Deghosting of UHR seismic data via dynamic ghost tracking

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Summary

This abstract proposes a novel deghosting solution for Ultra-High-Resolution (UHR) seismic data. The solution addresses the problem of the non-stationarity of the receiver ghost period which is caused by variations in the sea-state. This problem is more visible when the streamers are towed at a shallow depth which is often the case for UHR surveys. For this reason, most of the proposed solutions in the literature track the period of the ghost and then remove it by Wiener filtering. However, this is done trace-by-trace, and it is clearly sub-optimal because of the 3D nature of the ghost. Moreover, the Wiener deconvolution filter has a limited ability to control the amount of spectral boosting at the different orders of the notch frequency and this increases the potential risk for ringing artefacts in the output. The proposed solution solves these issues by tracking and deconvolving the ghost in the (τ-p) domain which is more physically correct. Deconvolution of the ghost operator is done via re-weighted iterative least squares which offers a better management of the ringing artefacts. The proposed deghosting solution has been validated on UHR dataset and was found to be effective and robust in removing the receiver ghost.

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Introduction

Ultra-High-Resolution (UHR) seismic data imaging is important for offshore near surface characterization in applications such as windfarm development. The seismic images obtained from these data provide a high level of detail of the geological features which is important to identify potential risks for foundation installation (faults, boulders, gas pockets, etc.).

There are however many challenges when processing UHR seismic data. The signal-to-noise ratio (SNR) is relatively poor, particularly below 100 Hz. This is due to limitations in the bandwidth and the power of the seismic source used for this type of survey (boomers and sparkers). The impact of sea surface variation on the data is pronounced because of the fine sampling both in time and space. Likewise, variation in the sea-state makes the period of the receiver ghost variable in time. Consequently, the receiver deghosting process is challenging because the depth of the receivers is not static. The time and space variation of the *apparent* receiver depth renders conventional inversion-based deghosting methods not optimal for UHR data (Provenzano et al. 2020). For this reason, most of the practical deghosting solutions for UHR seismic data track the period of the ghost and then perform deghosting by deconvolving the ghost operator in the frequency domain (Hellman et al. 2015), (Henderson et al. 2023). However, since tracking the ghost period is done in the time domain and performed trace-by-trace, all these solutions are effectively 1D. One can claim that 2D/3D effects are encapsulated in the ghost period. This is true to some extent, although obliquity which is needed for redatuming is not represented in the ghost period. However, going purely after any event that has a composition similar to an up-going wavefield + ghost with a specific period can potentially cause signal distortion. Therefore, in practice the estimated ghost period is smoothed both in time and space to avoid this problem. This in turn can lead to a sub-optimal removal of the ghost and add additional processing steps to the deghosting flow.

In this abstract we try to avoid this dilemma by proposing a true 2D/3D deghosting process that tracks the period of the receiver ghost but in the $(\tau - p)$ domain which is more physically correct. Once the period is estimated for a given p value, a re-weighted iterative least squares deconvolution problem is solved to estimate the up-going wavefield. Care is taken to account for cases where there is no reliable detection of the ghost period. The proposed method is tested on UHR dataset and shows good and consistent results compared to a conventional method. The solution has also been tested on slanted and flat streamer data. It showed similar good performance. However, this will not be shown in this paper.

Methodology

The 2D modelling of the ghost in the frequency-slowness domain $(f - p_x)$ is described as follows:

$$D(f, p_x) = P(f, p_x) + r\,\exp(-j2\pi fT)\,P(f, p_x) \qquad (1)$$

where $D(f, p_x)$ is the input data, $P(f, p_x)$ is the up-going wavefield, r is the sea-surface reflectivity (typically equal to -1) and T is the ghost's period. If the receivers are all at a constant depth Z_R, then the ghost period for a given slowness p_x is given as

$$T = 2Z_R\sqrt{\left(\frac{1}{V_w}\right)^2 - p_x^2} \qquad (2)$$

where V_w is the water column velocity. One can appreciate the fact that equation (1) can be solved in a least-square sense only if T is known. In fact, the ghost period abstracts all other information that is typically needed in the deghosting process such as Z_R and V_w. In other words, the receiver depth variation and the 3D effects affect the ghost only by changing its period. Now assuming that $\hat{T}$ is an estimate of the ghost period, we can solve for the ghost-free data using a re-weighted least squares deconvolution as described below.

