Ocean-bottom node survey shot geometry optimization – a FWI oriented study

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Summary

Ultra-long offset sparse Ocean Bottom Node (OBN) acquisition delivers full-azimuth coverage and long offsets, which are crucial for leveraging Full Waveform Inversion to resolve complex subsurface geology. However, these high-profile surveys come with significant operational costs, making it essential to find an optimal balance between cost efficiency and FWI benefits. In this study, we investigate various shooting strategies based on real large-scale sparse OBN surveys, focusing on the performance of Dynamic Matching FWI through both synthetic and real field data experiments. Our results demonstrate that reducing sail line density in the outer shot halo beyond 10 km and reallocating resources to extend the shot halo aperture is an effective approach. This strategy enhances operational efficiency while maintaining FWI performance.

Introduction

Ultra-long offset Ocean Bottom Node (OBN) surveys have recently gained traction in the Gulf of Mexico (GOM), driving significant improvements in velocity model building and subsurface imaging. Their full-azimuth illumination, rich low-frequency content, and ultra-long offsets enable more robust Full Waveform Inversion (FWI) compared to conventional surveys (Roende et al, 2020, Huang et al, 2023, Jonke et al, 2024). However, these enhanced capabilities come with high operational costs, prompting a need for more cost-effective acquisition strategies. Several studies have explored the trade-offs between cost reduction and imaging quality (e.g., Olofsson et al, 2012, Ahmed, 2018, Chakraborty et al., 2017). Yet, many of these focus on imaging quality and/or diving wave illumination rather than the impact of shot geometry to the capability of FWI. Consequently, an in-depth examination of shot density beyond 10 km from the node carpet and its effect on FWI remains essential as optimized acquisition time reduced operation, HSE and environmental exposures.

The motivation for this work is to analyze the impact of shot grid design on the performance of FWI and to provide technical support to the operational strategy for future sparse OBN acquisitions.

Method

This study incorporates both synthetic and real field data. The synthetic dataset models a swath of 480 ocean bottom nodes over a 20km x 30km area using acoustic modeling. The nodes are spaced at 1200m x 1200m, aligning with many real sparse OBN projects in the Gulf of Mexico. The water depth in this swath ranges from 900m to 1100m. Baseline survey design also simulates many real sparse OBN acquisitions, featuring a shot geometry of 50m x 100m and a 20km shot halo. Every three shot lines form a sequence, mimicking a triple-source acquisition. Several derivative scenarios are designed based on this baseline (Figure 1):

1. **Decimate-by-Two** – Every other sequence beyond the 10km shot halo is removed, reducing the crossline spacing between sequences to 600m in the outer halo (10km–20km shot halo).
2. **Decimate-by-Three** – Further reduces the crossline spacing between sequences to 900m.
3. **Decimate-by-Two-Extend** – Builds on the decimate-by-two scenario by reallocating saved resources to extend half of the remaining sequences to a 30km shot halo.
4. **75m x 75m Shot Grid** – Maintains the baseline design but adopts a denser 75m x 75m shot grid.

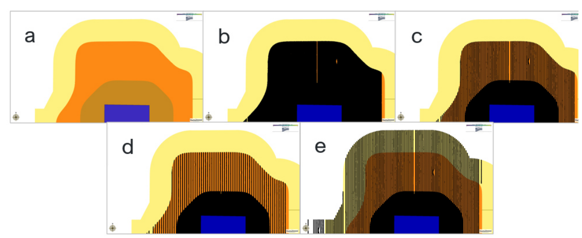

Figure 1: Synthetic shot geometries. (a). The acquisition layout. From bottom to top: node patch, 10km shot halo, 20km shot halo, 30km shot halo. (b). Baseline geometry (50m x 100m). (c). Decimate-by-Two. (d). Decimate-by-Three. (e). Decimate-by-Two-Extend. The 75m x 75m shot grid is not display, it is the same as the baseline scenario, but a different grid.

A checkerboard model (Pageot et al.,2013) with 2 km cubes and ±200 m/s perturbations below the base of salt (BOS) is constructed as the ground-truth velocity model, built on top of a real GOM model serving as the FWI initial model. The density field is derived accordingly using Gardner's equation. Synthetic OBN records are then generated for each shot geometry. To evaluate the resolution capability of these checkerboard perturbations, Dynamic Matching Full Waveform Inversion (Mao et al, 2020) is applied up to 4 Hz.

