A MAZ case study from the Jequitinhonha basin, Brazil: combining legacy conventional with dual-sensor towed-streamer data.

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Abstract

This paper describes aspects of the acquisition and processing of a three-survey multi-azimuth experiment in the Jequitinhonha Basin offshore Brazil. Two new surveys were acquired using a dual-sensor towed streamer over an area already covered by a legacy conventional hydrophone-only streamer survey. The three datasets were processed simultaneously through a broadband and multi-azimuth compliant processing sequence, providing significant uplift in bandwidth, illumination and signal-to-noise.

Introduction

Multi-azimuth (MAZ) acquisition refers to towed streamer surveys that combine two or more passes over the same area, using a narrow-azimuth (NAZ) spread, where each pass has a different sail-line orientation (Barley and Summers, 2007). A key objective of a MAZ survey is to provide better subsurface illumination by improving the source-receiver azimuthal sampling. This provides a dataset that comes closer to meeting the requirements for optimal seismic imaging compared to a single NAZ survey (Long *et al.*, 2006). This technique has been used in several hydrocarbon provinces around the world, in particular the Nile delta (e.g. Keggin *et al.*, 2006) as well as the Campos basin in Brazil (Cooke *et al.,* 2011).

MAZ acquisition also achieves significantly higher CMP fold, bringing improved signal-to-noise on the final stacked images. However, this benefit is often secondary to the gains from improved illumination (figure 1).

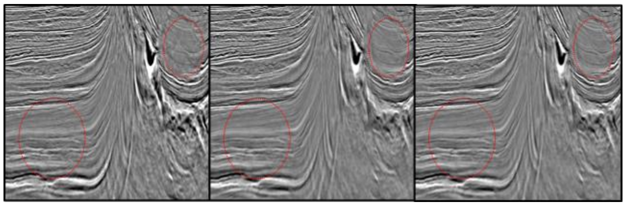

Figure 1: The image from a NAZ stack (75-fold, left) is improved with better azimuthal sampling even if fold is unchanged (75-fold MAZ stack, middle). Further gains in signal-to-noise are observed on the 225-fold MAZ stack (right).

Dual-sensor technology overview

Previous publications have described in detail the important differences between hydrophone-only and dual-sensor towed streamers (e.g. Carlson *et al.*, 2007, Tenghamn *et al.,* 2007, Long *et al.,* 2008 and Reiser, 2012). For this work it is only necessary to provide a summary of the key aspects.

Conventional hydrophone-only towed streamers record the total pressure wave-field and subsequently suffer from a “receiver ghost” – a consequence of the streamer’s tow depth and the sea-surface reflectivity, causing energy to be scattered downwards from the sea-surface to the receiver. The ghost manifests itself as a time-delayed reflection of opposite polarity that interferes continuously with the desired up-going wave-field, significantly limiting the usable bandwidth and introducing uncertainties in the phase and amplitude of the data.

A dual-sensor towed streamer, comprising co-located pressure sensors and particle-velocity sensors, provides a dataset from which the receiver ghost can be removed using wave-field separation techniques. Traditional pressure recordings from hydrophones are combined with the equivalent vertical component of particle velocity recordings providing the up-going pressure wave-field. This dataset is free the sea-surface effects associated with the receiver and consequently has a significantly broader bandwidth.

In addition to generating ghost reflections, the sea-surface is also a significant source of ambient noise observed on seismic data. The ability to perform wave-field separation to address the receiver ghost allows the streamer to be towed much deeper, providing significant improvements in signal-to-noise without compromising bandwidth. The deeper tow depth also provides stronger low-frequency content, leading to improved signal penetration.

Acquiring surveys with dual-sensor streamer is more efficient as the data quality is less affected by weather conditions, meaning less down-time and an extended window for field operations.

Furthermore, the resulting seismic images have greater value for interpretation, reservoir characterization and monitoring. The cleaner, broader bandwidth data has better resolution, providing improved calibration with well logs, allowing more precise reservoir properties to be derived with increased confidence.