$$\min_x \; \|D + Hx\|^2 + \delta\|W\,FFT^{-1}\,(x)\|^2 \qquad (3)$$

where $D = \{D(f, p_x)\}_{f=0}^{f_{nyq}}$, $x = \{P(f, p_x)\}_{f=0}^{f_{nyq}}$, $H = r\,\mathrm{diag}\{\mathrm{e}^{-j2\pi f\hat{T}}\}_{f=0}^{f_{nyq}}$, f_{nyq} is the Nyquist frequency and W is a diagonal weighting matrix with the purpose of enforcing time domain sparsity in the solution. δ is a user parameter that controls the amount of sparsity constraint. Formulating the ghost deconvolution process in this manner is important to avoid ringing artefacts at the notch frequencies that could appear on the output of the deghosting. Additionally, it can offer mild protection against deviation in the estimate of the ghost period. Figure 1-a is a synthetic data example that consists of three events with their ghosts causing a notch in the spectrum at about 85 Hz. The result of Wiener filtering (Figure 1-b) shows visible ringing around the reflectors and a notch in the spectrum. On the other hand, the solution obtained by re-weighted least-squares (Figure 1-c) is free of ringing artefacts and achieves a smaller estimation error.

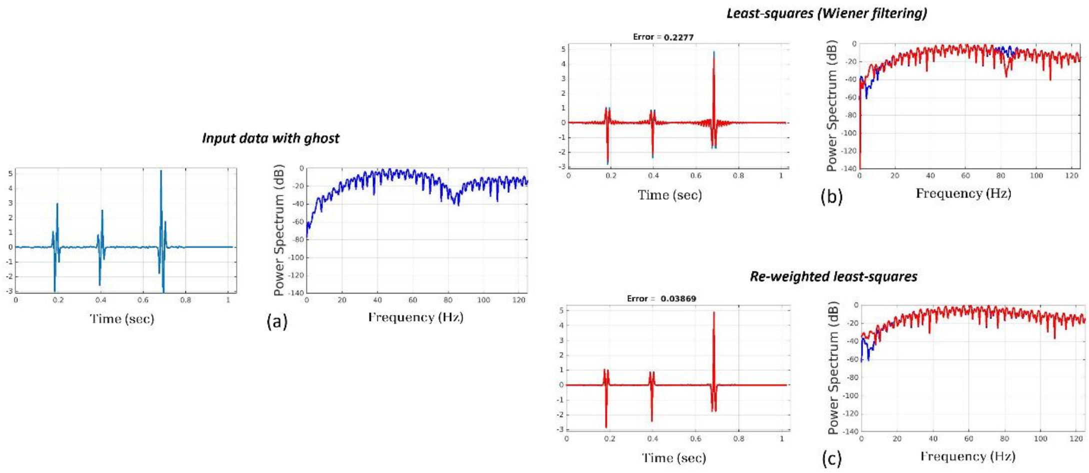

***Figure 1**. Least-squares vs. re-weighted least-squares deconvolution for the deghosting problem*

The proposed deghosting method works on sliding $(t - x)$ windows and is described in the flow below. The solution is wrapped around a Matching Pursuit (MP) decomposition to obtain a high-resolution mapping to the $(\tau - p)$ domain where the actual deghosting via ghost operator deconvolution is performed. One of the key design features of the solution is the integration of the MP decomposition and the ghost deconvolution in one block. This improves the robustness of the solution. The design also includes a provision for cases where no ghost is detected at a given dip decomposition and when the same dip appears more than twice in the MP decomposition. An updated receiver depth is obtained from the estimated ghost periods at different dips using least-squares.

