Optimized Traditional 4D Binning with Primary and Secondary Trace Integration – Usan Field

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Summary

It is widely accepted that 4D binning has a fundamental impact on the final data quality of time-lapse (4D) seismic volumes. Traditionally 4D binning is based on acquisition repeatability, using a principle such as minimum difference in source and receiver positions (ΔSrcRcv) between base and monitor surveys. This approach is sometimes combined with additional criteria such as data quality attributes. Binning is a pre-requisite for migration which requires uniform coverage: one trace per bin per offset class.

Often monitor surveys are acquired over tighter crossline sampling to ensure good repeatability on the receiver side (for streamer surveys), even though binning will reject many of these traces. Our approach is similar to the conventional approach, but we look to address signal to noise issues by using greater than a single fold data per vintage per offset and thus maximize the value of acquisition effort (Chu et al., 2024).

This paper presents an enhanced binning strategy that includes selections of both the best (primary or rank 1) and second-best (secondary or rank2) pairs of ΔSrcRcv. We then use regularization and co-denoise; however, the co-denoise and destriping is applied between the primary and secondary traces rather than between vintages. This reduces the risk of damaging the 4D signal but enables a significant reduction in noise which in turn leads to significant improvements in repeatability measurements such as Normalized Root Mean Square (NRMS) (Christie, 2002). We demonstrate this on the Usan field, offshore Nigeria.

Introduction

The Usan field, situated offshore in West Africa, presents a geologically intricate environment defined by a shale-cored anticline and a three-way dip closure. Its steeply dipping flanks, radial faulting, and thin, laterally confined channel sands pose considerable challenges for seismic imaging. Effectively monitoring subsurface changes and managing the reservoir in such a setting necessitates the application of advanced and precise seismic processing techniques. In this complex framework, even small, incremental advancements in processing can accumulate to deliver a significantly enhanced 4D seismic product, ensuring more accurate and reliable insights

In 4D seismic processing, achieving high repeatability between surveys is essential for accurately detecting subsurface changes. Acquisition repeatability, often assessed using ΔSrcRcv, guides the selection of the best matching traces for 4D binning (Helgerud, 2011). Traditional binning focuses on traces with the lowest ΔSrcRcv values (primary traces). However, even the best-matching traces can have relatively high ΔSrcRcv values in some cases, introducing noise, artifacts, and higher NRMS, which can degrade seismic image quality.

The geological complexity and subsidence challenges of the Usan field further underscore the importance of improving seismic repeatability and reducing NRMS for precise reservoir monitoring. To address these issues, we propose integrating secondary trace selections with advanced regularization and cooperative denoising techniques. This approach optimally leverages available data, minimizes artifacts, and enhances the integrity of the 4D signal.

By combining these strategies, we aim to produce high-quality 4D seismic data, ensuring better repeatability and reliable insights for effective reservoir management and decision-making.

Methods and Description

In traditional 4D binning, traces are selected based on the minimal value for the sum of the source positioning differences (ΔSrc) and the receiver positioning differences (ΔRcv), measured between the baseline and monitor surveys. This criterion, known as the minimum ΔSrcRcv selection or primary traces, aims to enhance the repeatability of seismic data. Reciprocity, where source and receiver locations are interchangeable in the calculation, can be enabled or disabled in this process, in our case, the source and notional streamer depths are very similar, and still reciprocity was invoked. Activating reciprocity is generally preferred, as it ensures more accurate and reliable ΔSrcRcv values, enhancing the overall authenticity of the trace selection process. However, even with reciprocity enabled, this method can include traces with high/anomalous ΔSrcRcv values, introducing significant noise and artifacts into the seismic dataset and potentially degrading the quality of the 4D

Traces with high ΔSrcRcv values often contribute to pronounced striping patterns in the NRMS maps, highlighting areas with elevated NRMS values and poor repeatability. These stripe patterns can lead to migration swings, further degrading the quality of the 4D seismic data. To address this, it is crucial to QC the NRMS maps in conjunction with ΔSrcRcv values to establish effective rejection criteria for maintaining the 4D data quality. To mitigate the impact of high ΔSrcRcv traces, a systematic rejection process is implemented to exclude those traces

Better optimized trace rejection workflow would minimize the impact of high ΔSrcRcv values on the NRMS maps, ensuring a high-quality less stripy dataset and reducing the likelihood of migration artifacts caused by flawed rejection criteria.