Case Study Overview

Many of Brazil's offshore basins are covered by large 3D exploration seismic datasets but prior to the large pre-salt discoveries – such as the Tupi field in July 2006, now called Lula – many of the survey objectives were the shallower post-salt reservoirs.

From February to April 2006, the M/V Ramform Valiant acquired 4900sqkm of 3D data over blocks BM-J-4 and 5 of Brazil's Jequitinhonha basin, using a spread of ten hydrophone-only streamers. Subsequent processing and re-processing efforts provided high-quality images typical for the geological setting and available imaging technology. However, the deeper targets identified subsequent to the acquisition proved challenging to understand due to poor illumination and signal penetration.

Re-surveying over areas of existing 3D data is not unusual, in particular when prospect objectives change or technology developments allow better data to be acquired, improving subsurface images (Comeaux *et al.,* 2013).

The velocity and structural information over a subset of the legacy Jequitinhonha dataset were used to create a synthetic model from which the illumination could be studied using different acquisition geometries (figure 2).

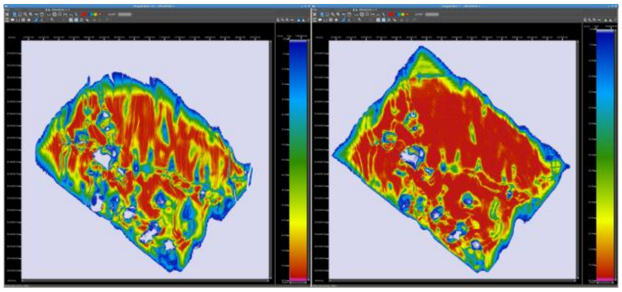

Figure 2: Modeled Illumination of a target horizon using a single pass acquired N/S (left) and three passes combined (right). Red indicates good illumination; blue indicates poor illumination.

Two new passes of acquisition were chosen – N/S and NNW/SSE to compliment the legacy survey acquired E/W – and the M/V Ramform Valiant returned to the prospect in April 2011 equipped with a spread of ten dual-sensor streamers.

Survey Matching

To create a single image the data from the different acquisition passes had to be matched in time, amplitude and phase. Information from all three datasets was combined in a simultaneous water-column static solution, correcting for timing differences between the passes. However, the matching of amplitude and phase required consideration of the different characteristics of the hydrophone-only and dual-sensor streamer data.

The field deliverable from the two new passes of acquisition was the up-going pressure wave-field output from the wave-field separation. The field deliverable from the legacy survey was the total pressure wave-field, which suffers from the effects of the receiver ghost.

Two approaches were available to harmonize the data: 1) impose a receiver ghost on the new data, or; 2) use a processing solution to de-ghost the legacy data.

A work flow for option 1 was presented by Day *et al.* (2010) as part of a time-lapse experiment conducted on data acquired using hydrophone-only and dual-sensor streamers. They demonstrated how separated wave-fields can be used to recreate the total pressure wave-field at different streamer depths. However, this option was not appropriate for the MAZ exercise as it effectively throws away much of the useful information expected to help achieve the objectives of the experiment. Instead, the methodology described by Tabti *et al.* (2009) was used to de-ghost the legacy data.

Wave-field separation of dual-sensor data

The success of wave-field separation using dual-sensor data typical of deep-water Brazil is demonstrated clearly in figure 3 where the vertical particle-velocity and pressures recordings have been combined to produce the up-going pressure wave-field. The wavelet associated with the receiver ghost is very apparent on the input data due to the nominal 15m tow depth. The precise character of the receiver ghost of the water bottom reflection is perfectly mimicked on both the pressure and particle velocity measurements allowing a successful wave-field separation.

Also noteworthy in this example is the undulating character of the receiver ghost along the streamer compared to the smoothly varying water-bottom reflection. The difference in the arrival times of these two events is related to the distance between the streamer and the sea-surface, so this pattern suggests this distance is changing along the cable.

