A conventional 4D and a snapshot 4D comparison in the Campos Basin

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Abstract

In 2017 a conventional narrow azimuth (NAZ) streamer-to-streamer 4D was planned to cover just 2 fields in the Campos Basin of Brazil. It was observed that the 4D shots would also cover a sizable portion of another field which has a Life of Field Seismic (LoFS) ocean bottom cable system. The survey was expanded to take advantage of the fact that the LoFS field could be switched on to record seismic from these shots thereby acquiring a "snapshot." This streamer-to-streamer 4D resulted in one of Shell's best ratio of repeatability to date. As well, we saw that using the sparser streamer shots with the LoFS system provided similar quality results as the dedicated LoFS monitors. From this work we have learned that there can be significant savings in the future by reducing the amount of shots. In all, 65% less shots are needed to image clear 4D signal on the LoFS field. Advances in processing techniques also make this work possible, not only the improvements in streamer-to-stream 4D, but the techniques required to use shots from a non-dedicated 4D survey.

Introduction

4D Time-lapse seismic is a proven approach for reservoir monitoring and management. Ocean bottom node (OBN) dedicated 4D has been demonstrated as the most effective time-lapse approach to achieve high repeatability and low (<10%) NRMS (Mestayer et al 2017, Galarraga et al 2015, van Gestel et al 2013, Stopin et al 2011). The advantage of OBN dedicated 4D is that the receiver positions can be accurately repeated between vintages. Comparatively, streamer-to-streamer or streamer-to-OBN 4D has previously achieved NRMS ranges of 12-30% (Hatchell et al 2017, Charron et al 2016, Broussard et al 2015, Elebiju et al 2014). This streamer-to-streamer 4D has a high quality 4D difference, 4D shift, dRMS map, and an NRMS of as low as 6%.

This conventional 4D NAZ streamer-to-streamer survey was acquired in the Campos Basin of offshore Brazil to provide images for in-fill and production drilling campaigns in the coming years. The baseline and monitor acquisitions cover 3 different producing fields with production histories ranging from 4 to 8 years. Key 4D anomalies (softening, hardening, time-shifts) were identified from these high quality 4D volumes, indicating depletion progress and aquifer movement.

In addition, results from using the 4D streamer shots with the LoFS system, the "snapshot," will be presented in this paper. The LoFS field already had a monitor planned for 2018, so there was no plan to turn on the system in 2017. However, the opportunity to "see what we could see" was too good to pass up and the LoFS system was set to record. It was uncertain if the streamer shots could be used with LoFS as they were much sparser than previous acquisitions. After running decimation test with previous data and with recent processing advances to handle directionality and gun differences, there was enough confidence to extend the streamer shots by a few lines to the north and switch on the LoFS system to record. Because of this work, the 2018 full shot monitor was able to be delayed to following years.

Acquisition

The conventional 4D baseline and monitor data cover a 2900 sq. km area, with water depths ranging from 1500 to 2000m. Three fields with producing histories ranging from 4 to 8 years exist in this area. Legacy NAZ streamer data was acquired in 1999 as a baseline survey when none of these fields started producing. In 2017 a field development update for infill opportunities was initiated, and the monitor NAZ streamer data was acquired. These two acquisitions were used to assess the effects of production and aquifer movement. The differences in acquisition can be seen in Table 1. The 4D processing workflow is composed of a re-processing of the baseline survey, a pre-processing of the monitor data, and the 4D co-processing on the two datasets. The whole processing project took 3 months to complete.

	Baseline	**Monitor**
Year of Survey	1999	2017
Number of Sources	2	2
Source Separation	50m	50m
Flip-flop Shot Interval	25m	25m
Number of Cables	6 or 8	10
Cable Spacing	100m	100m
Cable Length	5800m	6000m
Group Interval	25m	12.5m
Receivers per Cable	232	480
Nominal Fold	58	60

Table 1: Acquisition parameters for the baseline and monitor surveys.

