Title: Decoupled De-ghosting for Ultra-High Resolution Seismic Data

Authors: *Amarjeet Kumar, Rob Telling and Arash JafarGandomi*

Summary:

Ultra-high resolution (UHR) seismic data has emerged as a powerful tool for enhancing quantitative ground model building, particularly in applications such as offshore wind farm planning. However, effective utilization of UHR data hinges on overcoming unique preprocessing challenges, particularly receiver de-ghosting, which is complicated by dynamic sea-surface fluctuations and receiver depth uncertainties. This paper presents a novel, data-driven algorithm that decouples receiver depth and sea-surface height fluctuations into independent components using adaptive regularization techniques. The approach not only reduces artifacts such as ringing but also generates smooth, optimized receiver depth profiles for redatuming. Through both synthetic and field data from the German North Sea, the method demonstrates significant improvements in de-ghosting accuracy and preprocessing quality, making it a robust solution for UHR seismic applications and traditional seismic data scenarios.

Key Aspects: The paper addresses coupled receiver depth and sea-surface height estimation challenges in UHR seismic de-ghosting using an iterative, regularized algorithm that achieves cleaner wavefields and optimized depth profiles.

Novelty: The proposed algorithm uniquely decouples receiver depths and sea-surface height fluctuations, enabling artifact-free de-ghosting for UHR seismic data.

Decoupled De-ghosting for Ultra-High Resolution Seismic Data

Introduction

Ultra-high resolution (UHR) seismic data has emerged as a powerful tool for enhancing quantitative ground model building, particularly in applications such as offshore wind farm planning (Reveron, 2023; Karkov et al., 2022). However, effective utilization of UHR data hinges on overcoming unique preprocessing challenges, particularly receiver de-ghosting. Due to its shorter wavelengths, UHR seismic data presents significant obstacles in accurately estimating receiver depth and compensating for dynamic perturbations caused by sea-surface waves. Even modest amplitudes of sea-surface waves can lead to substantial phase distortions in UHR data, as highlighted by Henderson et al. (2023). In contrast to traditional seismic data, which may rely on simpler algorithms for receiver depth estimation, UHR data necessitates more sophisticated approaches due to its larger sensitivity to small perturbations.

Building on our previous work (Telling et al., 2024), which achieved constrained estimation of receiver ghost delay using spectral notch detection, we recently proposed a novel, data-driven iterative algorithm (Kumar et al., 2024) inspired by the foundational work of Vrolijk and Blacquière (2020). While this new approach significantly enhances de-ghosting accuracy, it has a critical limitation: the coupled estimates of receiver depth and sea-surface fluctuations cannot be directly applied for redatuming the upgoing wavefield, a crucial step in obtaining the de-ghosted wavefield.

In this paper, we introduce a novel method to address this limitation by decoupling receiver depth and sea-surface fluctuations into distinct components. This formulation is especially valuable for UHR seismic data, where accurately estimating both parameters is inherently challenging. The exact depths of the hydrophones are unknown, and small depth errors can substantially alter the ghost operator. Additionally, the non-flat sea surface can lead to significant changes over short distances when towing a streamer in rough conditions. This approach also serves as a refinement mechanism for traditional seismic data scenarios, where conventional methods may already yield reasonable receiver depth estimates. By reformulating the objective function and introducing tailored regularization terms for each component, this work provides a robust framework that mitigates against de-ghosting artifacts and improves receiver depth estimation used for redatuming. This advancement underscores the method's potential to enhance preprocessing quality for both UHR and traditional seismic data.

Method Overview and Key Innovations

To address the dynamic nature of the sea surface and the varying receiver depths, we adopt the adaptive de-ghosting algorithm proposed by Vrolijk and Blacquière (2020). In this algorithm, the ghost model is parameterized based on the discrepancy between the depth of the cable (z_d) and the sea surface level (z_0) at each location, denoted by $\delta z(z_d - z_0)$. The objective function includes a sparsity-promoting regularization term applied to the de-ghosted wavefield in the time domain, as follows:

$$J(P_0, \delta z) = \sum_{\omega} \left\| P - G_{(\delta z)} P_0 \right\|_2^2 + \lambda |p_0|_1 \tag{1}$$

where P represents the monochromatic representation of the shot record containing the receiver ghost, and P_0 is the estimated de-ghosted shot record. The ghost model, denoted by $G_{(\delta z)}$, is a function of the depth difference (δz). Due to the challenge of non-unique solutions, the algorithm prioritises selecting the sparsest one in the space-time domain. Hence, the second term in the objective function is represented by the lowercase p_0, signifying the de-ghosted shot records in the time domain. Since there are two unknowns in this objective function (P_0 and δz), the algorithm iteratively updates the estimates of the ghost-free data P_0 and the ghost-model parameter (δz) using the steepest descent algorithm in an alternating manner. The parameter λ is a user-defined regularisation constant that can be adjusted to generate the most optimal and sparse de-ghosted solutions.