Algorithm

1. Extract a local $(t - x)$ window $D(t, x)$, and set

   $P_{(0)}(t, x) = 0$ (initialise the ghost free buffer)
   $R_{(0)}(t, x) = D(t, x)$ (residual)

2. Do loop (Perform a matching pursuit decomposition)

   2.1 Find the dominant dip p_x in $R_{(k)}(t, x)$
   2.2 Extract the wavelet $d(\tau)$
   2.3 Estimate the ghost period $\hat{T}$ from $d(\tau)$ using autocorrelation (constrained search)
   2.4 Solve for the ghost free component $Q(f, p_x)$ using equation (3)
   2.5 Compute $U(f, p_x) = Q(f, p_x)\left(1 + r\exp\left(-j2\pi f\hat{T}\right)\right)$, map to $(t - x)$
   2.6 Update the residual $R_{(k+1)}(t, x) = R_{(k)}(t, x) - U(t, x)$
   Update the output $P_{(k+1)}(t, x) = P_{(k)}(t, x) + Q(t, x)$
   $if\ \|R_{(k+1)}\| < \varepsilon$ exit $else$ go to 2.1

***Table 1**. Descriptive flow of the solution*

Field data example

The proposed receiver deghosting method was tested on 3D UHR dataset. The survey was conducted using a P-Cable system that consists of 11 streamers, each of which is 100 meters long. Boomers were used as a seismic source with a time sampling of 0.25 ms, offering a bandwidth of up to 2000 Hz. The receivers were towed at a depth that varied between 0.5 m to 2.5 m as shown in Figure 2-a. An inversion-based *FK* deghosting method that handles variable cable depth was also tested for comparison (Riyanti et al. 2008). Figure 2-b shows the deghosting result achieved by this method when applied on the set of input shots in Figure 2-a. The result is clearly not optimal as ringing artefacts are observed in the output. This suggests that the cable depth is not accurate or there is a strong sea-state variation. After updating the cable depth with an estimate obtained from autocorrelations of the data around the water bottom, the deghosting result is improved slightly (Figure 2-c). The receiver ghost is removed in many places, but residual ringing artefacts are still visible particularly in the mid to far offsets. The result of applying the proposed deghosting method is shown in Figure 2-d with the estimate of the cable depth along the water bottom reflection. The result is now better in terms of removing the receiver ghost with no visible ringing. The extracted cable depth has a similar profile to the one estimated from autocorrelation, but it is smoother.