Figure 1 shows the acquired lines for both baseline and monitor surveys. The acquisition hole displayed in the monitor survey was due to a floating production storage and offloading unit (FPSO), and the lines close to the FPSO were split into deadhead and slide-in lines. The monitor survey acquired by Polarcus covers a smaller area to fit the 4D monitoring purposes only. The primary acquisition criteria of the monitor survey are:

- The error of the source positions relative to the preplots should be no more than 10m cross line and 5m inline.
- Predict and match target cable feather as closely as possible and for the feather to be within tunnels.
- Minimize the impact of simultaneous operations (SIMOPs) on survey acquisition.

To fulfill these objectives, Reservoir Imaging Limited (RIL) was contracted for the duration of the monitor survey to provide in-field feather predictions, optimize line selection, and perform repeatability analysis to determine the quality of the survey, as well as to mitigate the impact of SIMOPs on production. Figure 2 shows the repeatability map. Overall, the monitor survey was considered as a good replication of the baseline, except for the locations close to the FPSO.

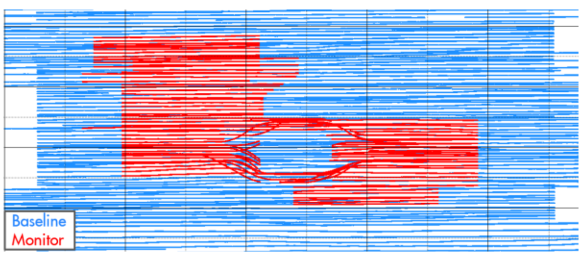

Figure 1: Baseline (red) and monitor (blue) acquired lines

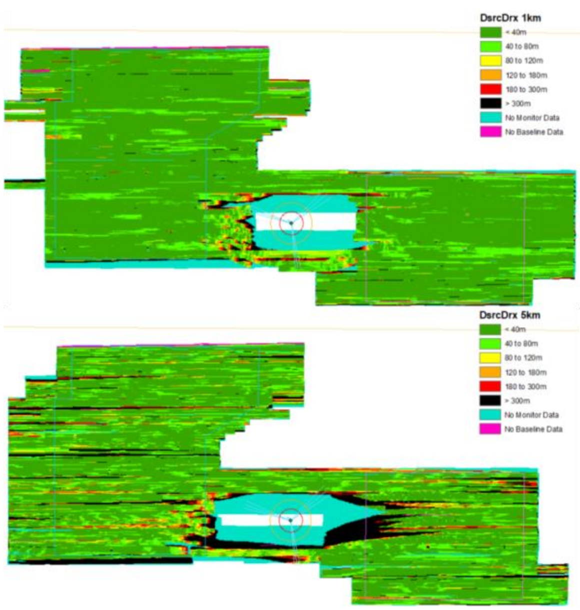

Figure 2: Repeatability (Dsrc+Drx) map. Top: offset slot of 900-1100m; bottom: offset slot of 4900-5100m.

4D Streamer-to-streamer Processing

The 4D processing was split into a fast track and a production phase. Minimal processing was applied in the fast track to obtain a first glance of 4D results as quickly as possible. Feedback was obtained from interpreters to guide the production 4D processing while the fast track results were still being evaluated. A production 4D processing workflow was designed carefully to achieve the best 4D performance. In this case study, the fast track 4D processing was completed in 5 weeks and the final production 4D results were delivered in 3 months.

The brief workflow of fast track 4D processing includes:

- Noise attenuation.
- Channel and shot amplitude correction.
- De-signature and zero phasing.
- Water column statics correction.
- 4D co-located trace selection.
- Global amplitude matching between baseline and monitor.
- Q compensation.
- Muting below the water bottom multiple.
- Kirchhoff PSDM.
- Post-migration amplitude matching in the migrated angle domain.
- Post-migration RMO correction.

In general, most steps are similar to a common 3D streamer processing workflow, except that co-located trace selection is a co-processing of both baseline and monitor data. Distances of shot and receiver positions (DSR) and differences of azimuth (DAZ) are used, and the pair of traces with minimum DSR values was selected for each bin. Then a threshold for DSR and DAZ were applied to remove paired traces with poor repeatability.