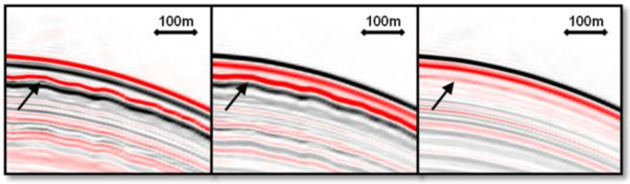

Figure 3: Zoom over a common shot gather showing the recording of the vertical particle-velocity sensor (left), pressure sensor (middle) and the resulting up-going pressure wave-field (right). The receiver ghost stands over clearly on the two inputs but is absent on the up-going pressure data.

Observations made in the field show this sail-line was acquired in seas with up to four meter swells – equating to a ~25% variation from the nominal tow depth – so the position and control of the streamer in the water column could provide an explanation for this character. (The survey was acquired using typical streamer depth control units designed to maintain the required depth within industry-standard tolerances.)

Another explanation is the shape of the sea-surface above the streamer at the time of acquisition. In reality, the behavior of the sea-surface is more complicated than can be defined simply by the average or range in wave height. It is in a continuous state of flux so the character of the seismic signal reflected back as the ghost will be constantly changing in time and space. Orji *et al*. (2009) describe how dual-sensor streamer data can be used to image the sea-surface providing some support to this as a plausible explanation for the variations. The ideas were further developed and tested using modeled and real data in a later work, Orji *et al*. (2012).

No attempt was made to image the sea-surface, nor to quantify the variations in any detail. However, deviations from the measured cable depth derived from the receiver ghost arrival times were plotted for some of typical dual-sensor data from Brazil (figure 4).

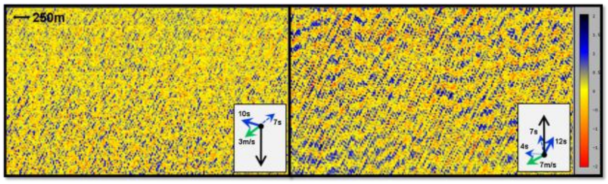

Figure 4: Plot of receiver depth deviations from the measured cable depth: vertical axis is channel; horizontal axis is shot. The annotations show the regional estimates for the dominant direction(s) of swell (blue) and wind (green); the black arrow shows the sail-line direction.

De-ghosting of hydrophone-only data

The precise cause of sea-surface variations is much less significant for dual-sensor data as both sensors observe the same character, at the same location and at the same time. The example shown in figure 3 provides a clear illustration of the receiver ghost of the water bottom reflector but it is important to remember that it will have a complicated and time-varying interaction with the desired signal throughout the data. As the sea-surface changes so too will the character of the ghost, with the impact becoming more significant as frequency increases (Tabti *et al.,* 2009).

De-ghosting techniques applied to conventional hydrophone-only streamer data must necessarily simplify this behavior by making assumptions about the average sea-state and streamer depth. This may limit the success of the process in correctly addressing the ghost, especially if the sea-state is varying in the manner observed on the dual-sensor data.

Hydrophone-only data before and after de-ghosting is compared with up-going pressure data from one of the dual-sensor passes (figure 5) demonstrating the desired broadening of the bandwidth and shaping of the spectra, though some differences remain at both the low and high frequencies.

