Reliable Imaging with Sparse WAZ via NAZ-Guided 4D Regularization

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SUMMARY

Wide-azimuth (WAZ) towed streamer acquisition provides enhanced directional illumination but inherently produces irregular midpoint distributions and crossline offset-dependent coverage gaps. These limitations degrade spatial continuity and can introduce migration noise, particularly in Kirchhoff-based imaging workflows. As fully sampling WAZ geometries would require a drastic increase in sail line density, such gaps are an unavoidable characteristic of practical acquisition designs.

We present a Narrow Azimuth (NAZ) guided 4D Fourier-domain regularization workflow that restores spatial continuity while preserving the illumination advantages of WAZ data. The method combines Anti-Leakage Fourier Transform (ALFT) regularization with azimuth-aware conditioning and selective integration of narrow-azimuth (NAZ) data. The resulting dataset demonstrates improved sampling consistency, reduced acquisition footprint, and enhanced imaging quality without compromising azimuthal diversity or increasing acquisition cost.

INTRODUCTION

Wide-azimuth seismic acquisition has become increasingly important in complex geological environments, where improved illumination is required to resolve subsurface structures beneath complex geology such salt, faulted systems, or areas with strong lateral velocity variations. By sampling a broader range of azimuths, WAZ surveys provide additional wavefield diversity that benefits both imaging and reservoir characterization.

This advantage comes with a fundamental limitation. WAZ acquisition geometries are not designed to produce uniform midpoint and offset sampling. Instead, they generate irregular spatial coverage with offset-dependent gaps that vary across azimuth directions. These gaps manifest as acquisition footprint, striping in time and depth slices, and instability in migration results.

In practice, achieving fully populated WAZ coverage would require a drastic increase in acquisition effort, including tighter sail line spacing (or wider tow sources) and higher operational cost. As a result, incomplete sampling is accepted as a necessary trade-off for improved illumination.

The Angola MC3D Gemini (Udengaard et al., 2023) Mini-WAZ survey provides a clear example of the acquisition challenges associated with wide-azimuth marine geometries. The project combines two complementary datasets: a WAZ component acquired by the Oceanic Champion source vessel, and a densely sampled NAZ component acquired by the Ramform Tethys source-and-streamer vessel (Figure 1). Together, these datasets offer both the broad azimuthal illumination characteristic of WAZ acquisition and the uniform spatial sampling typical of NAZ geometry. This complementary pairing enables a processing-based approach to compensate for WAZ sampling gaps (Figure 2) without requiring additional acquisition passes or modifications to the survey design. The objective of this work is to develop a workflow that leverages the strengths of both datasets while preserving the physical illumination characteristics unique to each acquisition mode.