However, this algorithm encounters two challenges. First, it generates coupled estimates of receiver depths and wave heights ($\delta z = z_r + \Delta z_w$), creating uncertainty regarding the reliability of receiver depths for *redatuming*. Second, the solutions tend to converge toward the initially assumed depths, which may not accurately represent the actual conditions. To address the second challenge, instead of relying on a constant assumed starting receiver depth, we use a prior solution derived from the smoothed depth estimated via the spectral notch technique, as outlined in Telling et al. (2024). To tackle the first challenge, we reformulate Equation 1 to decouple the estimates and introduce distinct constraints for the separate components of the depth parameters. The revised formulation is expressed as:

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

Here, z_r represents the receiver depth relative to the mean sea level, and Δz_w corresponds to the wave height fluctuations. The ghost operator $G_{(z_r, \Delta z_w)}$ depends on both terms. The third term in equation 2 enforces smoothness in the receiver depth by penalizing the ℓ_2-norm of its spatial gradients (∇z_r), while the fourth term encourages sparsity in the wave height estimates using the ℓ_1-norm, allowing for small, localized variations and oscillations due to the dynamic nature of the ocean. The gradients with respect to z_r and Δz_w will differ because of the regularization term added to the cost function. The weight parameters γ_1 and γ_2 play a crucial role in balancing these terms. Specifically, γ_1 controls the degree of smoothness applied to the receiver depth estimates, while γ_2 governs the sparsity of the wave height fluctuations. A practical strategy for setting these parameters for normalized input data is as follows:

- γ_1: Start with a relatively large value (e.g., 10) to strictly enforce smoothness in the receiver depth estimates. This ensures the depth remains close to the initial receiver depth during the initial iterations, preventing unrealistic abrupt changes. The value can be reduced gradually if finer adjustments to the receiver depth are required.
- γ_2: Start with a smaller value (e.g., 0.1) to allow sufficient flexibility for wave height fluctuations. This enables the algorithm to capture localized variations effectively. If greater sparsity is desired, it can be increased incrementally to suppress minor, non-physical fluctuations.

By carefully tuning these regularization parameters, the proposed method achieves a balanced approach that ensures smooth receiver depth estimates while also capturing and including the small-scale wave height fluctuations into the de-ghosting operator. This adaptability makes the method robust for diverse seismic data conditions, including challenging UHR data and traditional seismic data scenarios. Additionally, the method can be applied in time windows to estimate the time-varying sea-surface profile.

Examples

We demonstrate our methodology using two examples: one with synthetic modeled data and another with field data from the German North Sea. Figure 1a (courtesy of Vrolijk et al., 2020) displays a shot record exhibiting the dynamic ghost effect. The imprint of the dynamic sea surface is evident on the down-going ghost wavefield, manifesting as small-time variations. In contrast, the primary upgoing wavefield, which has not interacted with the sea surface, remains unaffected. In the wavenumber-frequency domain (top corner of Figure 1a), notches corresponding to the receiver depths relative to the dynamic sea surface are clearly visible.

Figure 1b presents the outcome of non-adaptive deterministic de-ghosting, which assumes a flat sea surface at a depth of 30m. Ringing artifacts are prominent, indicating inaccuracies in the non-adaptive de-ghosting method. These artifacts appear as over-amplified amplitudes in the notch regions of the wavenumber-frequency domain. Figure 1c illustrates the proposed adaptive de-ghosting method, which significantly reduces these ringing artifacts. The key focus lies in the estimated depths. To maintain the receiver depths close to the original 30m, we set $\gamma_1 = 10$ and $\gamma_2 = 0.01$, allowing flexibility for capturing the wave height fluctuations. Figure 2 depicts both the estimated receiver depths and the wave height fluctuations. The new formulation successfully decouples the receiver depth updates from the wave height fluctuations. In this synthetic example, the estimated receiver depths remain near the original 30m, with the sea-surface-induced fluctuations captured in the estimated wave heights.