In addition to the synthetic tests, real field data experiments are conducted using the baseline and decimate-by-two scenarios on a large multi-client sparse OBN survey in the

Mississippi Canyon and Atwater Valley, GOM. The 4 Hz FWI models are evaluated using 12Hz RTM.

Synthetic Examples

Despite the records being synthetically modeled, the baseline model resembles real Mississippi Canyon geology that contains large-scale structures such as salt feeders, salt canopies, and small-scale structures such as rafted carbonate carapaces (Figure 2).

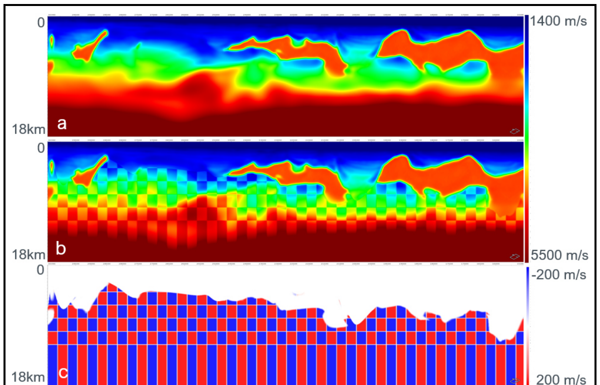

Figure 2: Synthetic study models: (a). the initial model which resembles real Mississippi Canyon geology. (b). The checkerboard model. (c). Checkerboard perturbations with 2 km cubes and +/- 200 m/s velocity errors.

The baseline scenario effectively resolves the checkerboard perturbations. At velocity contrast boundaries, we observe the FWI solution appears smoother than the ground truth (Figure 3b), resulting in red and blue frames in the deviation map (ground truth minus baseline 4Hz FWI model, Figure 3c). This smoothing effect is expected for a 4Hz solution and is commonly observed at velocity discontinuities in real FWI-driven velocity model building (VMB), such as the “salt halo artifact”. As the inversion frequency increases, the velocity contrasts become more sharply defined. Within the node patch, we observe good reconstruction of the checkerboard pattern. However, in the shot halo zone, distortions become more noticeable as we move toward the edges (Figures 4b, 4c, 4d), primarily due to unbalanced shot illumination. In this region, particularly near the edges, illumination is dominated by a limited azimuth range, unlike the full-azimuth coverage inside the node patch. With a 20 km shot halo, reliable reconstruction extends up to 10 km outside the node patch at the general subsalt sediment basin level, around 7–8 km depth.

The decimate-by-two scenario does not show significant degradation (Figure 4c). A detailed comparison between the baseline and decimate-by-two scenarios reveals no noticeable bias (Figure 3d); the differences are neutral and within 20 m/s (two standard deviations). However, the precision in resolving velocity contrasts is slightly reduced. Further reducing the shot density, the decimate-by-three scenario leads to a more pronounced loss of accuracy, as expected, with deviations from the baseline reaching 40 m/s (two standard deviations, Figure 3e). While the decimate-by-two scenario remains acceptable, decimate-by-three will start creating noticeable errors in velocity inversion and depthing of events.

By reallocating acquisition time saved from decimating the outer shot halo to extend the remaining sequences to a 30 km shot halo, the decimate-by-two-extend scenario introduces notable improvements (Figure 4e). First, the longer offsets enable updates to extend further, enhancing reliable checkerboard reconstruction up to approximately 15 km outside the node patch at the general subsalt sediment basin level. More importantly, even within the node patch, the reconstruction quality surpasses that of the baseline solution (Figure 3f). Though the improvements are subtle (two standard deviations = 10 m/s), this suggests that trading off shot density in the outer halo (10–20 km) for increased offsets is a viable strategy within a fixed operational cost.

Adjusting the shot grid from 50m x 100m to 75m x 75m does not bring significant changes. Strictly speaking, the 75m x 75m shot grid produces updates that is closer to the ground truth (Figure 3g), however, the difference is practically negligible (two standard deviations = 5 m/s).

Field Examples

The large multi-client sparse OBN survey used in the real data experiment features a nominal node spacing of 1200 m × 1200 m and a source spacing of 50 m × 100 m, with an 18 km shot halo. For the baseline shot geometry, we use the data as-is. In the decimate-by-two scenario, every other sail sequence is removed between 10 km and 18 km. Acoustic DMFWI is then run from 1.6 Hz to 4 Hz, using the same initial model as in the synthetic study (Figure 2a).

