8

Decoupled Approach to UHR De-ghosting with Proximal Gradient

A. Kumar[1], R. Telling[1], A. JafarGandomi[1]

[1] Shearwater GeoServices

Summary

Ultra-high resolution (UHR) seismic data faces significant de-ghosting challenges due to uncertainty in receiver depth and sea-surface fluctuations. We propose a novel approach that decouples these effects using tailored regularization and proximal gradient methods. This improves de-ghosting accuracy, addressing ghost model uncertainty for enhanced preprocessing and precise wavefield redatuming.

Introduction

Ultra-high resolution (UHR) seismic data is essential for quantitative ground model building with applications such as offshore wind farm planning (Reveron, 2023). However, the shorter wavelengths of UHR data exacerbate preprocessing challenges, particularly in receiver de-ghosting. Accurately estimating receiver depth and accounting for sea-surface fluctuations are critical, as even small sea-surface wave amplitudes can introduce significant phase distortions. These distortions demand advanced techniques that go beyond traditional seismic processing methods.

Building on our previous work, which utilized spectral notch detection for constrained receiver ghost delay estimation, we recently proposed a data-driven iterative algorithm (Kumar et al., 2024) inspired by Vrolijk and Blacquière (2020). This algorithm improved de-ghosting accuracy by leveraging adaptive adjustments to the ghost model. However, it struggles to decouple the effects of receiver depth and sea-surface fluctuations, a critical limitation when addressing cases commonly encountered in UHR acquisitions. In such scenarios, uncertainty over the ghost model arises from either the sea-surface profile above the streamer, unknown receiver depth, or a combination of the two. This combination presents a significant challenge, as decoupling the two contributions is crucial for achieving high-quality de-ghosting and accurate redatuming of the upgoing wavefield.

In this paper, we address this limitation with a novel formulation that separates receiver depth and sea-surface fluctuations into distinct components. This approach leverages tailored regularization terms and reformulates the objective function to improve accuracy in both UHR and traditional seismic data. By solving the new formulation using proximal gradient methods, we provide a robust framework for mitigating de-ghosting artifacts and enhancing preprocessing quality.

Method

We propose a decoupled approach to enhance de-ghosting accuracy for UHR seismic data by separating receiver depth and sea-surface fluctuations into distinct components. The formulation addresses the inherent coupling challenges in estimating depth and wave height fluctuations while introducing tailored regularization terms for improved stability and adaptability. The objective function is expressed as:

$$J(P_0, z_r, \Delta z_w) = \sum_{\omega} \left\| P - G_{(z_r,\Delta z_w)} P_0 \right\|_2^2 + \lambda \left| p_0 \right|_1 + \gamma_1 \|\nabla z_r\|_2^2 + \gamma_2 |\Delta z_w|_1 \quad (1)$$

Here:

- P: Monochromatic input shot record with the receiver ghost.
- P_0: Estimated de-ghosted shot record.
- z_r: Receiver depth relative to mean sea level.
- Δz_w: Sea-surface wave height fluctuations.
- $G_{(z_r,\Delta z_w)}$: Ghost operator dependent on z_r and Δz_w.
- Regularization terms:
  - $\|\nabla z_r\|_2^2$: Enforces smoothness in the receiver depth.
  - $|\Delta z_w|_1$: Promotes sparsity in wave height fluctuations.

The parameters γ_1 and γ_2 balance the smoothness and sparsity of the depth and wave height estimates, respectively. Proximal gradient methods are particularly effective for solving optimization problems with composite objective functions like the one formulated here, which includes both smooth (L_2-norm) and non-smooth terms (L_1-norm). The proximal gradient approach alternates between gradient descent for the smooth term and proximal updates for the non-smooth terms. The method can also adapt to time-varying sea-surface profiles by processing data in time windows, making it well-suited for UHR seismic data and traditional seismic scenarios.

Examples

We applied our decoupled de-ghosting algorithm to UHR seismic data from the German North Sea, acquired with a 0.7m tow depth and 72 channels spaced 1m apart. Replacing the de-ghosting steps from

Telling et al. (2024) with our method, Figure 3 compares the results. The top section shows shot gathers before and after de-ghosting using both methods. Accurate receiver depth estimation was challenging due to out-of-band notches, shallow tow depth, and rough seas, so a smooth starting depth was used without systematic corrections. The bottom section highlights the proposed method's core innovation: separate estimation of receiver depths for redatuming and wave height fluctuations. Unlike the baseline, which exhibits ringing artifacts from depth inaccuracies, our method reduces these artifacts and produces cleaner outputs with a smooth, optimized receiver depth profile. While demonstrated on UHR data, our algorithm shows promise for de-ghosting challenging datasets with complex reservoirs, paving the way for future work.

