Title: Mitigating Airgun Seismic Interference on Phase-Sequenced Marine Vibrator Data

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Summary:

Marine vibrators (MVs) have emerged as a promising alternative to traditional airgun arrays, offering precise signal control, reduced environmental impact, and a broad frequency range. However, seismic interference (SI) from nearby airgun surveys poses challenges during MV acquisition. This study introduces a tailored SI mitigation strategy using an adaptive inversion-based de-blending algorithm designed to preserve the phase-sequencing patterns critical for accurate imaging. Through field test data with single-unit and double-unit MV configurations, we demonstrated that the proposed method effectively removes SI noise while maintaining the integrity of MV signals. The results, validated through difference plots and FK spectra analysis, highlight the robustness of this approach in addressing mixed-source interference scenarios, enabling cleaner and more reliable seismic imaging for marine vibrator acquisitions.

Key Aspects: The paper focuses on mitigating seismic interference from airgun surveys on marine vibrator data using an improved adaptive inversion-based de-blending, preserving phase-sequencing critical for seismic imaging.

Novelty: This study introduces a tailored seismic interference mitigation strategy for mixed-source interference scenarios, ensuring the integrity of MV phase-sequencing patterns while effectively removing SI noise without requiring extended record lengths.

Mitigating Airgun Seismic Interference on Phase-Sequenced Marine Vibrator Data

Introduction

Marine seismic data acquisition using marine vibrators (MVs) has emerged as a promising alternative to traditional airgun arrays due to their enhanced precision in signal control, reduced environmental impact (Southall et al., 2019), and the ability to emit broadband frequencies spanning from ultra-low to high frequencies, such as 1-150 Hz. Initial 3D alpha tests conducted over the Johan Sverdrup field in the North Sea validated the potential of MVs to deliver data comparable in quality to legacy airgun systems despite lower emitted energy levels (JafarGandomi et al., 2024). This field is operated by Equinor ASA in partnership with AkerBP ASA, TotalEnergies EP Norge AS, and Petoro AS.

A challenge encountered during MV-based acquisition is seismic interference (SI) from neighbouring airgun-array seismic sources. This interference manifests as unwanted noise patterns that obscure subsurface signals, reducing data quality. For instance, during the initial 3D alpha tests, MV data were significantly contaminated by SI from an airgun survey conducted approximately 35km away. This issue underscores the need for robust SI mitigation strategies tailored to varying acquisition scenarios, including those involving mixed-source types such as impulsive and continuous sweep sources.

This study introduces a robust methodology to mitigate airgun-related SI in MV data, utilizing advanced processing techniques that preserve the integrity of phase-sequenced sweeps. Our approach represents a significant step forward in processing MV data, protecting signal fidelity, allowing for cleaner imaging results, and improving comparability with legacy airgun acquisitions.

Marine Vibrator data acquisition setup

The MV alpha tests used diverse acquisition configurations to cover the 1-150Hz frequency range. These included single-unit MV lines covering the entire frequency band or split-frequency double-unit arrays. In the split-frequency setup, the low-band (LB) unit covered 3-25Hz, while the high-band (HB) unit handled 25-150Hz. For single-unit configurations, a 10-second nonlinear up-sweep was utilized, with phase modulation alternating between [0°, 90°, 0°, 90°, …] across successive sweeps, effectively attenuating residual sweep noise as demonstrated by Laws et al. (2019).

In the double-unit vibrator setup, the LB unit performed a 10-second sweep, while the HB unit conducted a 5-second sweep. Notably, phase modulation in the frequency-wavenumber (*f*-*k*) domain causes effects similar to spatial aliasing by replicating the spectral signal cone. This approach differs from dither-blended acquisition, where blending energy appears incoherent in common-receiver gathers. In phase-sequenced setups, events remain periodical (one may call them semi-coherent) in the common-receiver domain and coherent in the common-source domain, making traditional dither de-blending methods ineffective.

As highlighted earlier, the MV acquisition was simultaneous with an airgun acquisition with natural dithering just 35km away. This resulted in blending impulsive airgun signals with the continuous, phase-sequenced MV sweeps, creating a distinct SI problem. The differing characteristics of the two source types – the natural dithered impulsive airguns and the continuous MV sweeps - pose a significant challenge for standard de-blending algorithms. Addressing this requires tailored processing strategies to effectively suppress interference while preserving the essential phase-sequencing of the MV data.

