br>Std. deviation 0.035 |

***Figure 4**: NRMS histograms and maps along inlines for 4-8 Hz and 4-160 Hz bandwidth.*

## Discussion

It should be noted that the reconstructed shallow hydrophone (4m cable depth) used for this test replicates the frequency notches of a 4 m depth streamer but does not reproduce the 3D/4D noise level inherent to a shallow towed streamer. A conventional shallow single hydrophone should contain more ambient noise than the hydrophone reconstructed (H-REC) using deep recorded wavefields. We would therefore expect that the repeatability of the reconstructed hydrophone is already an uplift compared to a 4D conventional dataset.
NRMS is probably not the best metric for estimating the quality and the benefit of the 4D broadband data because of the dominant frequency bias. Frequency calibrated NRMS or frequency dependant NRMS seems to be more useful for quantitative measurement. Nevertheless, with very little matching, the repeatability of the 4D broadband data reaches less than 8% NRMS, which represents a very good result for a streamer acquisition. The use of such broadband technology should be considered as a step forward in 4D seismic detectability. In this deep water case, it is important to note that the target window is not affected by multiples. In addition, the acquisitions have been nearly perfectly repeated using same boat and equipment, and no strong feathering has been observed for the repeated sail-lines. These are probably ideal conditions for getting an optimum 4D broadband signal repeatability.

## Unexpected 4D results

In a targeted and tuned observation at the reservoir level, a subtle 4D signal has been revealed (Figure 5). According to 4D interpreters, it probably corresponds to a distant production effect which has occurred during the 76 days time-lapse. This 4D signal was not observable on the conventional bandlimited 4D difference using shallow towed streamer legacy data as a base-line despite having a geometrical repeatability similar to the dual-sensor streamer repeat dataset. The lack of 4D resolution is probably due to the higher noise level coming from the legacy dataset (shallow towed streamer) and the use of different acquisition hardware between baseline and monitor.

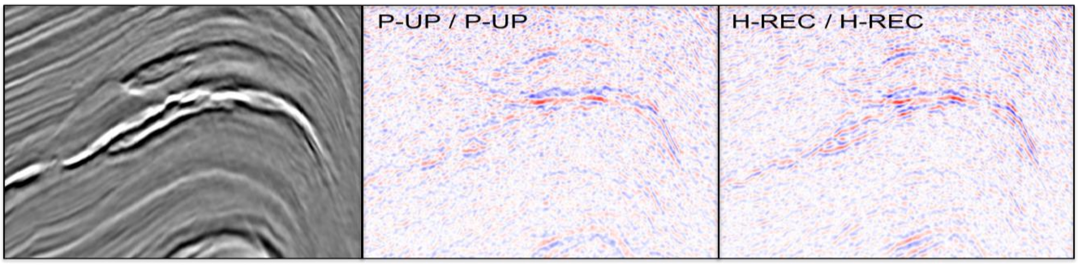



***Figure 5**: 3D P-UP, 4D P-UP and 4D H-REC final images at the reservoir level. An unpredicted 4D signal has been observed which may correspond to a reservoir production effect during the 76 days time-lapse. 4D signal in the P-UP difference contains less 4D leakage than the H-REC difference.*

## Conclusions

A 4D broadband assessment has been performed in a deep offshore West Africa environment using repeated dual-sensor streamer acquisitions. Three sail lines have been re-acquired only a few weeks after the original acquisition with standard 4D acquisition consideration. The study has compared the data repeatability metric NRMS along the processing sequences using, on one side, a reconstructed band limited 4D data corresponding to a single hydrophone and on the other side an extended bandwidth 4D data using the up-going wavefield only. Because the datasets have been recorded using the same acquisition, the main differences come from the bandwidth discrepancy and the variable sea-state. The 4D "Up-going on Up-going" preserves, for all processing steps, around 1% NRMS benefit against the 4D hydrophone-only. Because the NRMS comparison is biased by the dominant frequency discrepancy, the 1% gain does not fully reflect the detectability advantage of the 4D broadband. The NRMS analysis on the low frequency part has demonstrated the clear improvement on 4D broadband and a qualitative evaluation on the 4D differences has highlighted the negative effect of the sea-state on the hydrophone-only 4D results. Such emerging 4D technology will probably allow extending the capability range of 4D streamer acquisitions for challenging reservoir monitoring cases.

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