In pre-processing, no de-multiple algorithms have been applied but instead multiples were muted out, since all 4D targets are above the first water bottom multiple. In post-processing, amplitude matching in the migrated angle domain (Theriot et al 2015) was performed to compensate for small amplitude variations between the two surveys. Figure 3 shows the baseline stack and 4D difference from the fast track 4D processing. 4D difference is derived by subtracting the aligned monitor stack from baseline stack data. An NRMS of 19% was achieved on a window length of 1000m, starting at 100m below seafloor.

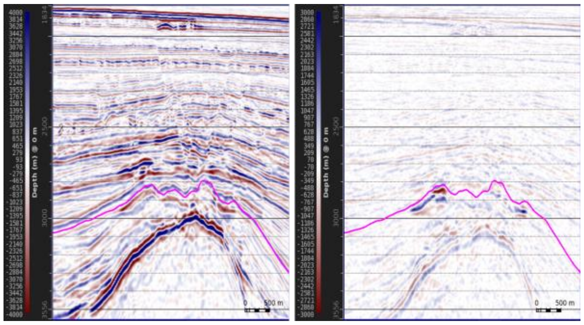

Figure 3: Fast track baseline stack (left) and 4D difference (right). Magenta lines represent the top reservoir.

Production 4D processing commenced immediately after the fast track was completed. The additional processing steps in the production 4D include:

- Water column statics correction using pressure inverted echo sensor data (PIES) on the monitor survey.
- 4D statics correction.
- Dedicated noise attenuation to address noisy sail lines in the monitor survey.
- Data regularization.
- Post-migration wavelet domain denoise.

The first improvement in the production 4D phase is the method used to correct for the statics issue on both acquisitions. A PIES device (Wang et al 2013) was placed on the seafloor within the monitor acquisition area to measure tides and water velocities. It was used to correct for the water column statics on the monitor data, and results in better statics solution compared to the commonly used data driven method. A 4D statics correction was then applied to the baseline which used the monitor as a reference. The first arrivals from the two surveys were aligned by the 4D statics correction which results in minimal 4D shift on the migrated stack data. Figure 4 shows the 4D depth shift on the water bottom, comparing the fast track and production 4D with PIES and 4D statics correction applied. The histograms of the depth shift show that the fast track has a depth shift peak at 0.7m on water bottom while the production 4D peaks at only 0.1m.

During 4D processing, feedback was received from interpreters using the fast track 4D results. The background 4D noise was as high as real 4D signal in some areas. By analyzing several sail lines in regions with different noise levels, quite different wavelets were observed on the monitor data, which showed large distinctions at low frequencies around 3 Hz. Figure 5 shows frequency spectra on 6 sail lines from the monitor data, color-coded by sail line sequence. A noticeable bump around 3 Hz occurred at some sail lines, even with the global noise attenuation applied in the fast track. The cause was later identified to be swell noise which relates to the weather conditions, since large wind forces were reported for these noisy sail lines (Table 2). Due to these large variations of frequency spectra among different sail lines on the monitor survey, an additional step of dedicated noise attenuation was performed. The noisy sail lines were first identified by checking the existence of the 3Hz bump in the spectrum, then an additional low-cut filter was applied to these sail lines to mitigate the frequency bumps. A total of 42 sail lines out of 79 were identified to be noisy and underwent the additional noise attenuation. Figure 6 shows the spectrum before and after the dedicated noise attenuation for one noisy sail line. The 4D difference before and after this process is shown in Figure 7.