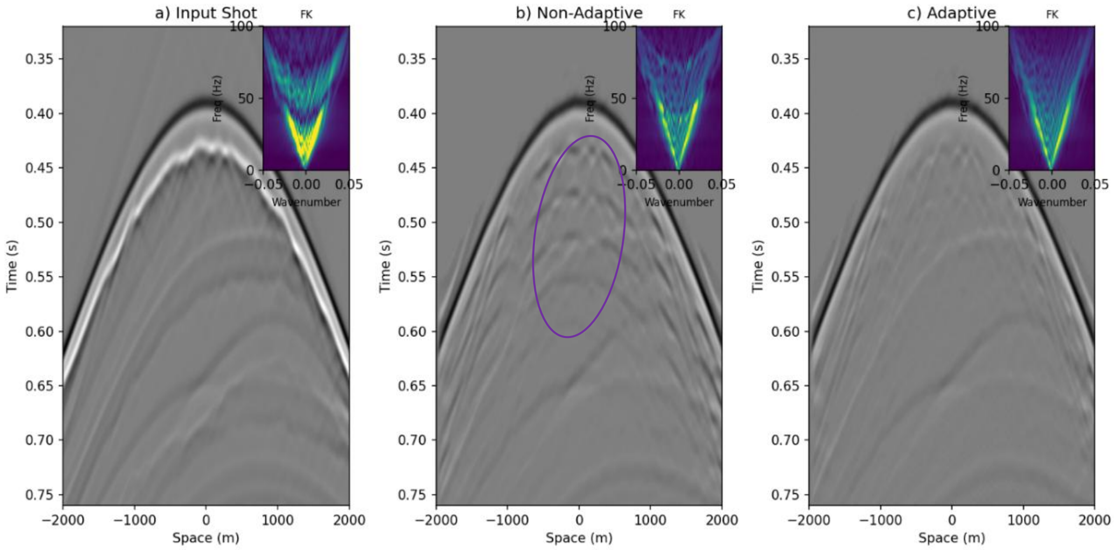

Figure 1 *a) Input shot record with the dynamic ghost effect and notches in the FK spectrum due to receiver depth; b) non-adaptive de-ghosting shows ringing artifacts (shown in the purple oval) and amplified amplitudes in notch regions; c) Adaptive de-ghosting reduces ringing and improves accuracy.*

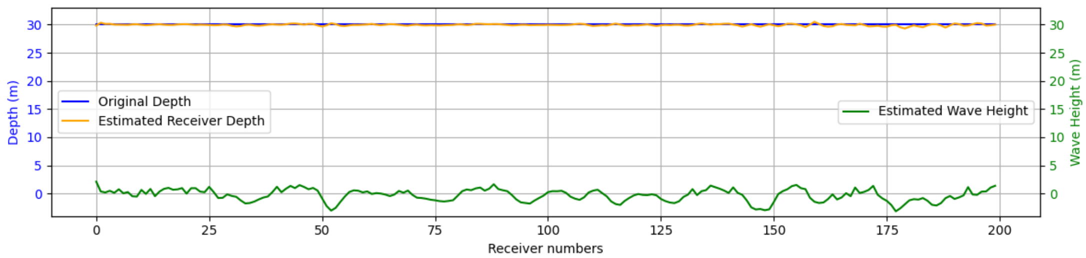

Figure 2 *Estimated receiver depths remain near 30m, while sea-surface fluctuations are captured in the estimated wave heights.*

We also applied our decoupled de-ghosting algorithm to UHR seismic data from the German North Sea, acquired with a nominal streamer tow depth of 0.7m and 72 channels spaced 1m apart. Following the processing steps outlined in Telling et al., 2024, we replaced the de-ghosting steps with our proposed algorithm. Figure 3 illustrates the comparative results. The top section showcases example shot gathers before and after de-ghosting, using both the baseline and proposed methods. In this particular shot, it was challenging to estimate the receiver depth accurately due to the notch being out of band, the shallow tow depth, and rough seas. Consequently, we used a smoothed starting depth without incorporating systematic corrections. The bottom section highlights the core innovations of the proposed algorithm, which decouples and separately estimates the receiver depths for redatuming and the wave height fluctuations. For this test, we set $\gamma_1 = 1$ and $\gamma_2 = 0.1$ enabling iterative updates that accommodate changes in both receiver depths and wave heights.