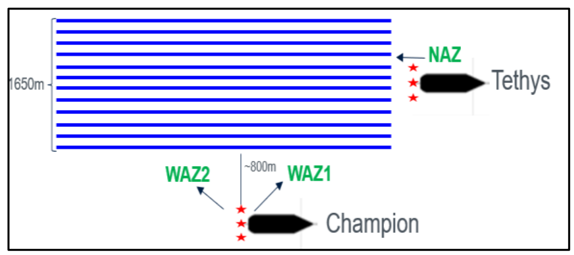

Figure 1 - 3D Mini WAZ Acquisition Configuration Scheme

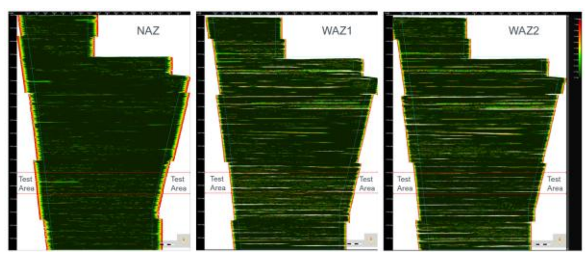

Figure 2 - Full Offset Coverage Plots for each azimuth

THEORY AND METHODOLOGY

The proposed workflow is built on the principle that NAZ and WAZ datasets contain complementary sampling characteristics. While the 3D Mini WAZ acquisition is not sparse in terms of streamer density, its midpoint and offset–azimuth sampling becomes uneven due to large sail-line spacing, strong feathering, operational positioning challenges, and azimuth-dependent illumination. This leads to systematic unpopulated CMP bins and offset gaps, especially in the near- and far-offset ranges. In contrast, the NAZ component provides dense and uniform spatial sampling, though with limited azimuth diversity. Rather than forcing WAZ into a fully regular grid through aggressive interpolation, we use the stable NAZ sampling as a physically consistent constraint to guide the reconstruction of missing WAZ coverage.

The methodology begins with a comprehensive preconditioning sequence applied to both NAZ and WAZ datasets to ensure they enter regularization with compatible wavelet, phase, and amplitude characteristics. This preconditioning includes inversion based deblending, wavefield separation (receiver-side deghost), and source-side deghosting, designature, 3D SRME demultiple, wavelet processing, and multi-stage noise attenuation. These steps harmonize the broadband content of both acquisitions and minimize acquisition-specific biases before interpolation.

Following amplitude, phase, and spectral alignment, the data are reformatted onto a common grid and partitioned into three azimuthal sectors — (1) NAZ, (2) WAZ1 (0–180°), and (3) WAZ2 (180–360°) — to preserve the directional illumination inherent to each component during subsequent multidimensional regularization.

Regularization is performed using a 4D Anti-Leakage Fourier Transform (ALFT) approach (Schonewille *et al.,* 2009). The method operates simultaneously across inline, crossline, offset, and time dimensions, allowing interpolation to honor both spatial and offset continuity. ALFT iteratively estimates the Fourier spectrum of the data by extracting dominant spectral components, reconstructing them on a regular grid, and removing them from the residual. This process continues until the spectrum is sufficiently represented, enabling reconstruction of missing traces while minimizing aliasing and spectral leakage.

A key aspect of the workflow is azimuth-aware conditioning through redundant offset rejection. For NAZ data, traces closest to the inline (E–W) direction are preferentially retained, while for WAZ data, traces aligned with the crossline (N–S) direction are prioritized. This ensures that each dataset preserves its intrinsic illumination characteristics and avoids artificial mixing of azimuthal information.

Following 4D regularization, midpoint positions are relocated to bin centers, and the data are resampled onto a consistent grid of 25 m inline by 12.5 m crossline with 200 m offset spacing. Despite these improvements, WAZ data still exhibits residual gaps in specific offset classes and CMP bins, reflecting acquisition limitations that cannot be fully resolved through interpolation alone.
To address these gaps, we introduce a selective NAZ-guided infill strategy. Only regions with insufficient WAZ coverage are populated using the regularized NAZ volume, with careful enforcement of midpoint alignment and offset consistency. This targeted approach preserves the directional illumination of WAZ data while restoring spatial continuity in poorly sampled regions.

RESULTS

The effectiveness of the workflow is evaluated through a comprehensive set of quality control analyses, including pre-processing domain diagnostics and migrated image assessment.

In the pre-processing domain, common-offset planes at near, mid, and far offsets (e.g., 1200 m, 3200 m, and 5200 m) show clear improvements in spatial continuity following regularization. Time slices exhibit a significant reduction in striping and acquisition footprint, while FK spectra demonstrate improved signal focusing and reduced spectral leakage. Diffraction energy, particularly steeply dipping events, is more accurately represented after regularization, indicating successful de-aliasing and interpolation.