Once the optimal trace selection method is established, the next step is to determine how to retain as many acquired traces as possible while ensuring they contribute to improved 4D quality and repeatability rather than being discarded

Use of secondary traces:

To maximize the use of existing data and reduce trace pair rejection in our 4D binning workflow, we incorporated a secondary selection of traces with the second-best ΔSrcRcv values (Chu, 2024). The aim is to determine whether these secondary traces can enhance the dataset by supplementing bins that already contain primary traces. This approach seeks to improve data utility, robustness, and continuity, thereby enhancing repeatability and overall image quality.

However, secondary traces, selected with relaxed ΔSrcRcv criteria, often exhibit higher ΔSrcRcv values, making them more prone to noise and striping patterns that can challenge data quality. To manage this, a rejection criterion is applied to exclude problematic secondary traces. This rejection, while seeming necessary, can leave gaps in the secondary volume, which may challenge regularization leading to amplitude fidelity loss. To address this issue, strategies are implemented to fill these gaps in the secondary traces volume These include borrowing traces from the primary selection or replacing problematic secondary traces with a weighted combination of primary and secondary traces. In this weighted approach, the higher-quality primary traces (selected based on higher S/N and lower NRMS) are prioritized, maintaining data integrity while still leveraging the supplementary benefits of secondary traces. Another strategy involves guiding the regularization process using primary trace pairs as a reference.

By integrating these strategies, relaxing rejection criteria, filling gaps with primary traces, or using weighted combinations or implementing guided regularization—this workflow ensures the controlled and effective inclusion of secondary traces. The result is a balanced, efficient process that improves the dataset's overall quality, continuity, and utility, ultimately delivering better auxiliary volume required for the purpose.

Regularization and Hole Filling:

Once the secondary trace pairs volume is strategically created, the next critical step is to focus on the respective regularization process. It is important to recognize that we are effectively regularizing both the primary and secondary volumes independently. While this increases computational costs, it is a necessary step to fill in gaps, enhance geological continuity, and prepare the dataset for subsequent processes like co-denoising. At this stage in our 4D seismic processing workflow, independent regularization of primary and secondary traces ensures the integrity and overall quality of the dataset. Regularization is essential for improving spatial coherence, maintaining geological continuity, and generating a more reliable seismic image while ensuring that the original traces remain unaltered and only the missing information is reconstructed

To achieve this, we employed Matching Pursuit Fourier Interpolation (MPFI) algorithm, we achieve precise interpolation of missing data and alignment of the dataset according to inherent geological structures. This capability is crucial in complex geological environments like the Usan field, where maintaining the continuity of steeply dipping flanks, weak events, and intricate structural features is essential for accurate interpretation. MPFI's strengths lie in its ability to handle irregular sampling and promote sparsity, ensuring that the detailed geological characteristics of the subsurface are preserved and highlighted in the final processed dataset.

Targeted Denoising for secondary traces:

After regularizing the primary and secondary traces, we proceed to refine the secondary traces, ensuring they contribute positively to the final seismic dataset. This step involves addressing the inherent noise in secondary traces and aligning them more closely with the quality of the primary traces through a detailed analysis and denoising process. To start, we employ a technique called 'quotient trace analyses (Hoffe, et al., 1999). We generate a quotient trace by dividing the amplitude envelope of each secondary trace by the corresponding primary trace in a 3D sense within the same bin. This comparison is crucial for evaluating the relative quality and behavior of the secondary traces against the more reliable primary traces. The envelope-based quotient provides a robust measure for noise levels of secondary traces. Through this analysis, we can identify secondary traces that deviate significantly from their primary counterparts. Traces with a quotient far from unity indicate higher noise levels or inconsistencies, flagging them as candidates for further denoising or, in extreme cases, rejection. This step is essential for maintaining the overall quality of the data set, ensuring that only traces that add value are included in the final output. Next, we focus on denoising the secondary traces using a targeted denoise process. This method is tailored to reduce noise specifically in the secondary traces without impacting the primary traces. By concentrating on the noise characteristics identified in the quotient analysis, the targeted denoise selectively attenuates noise while preserving the integrity of the true 4D signal. This targeted denoising approach ensures that even though secondary traces might initially be noisier, they can be refined and become valuable supplementary data in the overall 4D binning procedure. Through the combined use of quotient trace analysis and targeted denoising, we effectively enhance the usability of secondary traces. This process allows these traces to serve as a significant supplementary component to the primary traces, thereby contributing to a high-quality, comprehensive 4D seismic dataset and much lesser wastage of the trace pairs. It is worth mentioning that the co-denoising processes inherently carry the risk of damaging the 4D signal; however, our co-denoise workflow (as detailed above) for secondary traces was designed to mitigate this risk by safeguarding the 4D signal.

4D signal safeguarding was achieved by retaining the highest coefficients in the curvelet domain and iteratively reconstructing the signal. This approach ensured that the true 4D signal remained intact, allowing us to optimally parameterize the co-denoise without inadvertently attenuating important signal changes.

Integration and QC of the final 4D Binning product:

After refining the secondary traces through quotient trace analysis and targeted denoising, the next step in our 4D binning workflow involves integrating the primary and secondary traces (Campbell, 2015). This integration is achieved by summing the primary and secondary volumes, creating a comprehensive dataset that optimally leverages the available trace pairs. By combining the robustness of the primary traces with the enhanced quality of the carefully denoised secondary traces, this workflow maximizes data utility and efficiency.

The coherent 4D signals from both trace types combine linearly, reinforcing true subsurface changes, while the random noise, being uncorrelated, adds in quadrature, minimizing its impact. The careful alignment and processing of the secondary traces ensure that their inclusion enhances the dataset without introducing additional noise. Practically, this approach significantly improves the repeatability and clarity of the 4D seismic data, as evidenced by a marked reduction in NRMS values. Even though secondary traces may initially carry more noise, their thoughtful incorporation strengthens the overall dataset quality, making this methodology both robust and impactful.

Besides, pre-migration stacking of the primary and secondary volumes may be a more cost-effective option, especially when budget constraints are a factor. However, post-migration stacking has been observed to produce better repeatability. This approach requires migrating each volume separately before stacking, effectively doubling the computational cost. One key advantage of post-migration stacking is that certain 4D processing workflows, such as co-denoising, become easier to apply, minimizing the risk of distorting the 4D signal (Chu, 2024). If the improved repeatability and processing flexibility outweigh the additional cost, this method is worth considering for future projects to enhance 4D confidence and interpretability.

To confirm the effectiveness of our approach, we conducted thorough QC's particularly focusing on the reservoir zone. The results showed a significant improvement, with the reservoir zone appearing cleaner and more coherent. The enhanced repeatability and reduced noise levels facilitated a clearer interpretation of the subsurface changes.

Results

In this section, we evaluate the effectiveness of our enhanced 4D binning and denoising strategy using 4D difference and NRMS QC displays for a specified window (spanning from 100ms below the water bottom to the end of the reservoir horizon). Figures 1a, 1b, and 1c showcase primary traces, secondary traces, and denoised secondary traces for the target crossline section, respectively. Figures 1d and 1e display the sum of primary and secondary traces, both with and without denoised secondary traces. Notably, figure 1f illustrates the difference between the 4D differences of the primary traces and the proposed solution (summation of primary and denoised secondary traces), clearly indicating that no 4D signal (indicated by black oval shape in fig 1d) is compromised. While secondary traces provide additional data, they inherently bring more noise and exhibit noticeable stripes, as indicated by red arrows in Figures 1b and 1d. This increased noise results from their higher ΔSrcRcv values compared to primary traces. However, targeted denoising, as indicated by black arrows in Figures 1c and 1e, significantly reduces this noise