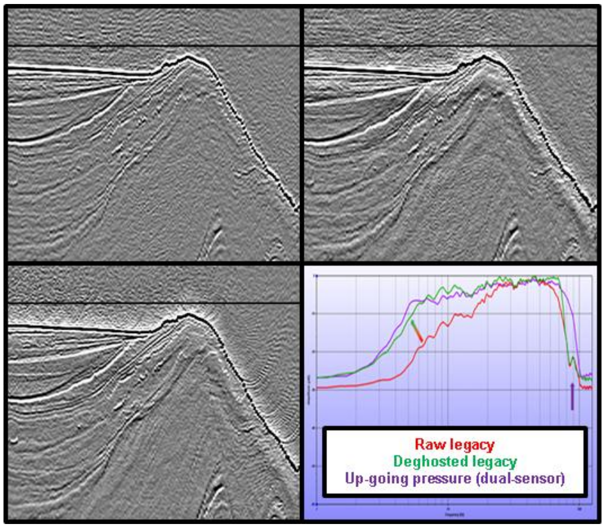

Figure 5: Single-fold time-migrated offset planes and their amplitude spectra: raw hydrophone-only data (top left), de-ghosted hydrophone-only data (top right), dual-sensor data (bottom left). Note the log-scale used for the frequency axis on the amplitude spectra (bottom right).

An examination of time-migrated gathers demonstrates noticeably higher levels of noise on the de-ghosted hydrophone-only data (figure 6). This is explained by the assumptions made about the sea-surface during de-ghosting of the hydrophone-only data. Its character suggests the stack response could suppress much of the noise but alternative tools would be required if the gathers were needed for AVO or inversion studies.

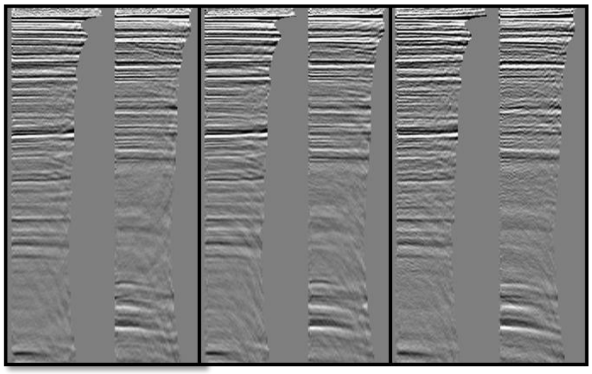

Figure 6: Coincident time-migrated gathers from the dual-sensor N/S pass (left), NNW/SSE pass (middle) and hydrophone-only E/W pass (right). Note the higher noise levels on the hydrophone only data.

The different noise levels are further illustrated by examining differences between the datasets. While the three passes are coincident and some of the processing stages can be considered compliant with time-lapse processing requirements, this comparison is not a rigorous time-lapse analysis because the source and receiver positions are significantly different. The impact of these differences can be partially mitigated by reviewing the simpler structures in the shallow section and by application of constrained local residual matching.

Analysis of amplitude spectra suggest minimal variation with frequency for the difference between the two dual-sensor passes, while the magnitude of the difference increases with frequency for the hydrophone-only data (figure 7). For MAZ images, the higher CMP fold should reduce the impact of this sea-surface related noise but it would prove detrimental to 4D-signal on time-lapse studies.

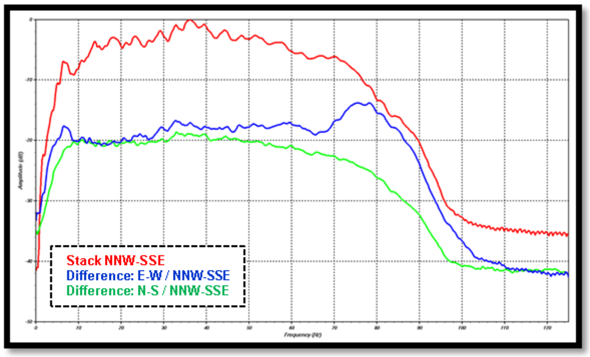

Figure 7: Amplitude spectra from a single dual-sensor dataset (red) compared to the differences between the two dual-sensor datasets (green) and between the NNW/SSE pass and the hydrophone-only data (blue). The lobe around 70-85Hz corresponds to the receiver-ghost notch on the hydrophone-only data.