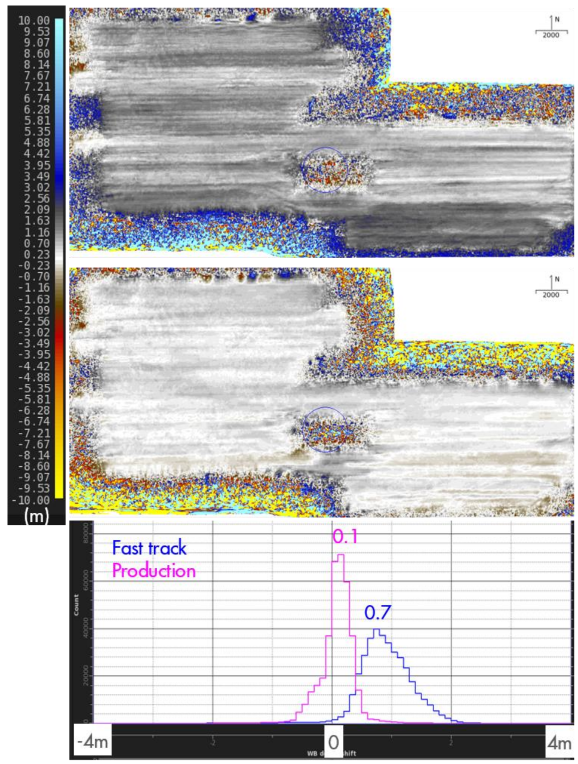

Figure 4: 4D depth shift (m) on water bottom, comparing fast track (top) and production 4D with PIES and 4D statics correction applied (middle). Histogram comparison shown on bottom.

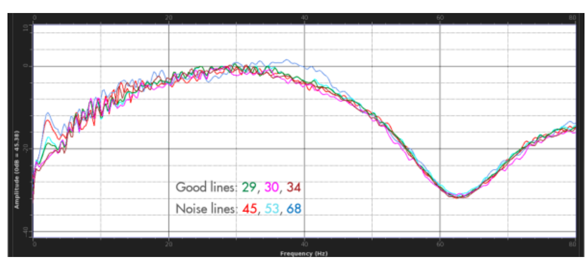

Figure 5: Frequency Spectrum of 6 sail lines on a window of 2 second, color-coded by sail line sequence.

		Wind force	
4D quality	**Sail line sequence**	**Start of line**	**End of line**
Good	29	10kn	13kn
	30	17kn	15kn
	34	7kn	13kn
Noisy	45	21kn	20kn
	53	29kn	27kn
	68	28kn	28kn

Table 2: Recorded wind force for 6 different sail lines, related to the 4D quality (good/noisy).

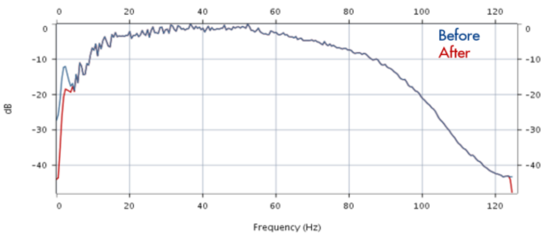

Figure 6: *S*pectrum before and after the dedicated noise attenuation for one noisy sail line on the monitor survey.

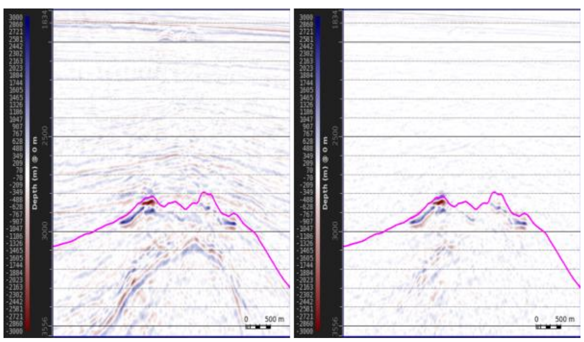

Figure 7: 4D difference without (left) and with (right) the dedicated noise attenuation. Magenta lines represent the top reservoir.

The additional post-migration processing step in the production 4D is the wavelet domain denoising. It decomposes the data into a complex wavelet domain, and measures the amplitude and phase similarities between the baseline and monitor data in this domain (Peng and Huang, 2014). Energy with large differences, such as noise, was attenuated. Figure 8 shows the final production 4D results compared to the fast track. An ultimate NRMS of 6% was achieved on a window length of 1000m, starting at 100m below the seafloor.