The baseline results exhibit ringing artifacts caused by inaccuracies in depth estimation, whereas the proposed method significantly reduces these artifacts, yielding much cleaner outputs. Beyond mitigating sea-surface wave height fluctuations, the method also produces a new, smooth receiver depth profile optimized for redatuming.

Conclusions

We propose a novel, data-driven receiver de-ghosting algorithm to address the critical challenge of de-ghosting in UHR seismic data processing. This approach successfully decouples receiver depths from sea-surface height variations, enabling independent estimation of both components. By independently addressing these components, the proposed method delivers cleaner de-ghosted results, minimizes ringing artifacts, and generates smooth, optimized receiver depth profiles for redatuming, as demonstrated through both synthetic and field data examples. Lastly, the improved de-ghosting facilitates better quantitative estimation of soil properties.

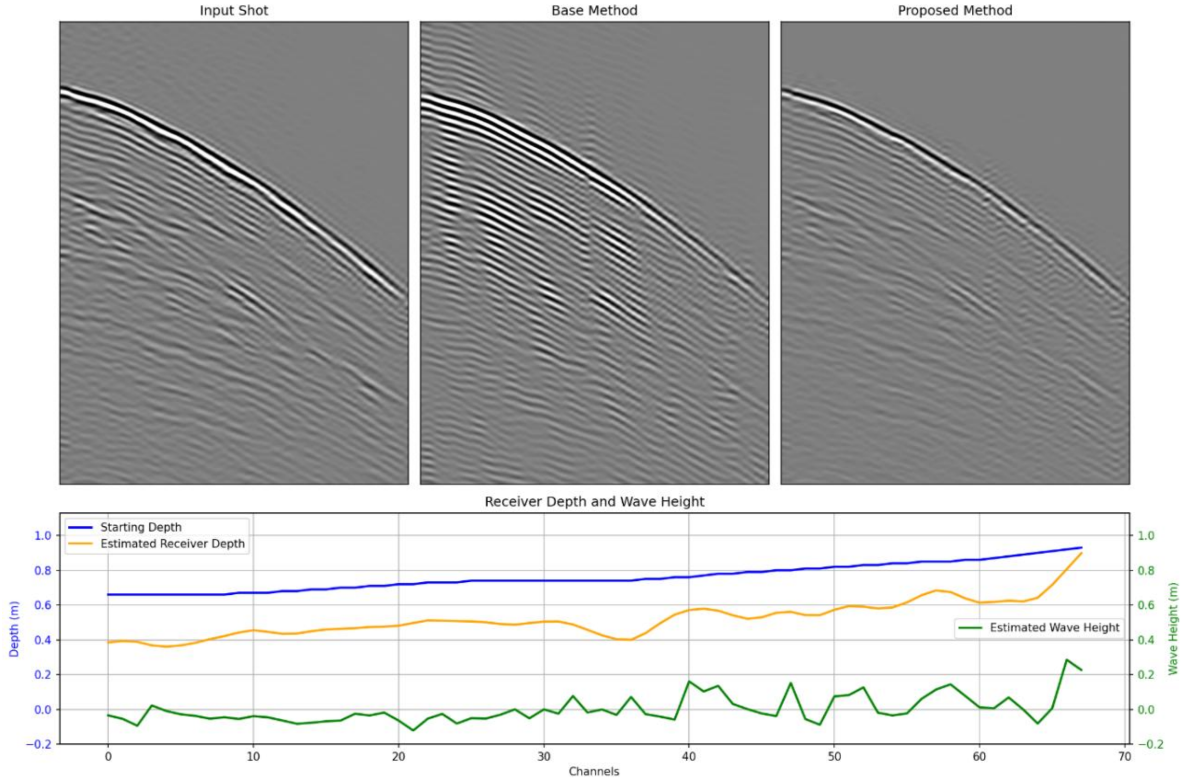

***Figure 3** Comparison of de-ghosting methods on UHR seismic data. (Top) Shot gathers: Input, Baseline, and Proposed Method. (Bottom) Receiver depth and wave height estimates: the proposed method reduces artifacts, optimizes receiver depths for redatuming, and captures wave height variations.*

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