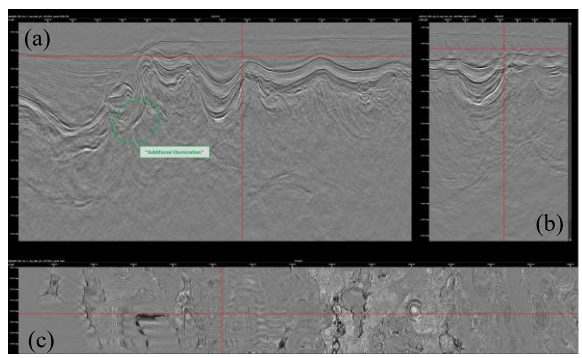

Figure 3 - KPSDM Common Offset 1200m: Inline (a), Crossline (b) and Depth Slice (c) using WAZ1 Only.

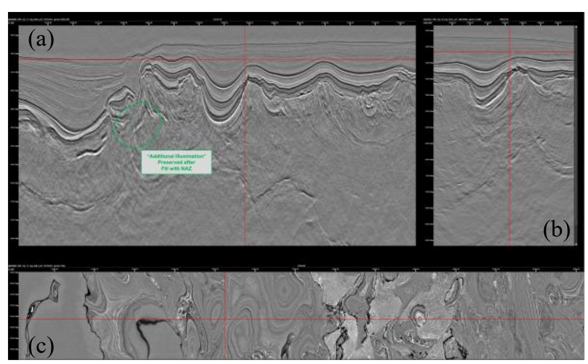

Figure 4 - KPSDM Common Offset 1200m: Inline (a), Crossline (b) and Depth Slice (c) using NAZ Guided 4D Regularization

The impact of the workflow is further validated in the migrated domain using Kirchhoff Prestack Depth Migration (KPSDM). Angle stacks and depth slices reveal enhanced reflector continuity and improved fault delineation. Areas previously dominated by acquisition gaps (Figure 3) show increased fold and more coherent imaging (Figure 4). Comparisons between WAZ-only and NAZ-Guided results demonstrate that the additional illumination provided by WAZ is preserved, while discontinuities associated with missing coverage are effectively mitigated.

Common Imaging Gather analysis further confirms the improvement in sampling density and stability in the near and far angles (Figure 5). After regularization, gathers display more uniform trace distribution across offsets, reducing shot and CMP cycling artifacts. Importantly, the integration of NAZ data into WAZ gaps enhances continuity without introducing inconsistencies between datasets.

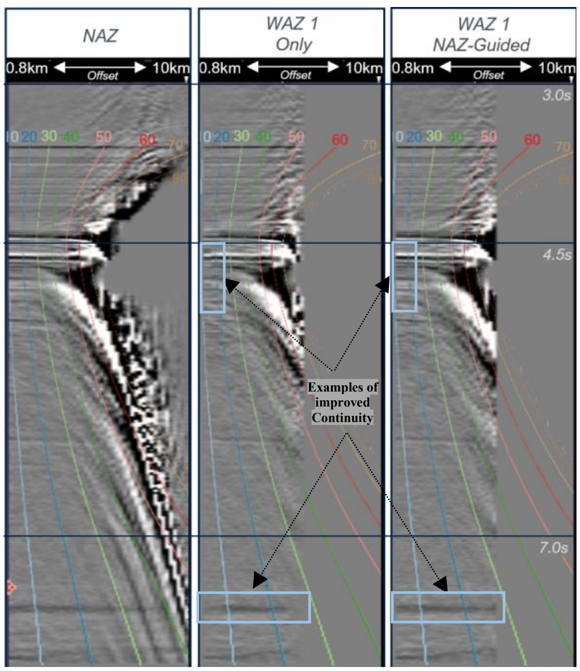

Figure 5 KPSDM Common Imaging Gathers (Stretched to time) of the NAZ data, WAZ1 Only and WAZ 1 NAZ-Guided. Colour overlays shows True Walden Reflection Angle in degrees (Yilmaz, 2001)

Amplitude behavior is assessed through RMS analysis across multiple offset planes and four time windows referenced to the Water Bottom Time (WBT): a WBT-centered window (WBT−200 ms to WBT+200 ms), a Shallow window (WBT+200 ms to WBT+1500 ms), a Deep window (WBT+1500 ms to WBT+3500 ms). The resulting RMS maps show improved lateral consistency and amplitude balance across the survey area, particularly in regions previously affected by uneven WAZ sampling. After NAZ-guided infill, amplitudes stabilize across offset classes while preserving the relative variations associated with true WAZ illumination (Figures 6 and 7).