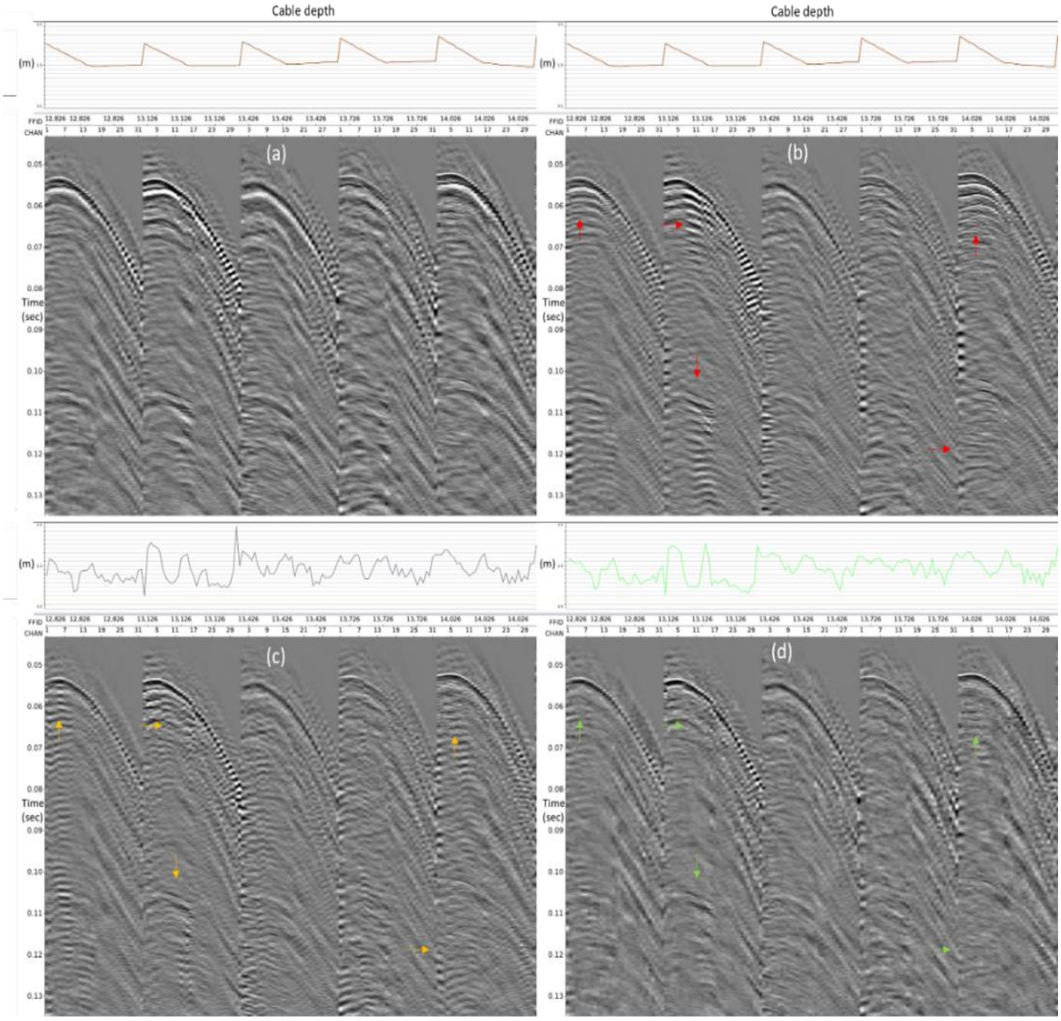

Figure 2. *Shot gathers. (a) Input, (b) deghosting with original receiver depth, (c) deghosting with updated receiver* depth, *(d) deghosting with proposed method*

Figure 3-a displays a zoom around the water bottom of a near offset channel (~24 m) of the input data and its associated amplitude spectrum showing a visible notch at about 420 Hz. The conventional method managed to remove the ghost to a reasonable extent, but some residual ghost can still be visible. Also, we observe an undesirable bump in the spectrum at around 630 Hz. The proposed method on the other hand (Figure 3-c) is better at removing the ghost and does not introduce any bumps in the amplitude spectrum. Overall, the result achieved by the proposed method is cleaner and does not boost the background noise. The same set of observations can be made when assessing the results for a large offset channel section (~80 m) shown in Figure 4. The 2D stack also leads to the same conclusion but it is not included here.

Conclusions

Receiver deghosting for UHR data is a challenging problem due to the required resolution of the image and the relatively moderate signal to noise ratio. The problem is made more diffucult with inacurate navigation, shallow cable towing and variable sea-state. It is important that the deghosting solution tracks the ghost period both in time and space to achieve optimal results.

