Campos Basin 4D study. A Case Study Integrating Conventional Hydrophone and Multisensor Towed Streamer for monitoring the Albacora Leste field

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Introduction

Time-lapse (4D) reservoir monitoring consists of acquiring several 3D seismic data at different stages of a field life and analysing differences in seismic images (4D signal). The variation in these time-lapse images provides insights into the dynamic fluid and pressure changes due to production effects. To enhance the quality of the 4D signal, exclusive time-lapse marine acquisitions require similar recording sensor types and steerable navigation equipment to ensure the repeatability of sources and receiver locations. However, Multi-Client seismic data is often acquired with efficiency in mind and is not usually optimum for 4D monitoring purposes, as the fundamental 4D principle of "repeating acquisition design" is generally not followed.

In this 4D case study, conducted in the Campos Basin, Brazil, we demonstrate that is possible to extract reliable field production information with relaxed constraints on the acquisition repeatability. We show how conventional shallow towed single hydrophone streamer data can be combined with deep towed multisensor acquisition data to monitor the production of the Albacora Leste field.

The Albacora Leste field, is located in the northern area of the Campos Basin about 120 km from Cabo de São Tomé with water depths ranging from 1000 to 2000 m. Discovered in 1986, the Albacora Leste Oil Field began its production in 2006. The field consist of Miocene sandstones units with high porosity and permeability. After the deposition stage, erosive channels introduced flow barriers that resulted in reservoir compartmentalisation (Lemos, 2006). the presence of low-impedance shale and interlaminated rocks (very thin shale/sandstone stacked sequences) causes negative-amplitude seismic responses. Typically, the low impedance shale and the interlaminated rocks can be identified through amplitude variation-with-offset (AVO) study and elastic inversion. However, in the case of Albacora Leste, this approach was challenged by the weak seismic resolution. Models indicate the manifestation of the small gas thicknesses observed in the drilled wells. Because of seismic interference effects, such thin gas presence would not have been detected in 3D AVO study. The hope is that 4D study will provide additional reservoir production information on fluid saturation and pressure changes.

4D Albacora Leste monitoring project

For this 4D project, the baseline data consists of a HD3D seismic, using high density of reflection points, acquired in 2005. In 2022, an 'opportunistic' monitor survey was conducted on the same area with the objective of gathering information of fluid and pressure changes in the reservoir targets. The term 'opportunistic' is used here, as opposed to 4D exclusive surveys, because the 2005 Baseline data was part of a multi-client library (TGS) and the 2022 Monitor data have been acquired using a different streamer configuration. The 2005 acquisition azimuth, sail lines, and dual source configuration were replicated as closely as possible for the 2022 survey (Figure 1). However, the shot positions were not repeated. On the receiver side, the baseline data was recorded using shallow tow (7m) hydrophone only streamers, while the monitor has been acquired with deep-towed (20m) multisensor cables providing a broadband seismic signal. The number of streamers and the separation distance was the same for both surveys.

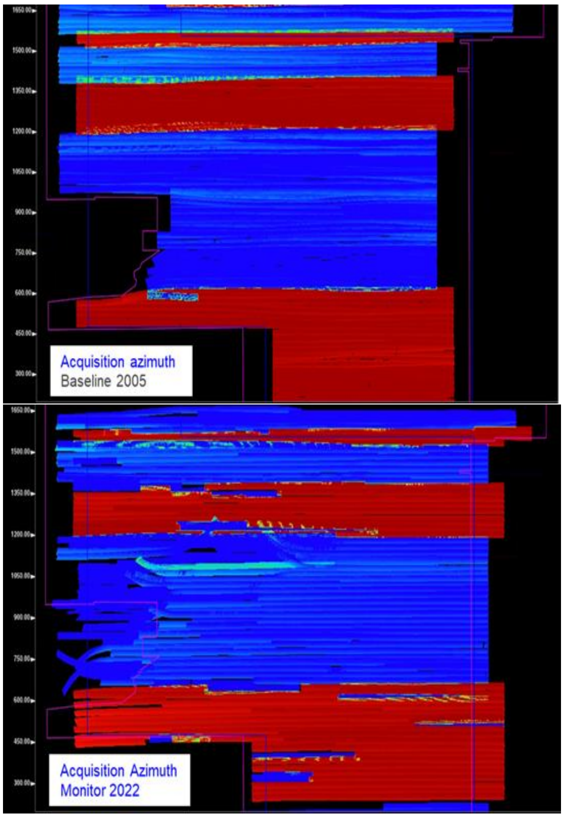

Figure 1: Acquisition Azimuth maps for the 2005 Baseline and for the 2022 Monitor. Red and blue colours represent the direction of the acquisition.

To enhance the seismic resolution, our strategy, already validated in West Africa 4D cases (Reiser et al., 2018), is to extend the 4D signal bandwidth by combining the deghosted (2005 Baseline) hydrophone data and the up-going wavefield data intrinsically produced by the deep tow multi-sensor streamer (2022 Monitor). In practice, the 2005 data recorded with the conventional shallow streamer is deghosted with a deterministic operator using the nominal source and receiver depth and could create a direct 4D comparison with the ghost-free up-going data of the monitor survey.