We compare the imaging results between these two scenarios. In both cases, deblended hydrophone data is used in DMFWI, with velocity updates applied without any constraints. Migration is performed using the underlying pre-processed WAZ data. Velocity models before and after FWI for the two shot geometries are shown in Figures 5a, 5b, and 5c, where decimation occurs to the left of the dashed line. The results indicate that the final FWI models for both shot geometries are nearly identical, with no visible transition imprint around the decimated area.

RTM images from the baseline shot geometry (Figure 5d) and the decimate-by-two scenario (Figure 5e) further confirm this observation, showing negligible differences between them that would not change interpretation of exploration targets nor other key parts of petroleum system as a whole. These field data results reinforce that decimating the outer shot halo is a viable strategy for improving operational efficiency without compromising FWI performance.

Conclusions

For ultra-long offset sparse OBN surveys with a shot halo extending beyond 10 km, both synthetic and real data studies confirm that decimating the sail sequence beyond the 10 km shot halo—reducing the crossline shot spacing to 600 m—is an effective strategy for improving operational efficiency without compromising FWI performance. However, further decimation clearly pushes the limit.

Changing acquisition design to shorten half of the sail sequences and extending the other half to longer offsets yields significant benefits for FWI. The increased aperture enhances FWI updates, extending reliable solutions further into the shot halo. Additionally, it helps stabilize and improve velocity resolution within the core node patch. Overall, trading off shot density in the outer halo (10–20 km) for longer offsets proves to be a viable approach within a fixed operational cost.

Acknowledgements

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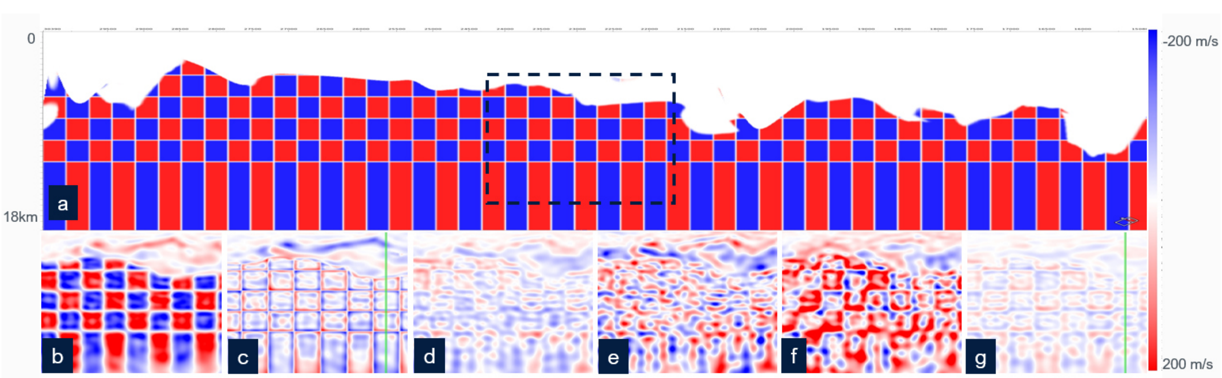

Figure 3: Checkerboard perturbation zoomed in to the node patch area. (a) Ground truth. (b) 4Hz FWI updated perturbation from the baseline shot geometry. (c) ground truth deviation (ground truth minus 4Hz FWI velocity). (d) 4Hz FWI velocity difference between the baseline and decimate-by-two scenarios. (e) 4Hz FWI velocity difference between the baseline and decimate-by-three scenarios. (f) 4Hz FWI velocity difference between the baseline and decimate-by-two-extend scenarios. The amplitude polarity and pattern similarity between (c) and (f) indicates a better checkerboard reconstruction from the 4Hz FWI velocity difference between the baseline and decimate-by-three scenario. (g) 4Hz FWI velocity difference between the baseline and the 75m x 75m shot grid scenarios.