The NRMS QC maps for secondary traces in Figure 2b show higher and more variable values due to the increased noise and striping inherent in these traces, which is resolved in the denoised secondary traces as seen in Figure 2c. Figure 2d still shows the presence of stripe when the denoised secondary traces are not used, whereas Figure 2e clearly shows that the NRMS display is free of stripe. Figure 2f highlights this reduction, with NRMS values decreasing from a mean value of 28.6 % to 22.7 %. This reduction in NRMS values signifies enhanced repeatability and signal integrity, resulting in clearer and more reliable seismic interpretations

Conclusion

In summary, the integration of primary and secondary traces within the simple traditional 4D binning strategy has enriched the dataset, significantly enhancing the quality and repeatability of 4D seismic data. By incorporating secondary traces alongside advanced regularization and targeted denoising techniques, this refined approach offers notable improvements over traditional methods. It effectively reduces NRMS, enhances data quality, and ensures the preservation of the 4D signal integrity.

Applied successfully in the complex geological setting of the Usan field, this dual-trace methodology establishes a new standard for 4D binning. It not only improves the clarity and reliability of 4D seismic data but also provides a more detailed and accurate understanding of reservoir dynamics over time—all while maintaining operational efficiency with minimal additional resources

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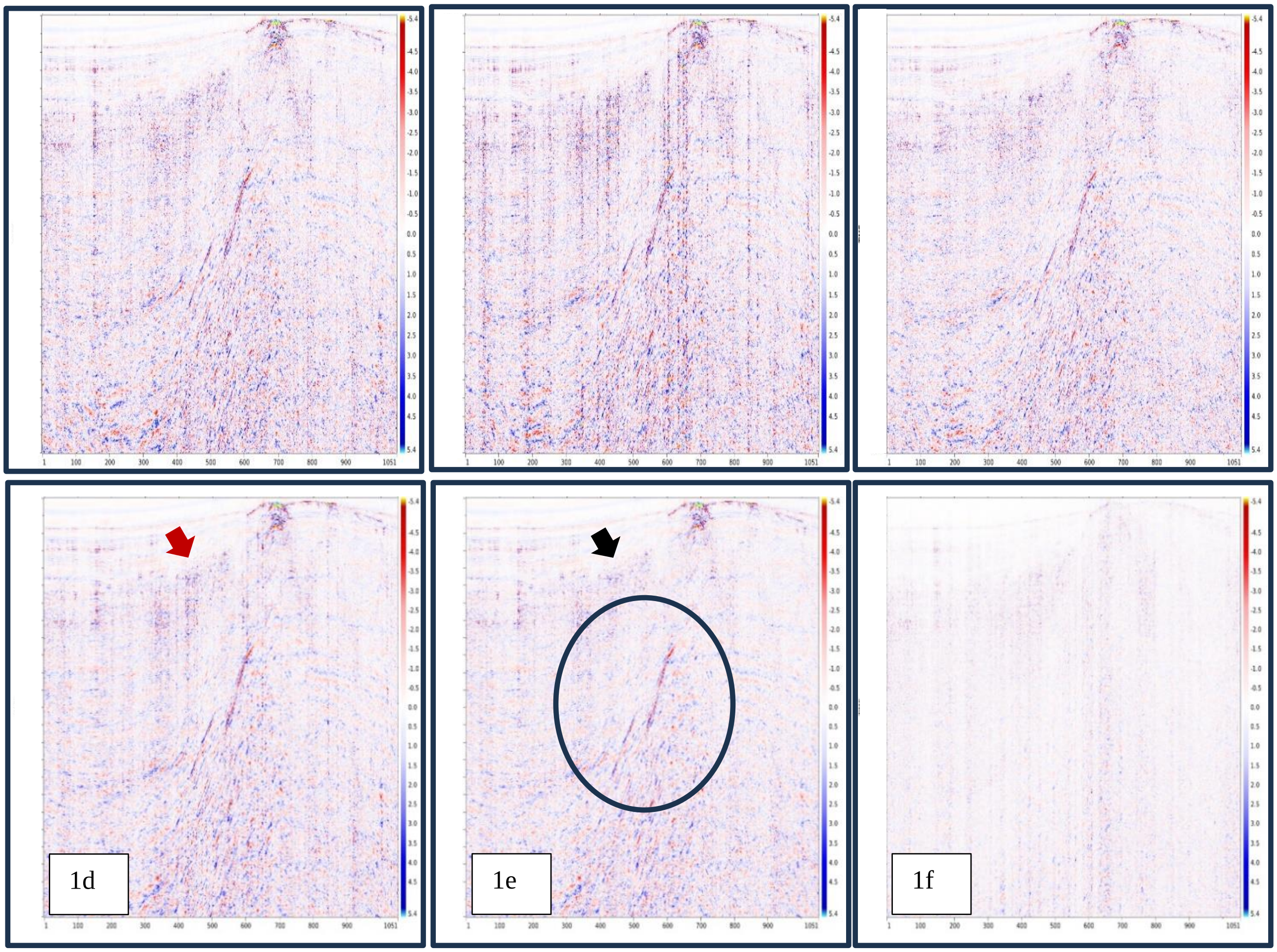