Final Imaging

The presence of large salt bodies and the general structural complexity means anisotropic depth migration is required to extract greatest benefit from the dataset. This paper frames the results in terms of Kirchhoff pre-stack depth migration; further discussion and alternative imaging methods applied to the same data are presented by Comeaux *et al.,* (2013).

A single, anisotropic velocity model was developed using tools that simultaneously consider all three passes. This allows well illuminated areas, perhaps visible only on one pass to guide the velocity updates (figure 8).

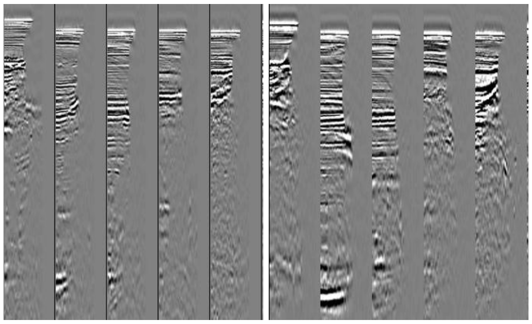

Figure 8: Coincident depth migrated gathers from the E/W pass (left) and the N/S pass (right). Information from one pass alone would be insufficient to derive the correct velocity model; combining all passes allows faster, more accurate and confident convergence during each update.

Comparison of migrated images from single and all acquisition passes clearly demonstrates the uplift in imaging of steep dips and reflections below salt (figure 9). The shallow sections, which do not suffer poor illumination, are almost identical.

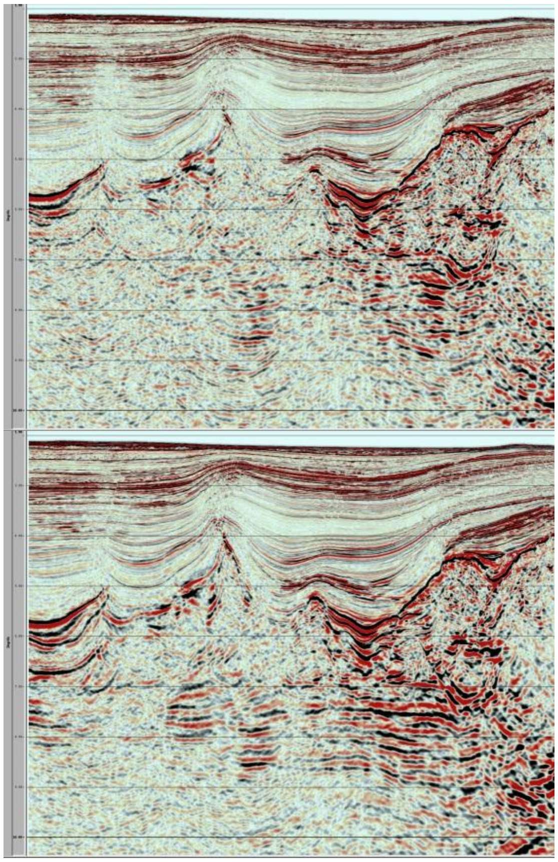

Figure 9: 3D TTI Kirchhoff pre-stack depth migrated images for single NAZ (top) and MAZ (bottom).

Conclusions

Data from legacy and new acquisition were successfully combined for a multi-azimuth study in the Jequitinhonha Basin. The anticipated improvements in illumination and signal-to-noise were realized, demonstrating the potential for efficient MAZ surveys in the basins of Brazil where existing 3D seismic already exists.

The simultaneous processing of hydrophone-only and dual-sensor data provided an opportunity to explore methods for utilizing the full benefits of different data types. Wave-field separation techniques applied to dual-sensor data demonstrate the impact of the sea-surface on seismic images, in particular regarding characteristics of the receiver-ghost. De-ghosting tools provide the potential for improving the match of hydrophone-only data with wave-field separated data, but some of the assumptions made will limit their success in fully addressing the impact of the sea-surface on bandwidth and noise. Though some of these limitations were discussed in the context of MAZ they are also applicable to other acquisition designs and time-lapse studies.

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