Data processing for 4D LSM imaging

To overcome the significant challenge of the acquisition differences, we implemented a 4D Least Squares Migration approach (LSM). This is a combination of 4D least-square imaging technology alongside specific 4D processing steps, which was the first instance of its application in the Albacora-Leste. Three key processing steps have been reviewed and adjusted to optimize the 4D LSM imaging result: 4D Binning, 4D Matching and 4D Denoise.

4D Binning

The aim of 4D binning is to ensure maximum uniformity in source-receiver location between the baseline and monitor data, without compromising the trace density needed for interpolation and regularization procedures. In our case of no-repeated source and receiver location, the 4D binning process was essential for optimally selecting trace pairs.
The sum of the source pair distance and receiver pair distance (denoted as dS+dR) is commonly used as a geometrical threshold to reject non-repeatable trace pairs. Analysing the dS+dR attributes mapped for a near and a far offset classes. It can be observed that most trace pairs fall below the limit of 100 m for the near offset, while the far offset has a larger statistical distribution. Consequently, we defined an adjustable threshold of geometry dS+dR in conjunction of a minimum of NRMS to maintain good repeatability without compromising trace-pair coverage for each offset class. This approach limits large areas with missing trace pair, facilitating signal regularization and interpolation before data migration.

4D Matching

In addition to the conventional pre-migration global matching steps, a specific local matching procedure was developed to cross-equalize the baseline and monitor signal spectra in the angle domain.
For the baseline data, the goal of deterministic source and receiver side deghosting was to enhance the hydrophone signal (band-limited data) to match the broader bandwidth of the monitor up-going wavefield data as closely as possible. Assuming a flat sea surface, the deterministic operator uses the nominal source and receiver depth.
However, inaccuracies in cable depth measurement and/or high swell conditions can cause undesirable artifacts, seen as residual ghost mismatches, which can affect the repeatability of the 4D data. A joint 4D matching process is designed for each angle-traces to mitigate residual effects on the baseline dataset. These joint operators are constrained by frequency dependant signal-to-noise to ensure signal-only matching. In addition, operators are computed with an adaptive time window, resulting in the matching filter 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 shorter for the high frequencies.
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.

4D Denoise

Despite advanced 4D joint matching process to handle the signal calibration, we still observed some 4D noise remaining in the seismic differences. This noise is likely due to the non-repeated shot and significant streamer feathering issues. The residual noise primarily appears at the edges of the signal bandwidth (below 8 Hz and above 60 Hz) and should be addressed as a function of a wave numbers. To tackle this, we performed 4D denoising in the curvelet domain which decompose the images into wave number bands. Figure 2 shows the results of the 4D denoising application.

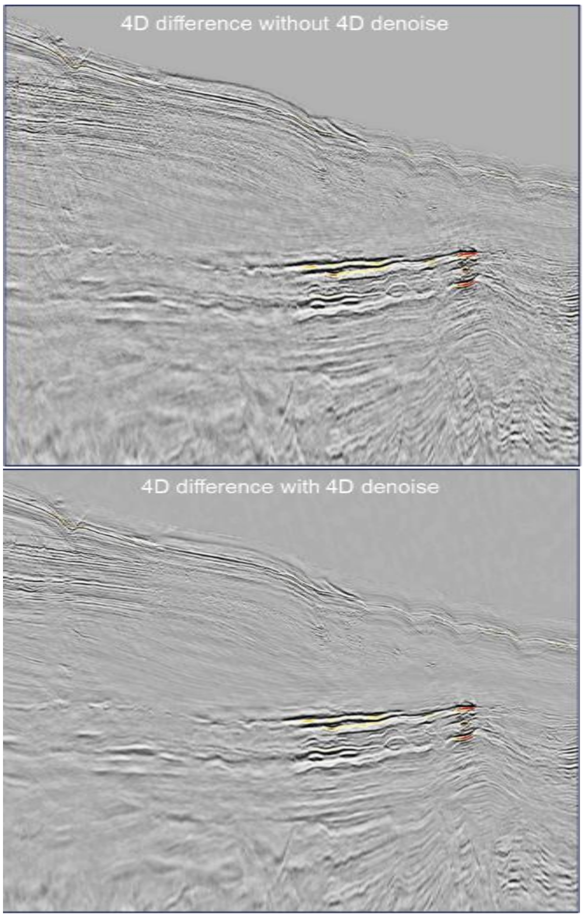

Figure 2: 4D differences without (left) and with (right) the 4D denoise in curvelet domain.