FWI oriented shot halo decimation study for ultra-long offset sparse OBN survey

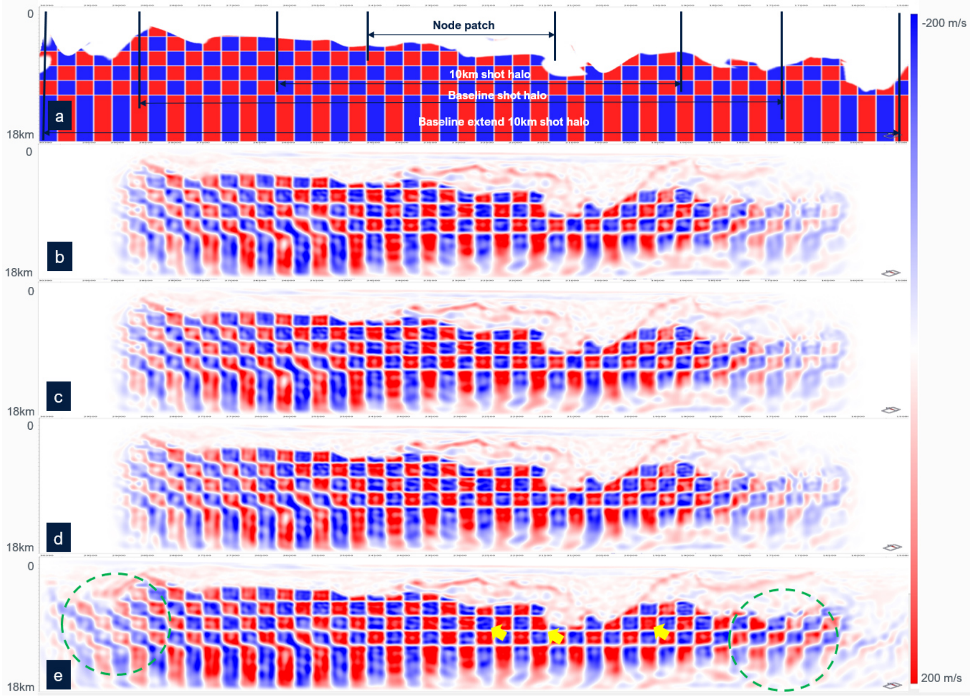

Figure 4: Checkerboard perturbation. (a) Ground truth. (b) 4Hz FWI updated perturbation from the baseline shot geometry. (c) 4Hz FWI updated perturbation from the decimate-by-two shot geometry. (d) 4Hz FWI updated perturbation from the decimate-by-three shot geometry. (e) 4Hz FWI updated perturbation from the decimate-by-two-extend shot geometry. Reliable updates extend more into the shot halo zone. Checkerboard pattern reconstruction is also better compared to other scenarios.

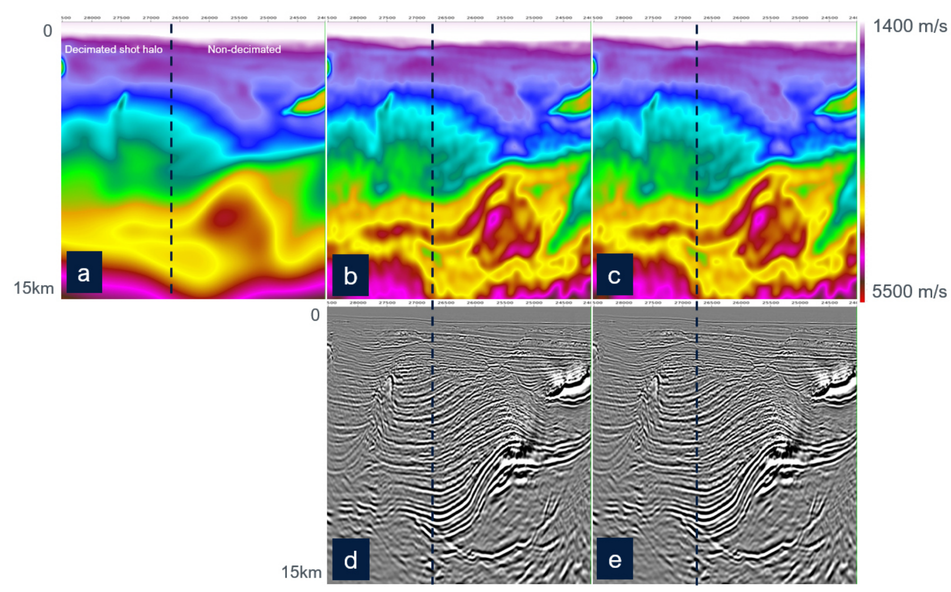

Figure 5: (a) The field data experiment initial model. (b) FWI velocity model with the baseline shot geometry. (c) FWI velocity model with the Decimate-by-Two shot geometry. (d) WAZ RTM image with model in (b). (e) WAZ RTM image with model in (c). The final FWI models for both shot geometries are nearly identical. RTM images further confirm this observation.