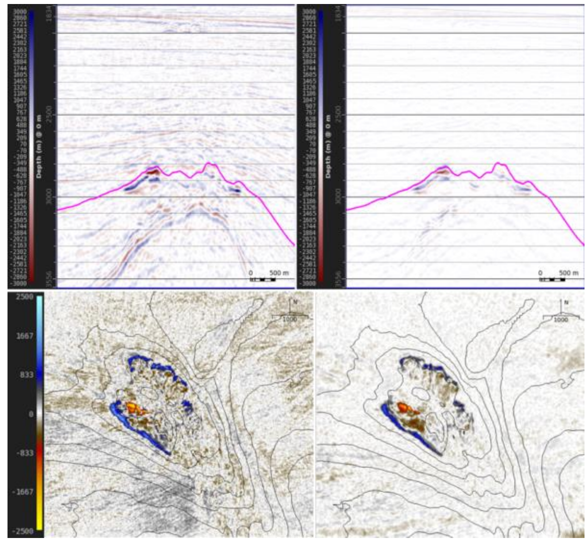

Figure 8: Final production 4D results compared to fast track. Top: 4D difference of fast track (left) and production 4D (right). Magenta lines represent the top reservoir. Bottom: dRMS map of fast track (left) and production 4D (right).

4D Streamer Shots to Ocean Bottom Cables "Snapshot"

In November 2017 the 4D streamer monitor survey was scheduled to start and designed for just two fields. After consulting with processing, the survey was extended to cover the third LoFS field to the north as it was realized the streamer shots could be used with the LoFS system to record a "snapshot" of the field production outside of the regularly scheduled monitors. As well, the streamer-to-streamer 4D would be available for comparison.

The LoFS system was deployed in 2013. This system has 98.6 km of ocean-bottom cables (OBC) sitting at an average water depth of about 1650 meters. Connected to a recording system located on a facility within the production infrastructure (FPSO). The LoFS system has proved itself several times over with continuous reservoir monitoring to assist field management (Chen and Farmer, 2015). Over the years, 4 dedicated 4D surveys have been acquired with this system, with "Baseline" in 2013, "Monitor 1" in 2014, "Monitor 2" in 2015, and "Monitor 3" in 2016. This 2017 acquisition was known as the "snapshot," as it was not a full monitor.

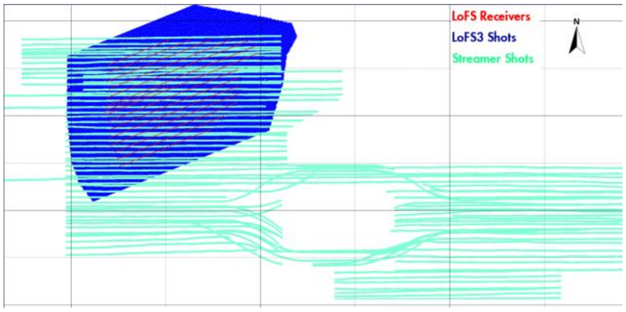

Figure 9: Shot map comparison. The blue shots are from a dedicated LoFS survey on a 50x50m grid. The red dots represent the ocean bottom cables. The cyan shots are from the streamer 4D acquisition.

In retrospect, recording with the LoFS seems like an obvious choice, but many uncertainties remained in processing since the streamer survey's shot configuration was very different from that of previous LoFS surveys (Figure 9). First there are 65% loss shots in the streamer design. Second, shooting directions are different. Third, a different gun array and gun volume was used (Figure 10). Last but not the least, even with the extended shot lines, the streamer's shot coverage stopped right at the northern edge of the cables. Decimation tests were run to mimic the streamer shot distribution using the Baseline and Monitor 3 datasets, which still showed a reliable 4D signal should be achievable (Figure 11).

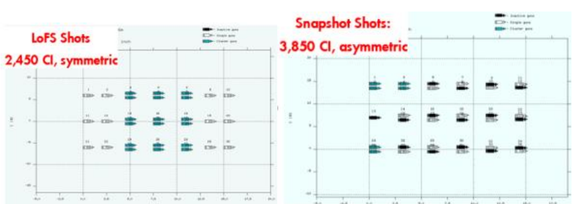

Figure 10: Different gun configurations from a typical LoFS Monitor (left) to the shots from the streamer acquisition (right).