Proposed SI Mitigation Strategy

Seismic interference is essentially an unintended form of blended acquisition, with firing times dictated by other contractors, as noted by Kumar et al. (2020). As a result, it can be effectively addressed using inversion-based de-blending algorithms. Fu et al. (2019) introduced the joint de-blending approach, which generalized the methodology to handle data from multiple source types. However, their approach assumes a dither-type acquisition for all source types. In contrast, we are faced with a more complex scenario involving mixed source types and mixed blending setups. This presents a unique challenge requiring a different strategy to achieve successful mitigation of the SI shots.

In particular, preserving the phase-sequenced signals in MV sweeps is vital to maintain the integrity of subsequent processing and imaging stages, particularly for the sweep deconvolution step. Additionally, processing data with an extended record length is essential to achieve optimal de-blending results in a natural dither-blended acquisition. For example, suppose the original record length is 8 seconds, and the acquisition incorporates N+1 shot times at 6 seconds plus some additional dither with a triple-source configuration. In that case, the minimum de-blending length should be at least 14 seconds to produce clean and accurate results for the 8-second record. Extending the record length beyond 14 seconds poses no risk, but using less than 14 seconds may degrade the quality of the de-blended data within the 0 to 8-second window. Therefore, to completely remove SI shots, the record length must be extended, followed by inversion-based dither de-blending. However, in the case of MV phase-sequencing signals, which are coherent and periodical in the common-source and common-receiver domains, respectively, extending the record length and running iterative-based inversion de-blending will harm the phase-sequencing signals. This is because MV sweeps have fixed intervals between firing times, unlike SI shots. As a result, extending the record length is not a viable option in such scenarios.

To remove SI shots in such scenarios, de-blending must be performed on the original 10 seconds of record length to preserve the phase-sequencing in MV data. While this approach effectively eliminates most of the SI shots, there is a possibility that small traces of SI noise may remain in some places. This limitation arises because extended record-length de-blending cannot be applied in this case. However, most of the SI noise is mitigated, resulting in significantly cleaner shots for further processing, all while ensuring that the phase-sequenced signals remain intact.

The de-blending algorithm used in this study builds upon the adaptive inversion-based method for dithered simultaneous sources outlined by JafarGandomi et al. (2021). This approach leverages wave propagation physics and iterative thresholding in the 3D *f-k* domain to separate dithered simultaneous sources effectively. It incorporates direct wave and ghost modelling, along with frequency-dependent thresholding adjustments, to enforce sparsity constraints while gradually relaxing them for improved separation quality. In this study, we introduced additional features to the algorithm, such as variable time windowing, which dynamically adapts to different signal regions, and multi-thresholding schedules designed to target blended and non-blended regions separately. These enhancements significantly enhance the recovery of weak signals, particularly at later times, while preserving the integrity of phase-sequenced sweeps.

Real data examples

We demonstrate the effectiveness of our proposed SI mitigation strategy using both single-unit and double-unit MV configurations, with datasets acquired during the alpha test described earlier. First, we present a common-shot gather contaminated by SI noise from a nearby airgun survey (Figure 1a). With the firing times for the SI shots graciously provided by the other contractor, we applied our proposed de-blending algorithm to remove this interference. Since the single-unit vibrator swept at a fixed interval of 10 seconds, a 10-second de-blending was performed. The results are shown in Figure 1b, where the clean de-blended MV source-gather is free of all seismic interference noise. Figure 1c displays the difference between the input and de-blended output, clearly demonstrating the effectiveness of our strategy – no leakage is observed, and only the SI shots remain in the difference plot.

Next, we analyse a common-receiver gather for the same single-unit configuration. Here, the MV sweeps remain coherent (periodical) in this domain too, while the SI shots appear as expected incoherent noise as indicated by the yellow oval and arrows. Figure 2 (top row) illustrates the input data with SI shots, the de-blended clean output, and the difference between them. Once again, it is evident that our method successfully removes SI noise without impacting the phase-sequenced MV signal, as confirmed by the difference plot. The phase-sequencing behaviour is further validated by examining the *f-k* spectra of the same common-receiver gather (Figure 2; bottom row). In the *f-k* spectra difference plot, there is no evidence of phase-sequencing signal leakage; only the incoherent SI noise appears as white noise spectra. These results highlight the robustness of our proposed SI mitigation strategy in preserving MV signals while effectively eliminating seismic interference.