4D Least-Square Kirchhoff Migration (LSK)

Due to the presence of thin sandstone layers in the Albacora Leste reservoir, advanced imaging technology, such as least-square migration, was evaluated to push the boundaries of the seismic resolution in both 3D and 4D context. We tested the capabilities, and constraints, of a 4D joint Least-Squares Kirchhoff migration solution, which compensates for multi-dimensional illumination variability and recovers legitimate reflectivity changes due to the reservoir production.
The 4D LSK methodology used in this study is based on image-domain reflectivity inversion using Point Spread Functions (PSFs). Our two-step imaging method recovers reflectivity by explicitly computing multi-dimensional PSFs and deconvolving accordingly the final pre-stack migrated image. We introduced a 4D formulation that is

independent of geological and reservoir production constraints by incorporating the concept of cross-survey PSFs (Lecerf, 2018). Working in the image domain allows our solution to directly evaluate and compensate for illumination discrepancies from various data acquisition geometries at any location in the 4D image. Recovering reflectivity images involves regaining high wavenumbers of the signal, which are challenging to repeat and can introduce some extra 4D noise. It is crucial to control this recovery process in both 3D and 4D contexts simultaneously. We developed a specific quality control (QC) workflow that examines Amplitude Versus Angle (AVA) consistency between reflectivity angle gathers and 4D differences. Figure 3 shows the comparison of 3D and 4D images resolution between conventional Kirchhoff migration and the Least-Square Kirchhoff approach. We can observe how the 4D signal change within the various thin layers present in the reservoir.

Conclusion

This "opportunistic" Albacora Leste 4D case study has combined a 2005 Multi-Client Baseline dataset, acquired with shallow towed conventional hydrophone streamer, with a 2022 Monitor dataset acquired with deep towed multi-sensor streamer. One of the 4D imaging challenge was to accommodate the two types of streamer and non-repeated shot positions for computing an accurate 4D signal. Through specific 4D processing sequences and a Least-Square Kirchhoff imaging approach, we succeed to improve the seismic signal resolution and be able to detect consistent fluid saturation and pressure changes within thin sandstone layers within the reservoirs.
This 4D Albacora Leste project has enable us to map and better understand the longstanding production of this complex and compartmentalized reservoir composed of turbiditic stacked channels with the aim of identifying new business opportunities.

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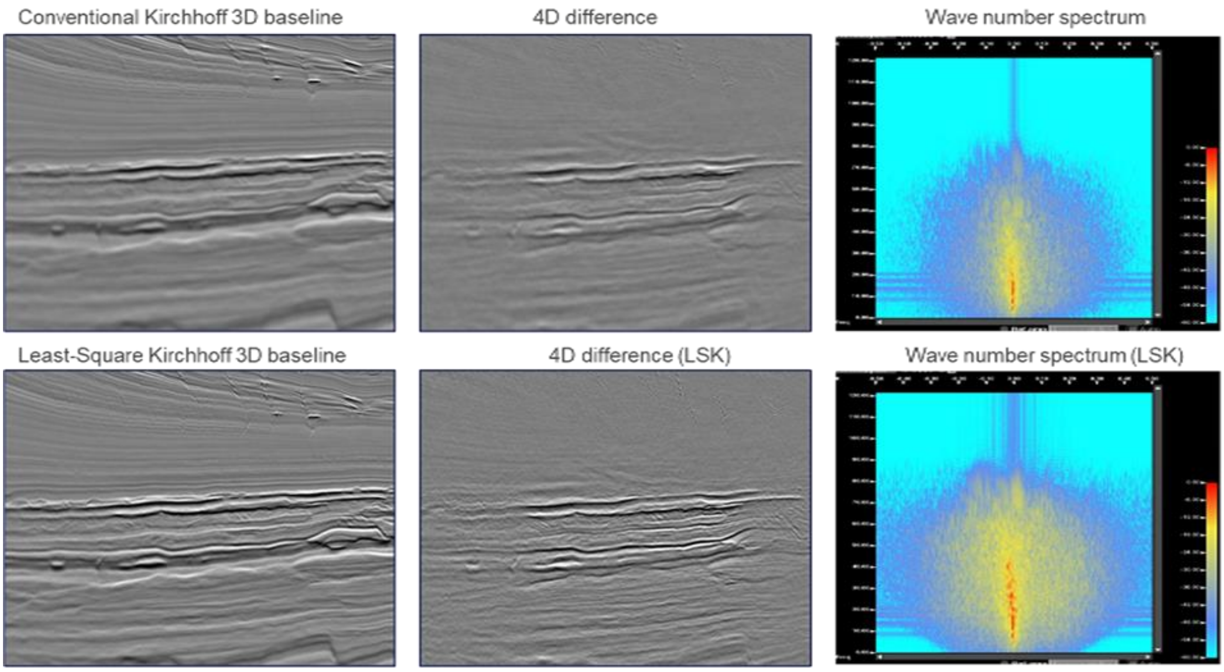

Figure 3: Effect of the Least-Square Kirchhoff migration (LSK) on the 3D seismic images (left), on the 4D differences (central) and the corresponding wave number analyses (right).