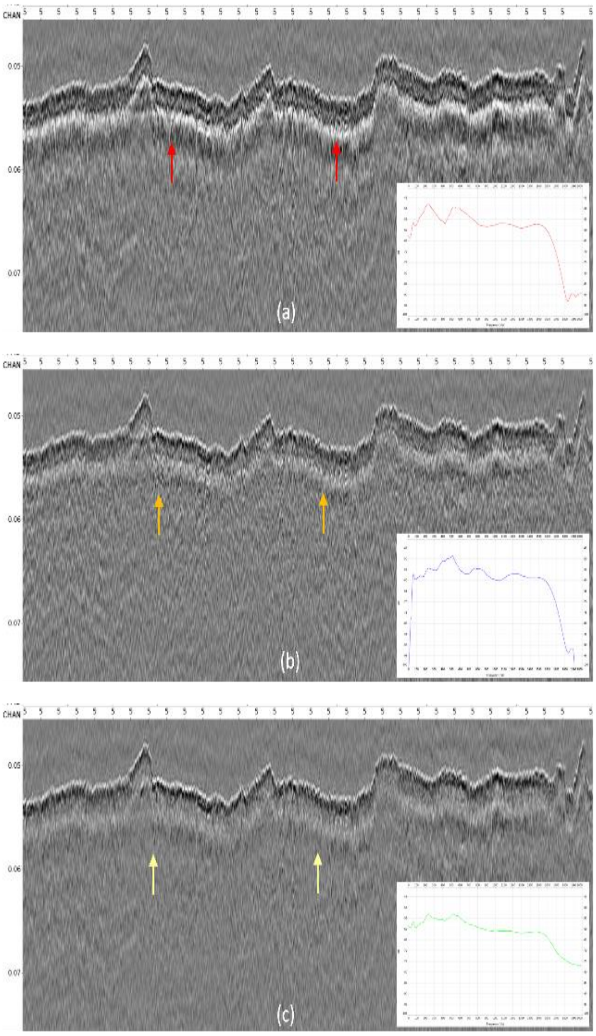

Figure 3*. Common channel gather (near offset). (a) Input, (b) conventional deghosting (c) proposed deghosting*

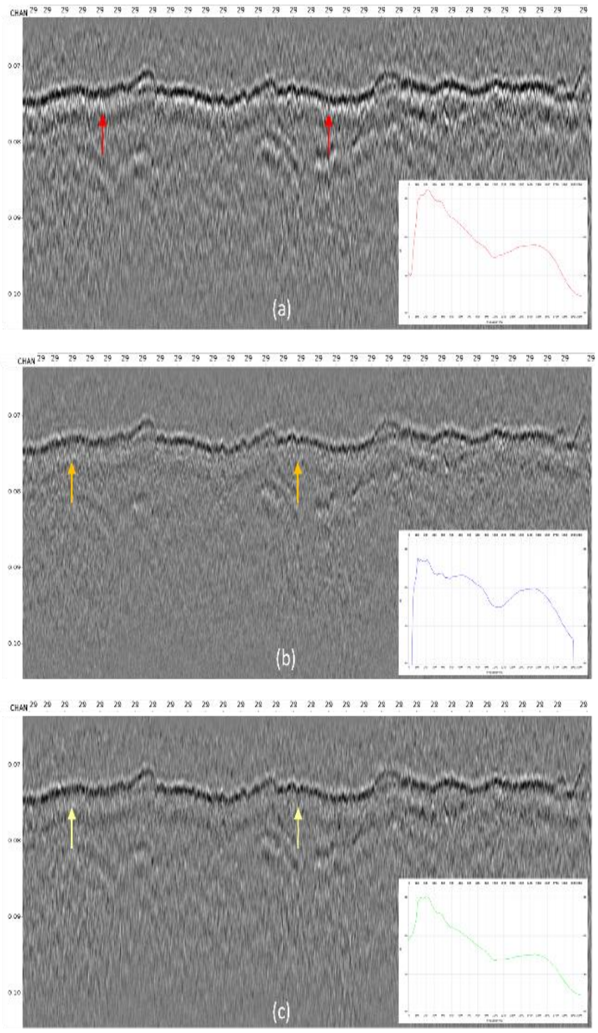

Figure 4*. Common channel gather (far offset). (a) Input, (b) conventional deghosting (c) proposed deghosting*

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