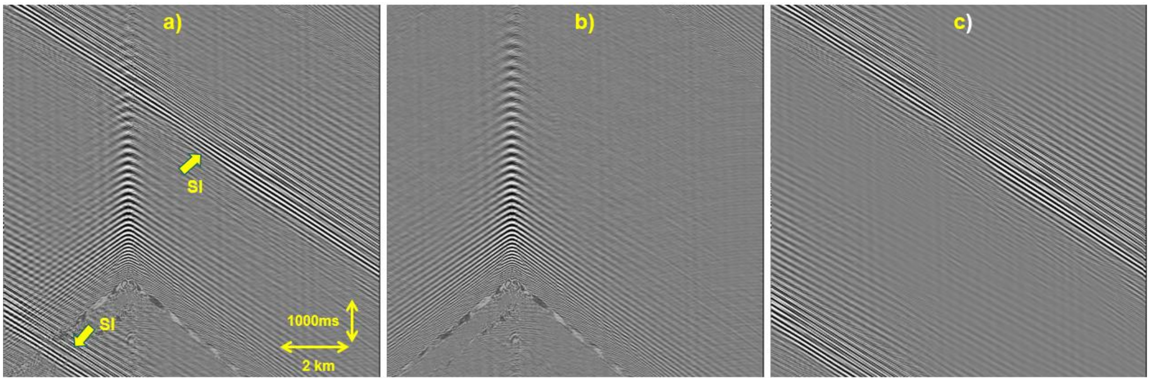

Figure 1 *a) A sample MV common shot gather from the 3D swath contaminated with SI shots; b) clean de-blended MV shot; c) difference between a) and b, highlighting the removed SI shots.*

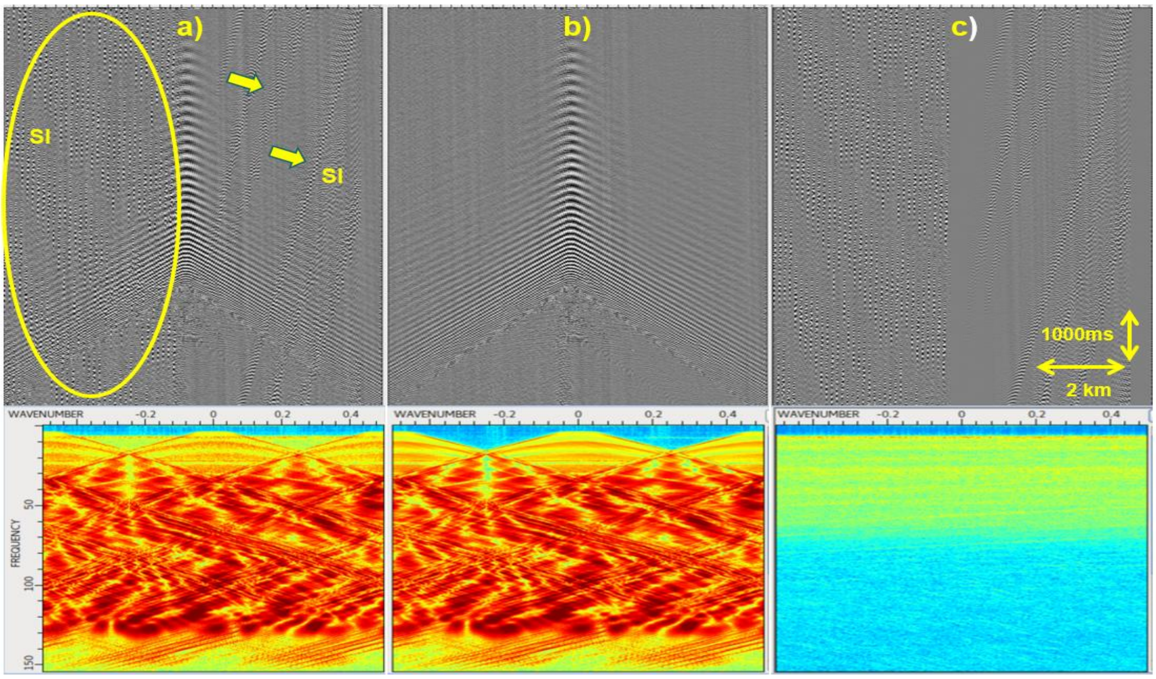

Figure 2 *The top row displays a common-receiver gather from the 3D swath single-unit configuration, where a) shows the input contaminated with SI shots; b) the clean de-blended output; and c) the difference. The bottom row presents the corresponding f-k spectra for each case. Wavenumbers are normalized (multiples by the spatial sampling interval 25m).*

Lastly, we present an example from the double-unit vibrator configuration. With two units, the signal strength is higher than the SI shots, though interference remains noticeable in some instances. This is partly also due to diminished operations in the neighbouring survey during the acquisition of this line. Given that the LB unit emits a 10-second sweep and the HB unit emits a 5-second sweep, de-blending was performed on a 5-second record to achieve optimal results while avoiding the extension of the HB unit's record length. The weaker SI shots were effectively removed from the double-unit MV datasets without compromising the phase-sequencing of the two distinct band patterns, as shown in Figure 3. We are currently progressing to further processing and imaging steps, which will be discussed in a future publication.