Figure 1 – Top row left to right: a) Primary traces difference of a crossline section. b) Secondary traces difference. c) Denoised secondary traces difference. Bottom row left to right: d) Primary 'plus' secondary traces difference. e) Primary 'plus' denoised secondary traces. f) Difference of the difference (a) minus (e) …

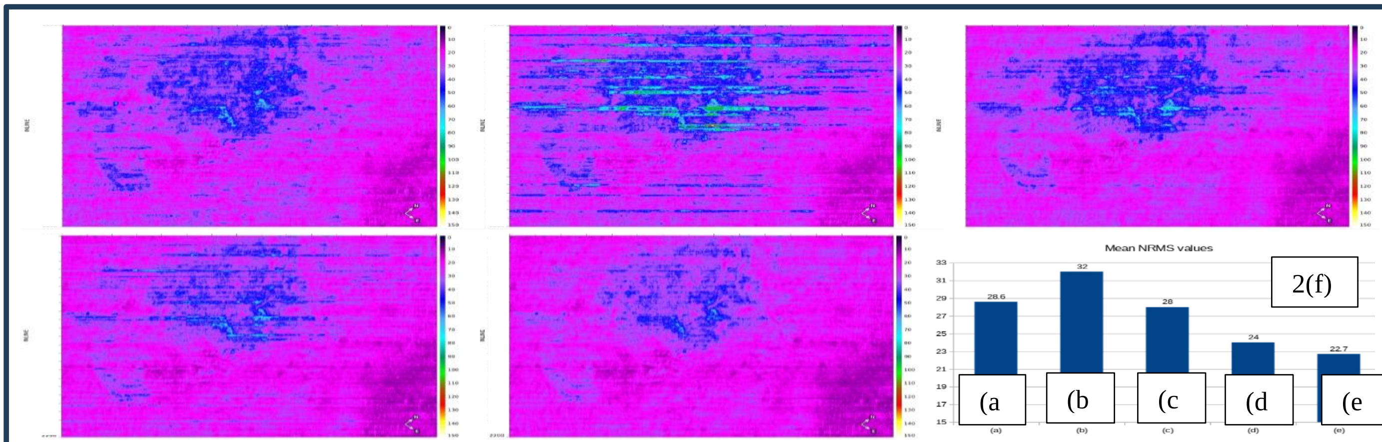

Figure 2 – Top row left to right: a) Primary traces NRMS b) Secondary traces NRMS. c) Denoised secondary traces NRMS Bottom row left to right: d) Primary 'plus' secondary traces NRMS. e) Primary 'plus' denoised secondary traces NRMS. f) Mean NRMS at each

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