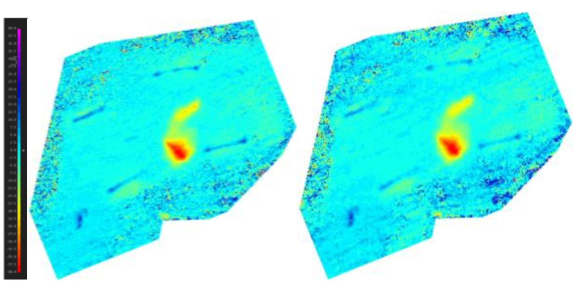

Figure 11: A decimation study from the 2013-2016 Base to Monitor acquistion gave confidence that the survey would yield usable results. Left figure shows NdRMS with all shots input, right figure shows a 66% reduction in shots.

This snapshot dataset was co-processed with Baseline and Monitor 3 to create differences from 2013 to 2017 and 2016 to 2017. In the 4D processing flow several key steps were considered essential to account for the differences from acquisition including shot co-selection, regularization, angular deghosting, and source wavefield corrections. A Kirchhoff least squares migration was performed to image the final 4D volumes. Figure 12 shows the closest time difference comparison that can be made between a full OBN LoFS monitor 4D and the snapshot 4D. The noise level of the snapshot is higher than compared to a full monitor, but 4D signal is clearly visible

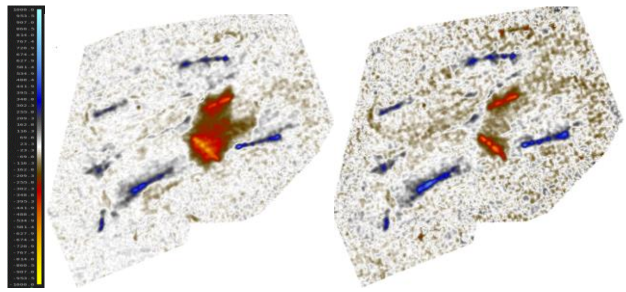

Figure 12: OBN dRMS maps. Left: Full shot Baseline to Monitor 3, 2013-2016. Right: Limited shot snapshot 2013-2017. Although slightly noisier, the 4D signal is still clearly visible on the snapshot. Note, 4D signal is different due to different time periods. The red area dimming shows re-pressuring, which is to be expected from 2016-2017.

Meanwhile, the streamer-to-streamer 4D processing was running parallel to the snapshot 4D. Figure 13 shows the closest time difference comparison that can be made between the convention streamer 4D and the snapshot 4D. Here we see the noise level is similar, but the snapshot has better resolution.

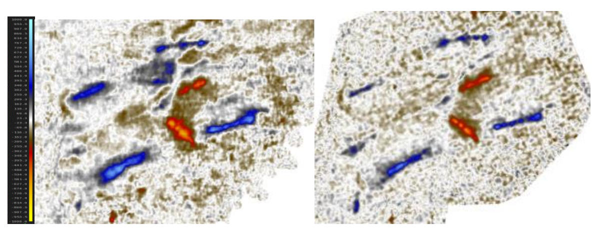

Figure 13: Streamer and OBN dRMS maps. Left is is the streamer-to-streamer from 1999-2017. Right is the snapshot from 2013-2017. 4D signal should be similar as there was little production before 2013.

Conclusions

The successful execution of the both the conventional 4D and the snapshot 4D has helped improve the subsurface understanding of these fields and allowed quick identification and de-risking of in-fill opportunities. The conventional 4D achieved a 6% NRMS, which are qualities usually only seen in OBN-to-OBN 4D surveys. The convention 4D result is so good that it almost negated the need for the snapshot 4D. However, without the snapshot 4D for confirmation it would have been difficult to gauge how well the conventional 4D results are in terms of noise content and resolution.

The activation of the LoFS system during the streamer survey turned out to be a prudent decision. This acquisition has proved that we can confidently reduce the number of acquisition lines and shots thereby allowing us to save significant costs in the future monitors. As well, a monitor for 2018 was able to be delayed into later years as a result of this work. This work has greatly increased the confidence and reliability of 4D signal with streamer and ocean bottom node data.

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