Conclusions

This study demonstrates a robust methodology for mitigating seismic interference in marine vibrator data while preserving the integrity of phase-sequenced signals. By leveraging an adaptive inversion-based de-blending algorithm, we successfully addressed SI contamination from neighbouring airgun surveys in both single-unit and double-unit MV configurations. Our approach effectively removed SI noise without impacting the coherence and periodicity of MV signals, as evidenced by the difference plots and *f-k* spectra analysis. The tailored processing strategy ensured that the critical phase-sequencing patterns remained intact, enabling accurate sweep deconvolution and subsequent processing and imaging. These results underline the feasibility of MV-based acquisition in environments with significant SI challenges, offering a pathway to achieve high-quality seismic imaging that is operationally robust.

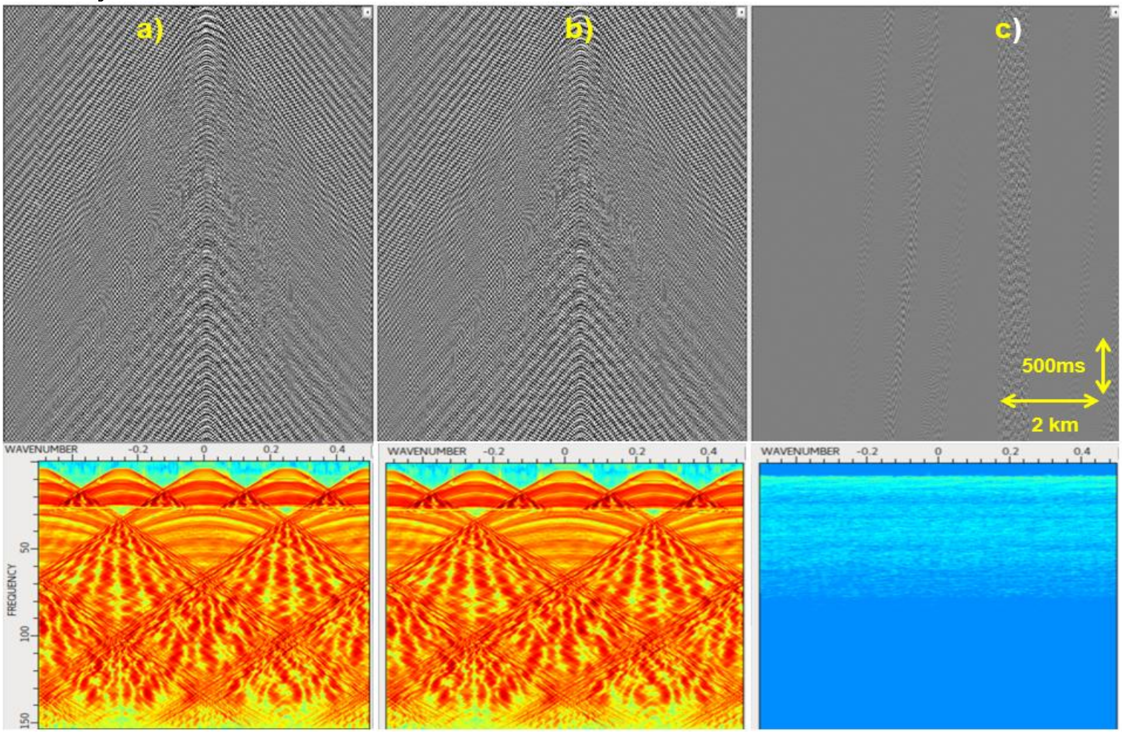

Figure 3 *The top row presents a common receiver gather from the 3D swath double-unit configuration: a) the input contaminated with SI shots; b) the clean de-blended output; and c) the difference. The bottom row shows the corresponding f-k spectra, clearly highlighting two distinct low- and high-band patterns, with the difference plot confirming no leakage.Wavenumbers are normalized (multiplied by the spatial sampling interval 12.5m).*

Acknowledgements

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