Coverage maps at representative offsets illustrate this balance clearly. Before regularization, WAZ data exhibits significant gaps and uneven fold distribution. After ALFT regularization and NAZ-guided infill, these gaps are largely eliminated, and the fold becomes more uniform. At the same time, the characteristic illumination patterns of WAZ acquisition are retained, confirming that the workflow does not compromise directional information.

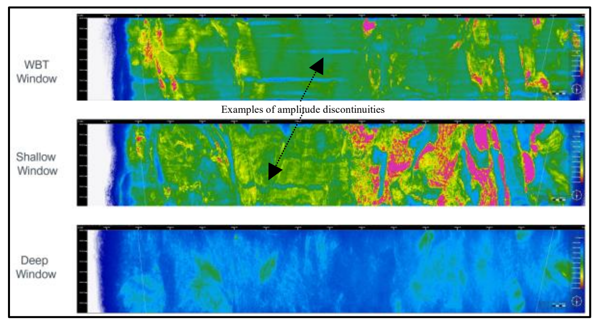

Figure 6 - RMS Maps of KPSDM Common Offset 2200m – WAZ1 Only

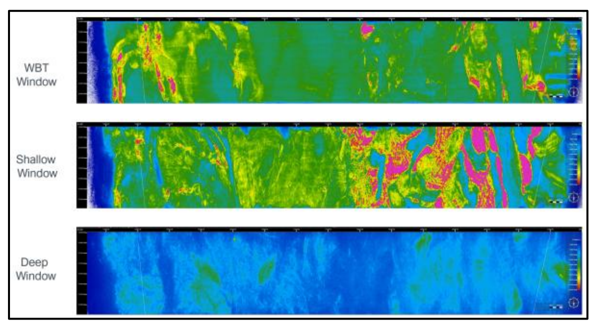

Figure 7 - RMS Maps of KPSDM Common Offset 2200m – WAZ1 using NAZ Guided 4D Regularization – Amplitude discontinuities are minimized compared to Figure 6.

DISCUSSION

The results demonstrate that 4D regularization combined with NAZ-guided integration provides a robust solution to one of the key challenges in modern seismic acquisition: the trade-off between illumination and sampling density. Traditional interpolation methods often rely on purely mathematical reconstruction, which can lead to over-smoothing or loss of directional information. In contrast, the proposed approach leverages physically consistent constraints derived from complementary datasets.

An important observation is that not all WAZ gaps should be treated equally. Some gaps correspond to regions where illumination is inherently limited, while others result from acquisition geometry constraints. By selectively filling only the latter using NAZ data, the workflow avoids introducing artificial coherence and maintains the integrity of the seismic response.

The approach is also scalable and compatible with standard processing workflows, making it suitable for large 3D surveys. As multi-azimuth acquisition becomes more prevalent, such integration strategies will be essential for maximizing data value without incurring additional acquisition cost.

CONCLUSION

We have developed a NAZ-guided 4D regularization workflow that effectively mitigates some of the sparse sampling limitations of WAZ acquisition. By combining ALFT-based interpolation with azimuth-aware conditioning and selective data integration, the method restores spatial continuity while preserving directional illumination.

The workflow demonstrates clear improvements in sampling density, amplitude stability, and imaging quality, as validated through both pre-processing diagnostics and migrated image analysis. Crucially, these benefits are achieved without increasing acquisition effort, providing a cost-effective solution for modern multi-azimuth surveys.
As wide- and multi-azimuth acquisition continues to expand in complex environments, robust processing techniques such as this will play a critical role in ensuring high-quality, reliable imaging.

ACKNOWLEDGMENTS

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