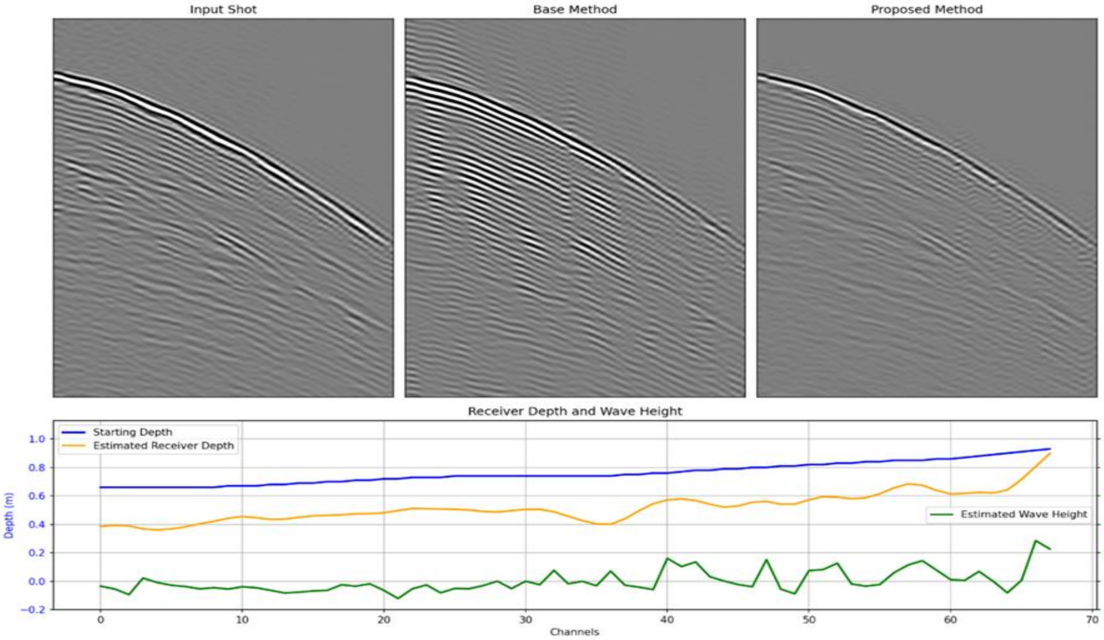

***Figure 1** Comparison of de-ghosting methods on UHR seismic data. (Top) shot gathers: input, baseline, and proposed method. (Bottom) receiver depth and wave height estimates: the proposed method reduces artifacts, optimizes receiver depths for redatuming, and captures wave height variations.*

Conclusions

We propose a data-driven receiver de-ghosting algorithm that decouples receiver depths from sea-surface height variations. This method improves de-ghosting, reduces ringing artifacts, and generates optimized receiver depth profiles for redatuming, as shown in the field data example. The enhanced de-ghosting is expected to lead to better soil properties estimations.

Acknowledgements

We thank Bundesamt für Seeschifffahrt und Hydrographie (BSH) for providing access to this data. We also thank Shearwater GeoServices for permission to publish this work.

References

Kumar, A., Telling, R., & JafarGandomi, A. [2024]. Pre-Processing UHR Seismic Data for Improved Quantitative Interpretation. In 1st EAGE/SUT Workshop on Integrated Site Characterization for Offshore Wind in Asia Pacific (Vol. 2024, No. 1, pp. 1-3).

Reveron, J. [2023] Correlation between geotechnical and geophysical data through seismic inversion, 84th EAGE Annual Conference and Exhibition.

Telling, R., JafarGandomi, A., Perratt, O., 2024, Towards quantitative interpretation of UHR marine seismic: an example from the North Sea, 85th EAGE Annual Conference and Exhibition

Vrolijk, J-W, and Blacquière, G. [2020] Adaptive estimation of the upgoing wavefield from a variable-depth recording in the case of a dynamic sea surface. Geophysics 85.1: V45-V56 recommendations for residual hearing effects. Aquatic Mammals 45, 125-232.