Premigration deghosting for marine streamer data using a bootstrap approach in Tau-P domain

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Summary

Removing the receiver ghost before migration provides better low and high frequency response as well as a higher signal-to-noise ratio. We recognize these benefits for preprocessing steps like multiple suppression and velocity analysis. In this paper, we modify a previously published bootstrap approach that self-determines its own parameters for receiver deghosting in a $t - x$ window. Similarly to the $t - x$ bootstrap method, the recorded data in shot domain are first used to create mirror data through a 1D ray-tracing-based normal moveout correction method. The recorded and mirror data are then transformed into $\tau - p$ domain and used to jointly invert for the receiver-ghost-free data. We apply this new algorithm to a field data set with a streamer depth of 27 m. Our deghosting method effectively removes the receiver ghost and the resulting image has broader bandwidth and a higher signal-to-noise ratio.
Introduction

In marine towed streamer acquisition, the upgoing wavefield reflected from subsurface reflectors is first recorded by the receivers. The waves continue to propagate to the free surface and reflect back down, where they are recorded by the receivers again as the downgoing wavefield (the receiver ghost). Because the reflectivity at the free surface is near -1, the downgoing wavefield has similar amplitude as the upgoing wavefield but opposite polarity. Thus the frequencies near the ghost notches in the recorded signal are attenuated. Removing the receiver ghost can potentially infill the ghost notches and help obtain images with higher quality in terms of frequency band and signal-to-noise ratio (S/N).

Historically, the receiver deghosting on constant-depth streamer data has been performed in the $f - k$ (frequency/wave number) domain (Fokkema and van den Berg, 1993). The limitations of such methods are: 1) the receiver depth needs to be constant, and 2) as an $f - k$ method, it is largely limited to 2D because the acquired data are often too coarsely sampled in the crossline direction for high frequencies in the seismic data.

A conjugate gradient method was proposed for receiver deghosting on non-horizontal streamer data by Riyanti et al. (2008). This method is capable of handling data with accurately-known variable receiver depth but is also limited to 2D due to its operation in the $f - k$ domain.

Carlson et al. (2007) proposed to attenuate the receiver ghost by using both the pressure and velocity wavefields, where the particle velocity is measured by geophones that bear the vertical direction (up or down) of the wave propagation. The upgoing wavefields detected by the geophone and hydrophone are in phase and the downgoing wavefields (the receiver ghost) are 180° out of phase. Therefore the summation of the two recorded data can attenuate the receiver ghost. However, the calibration between the two signals is difficult due to: 1) low S/N below ~20 Hz for particle velocity data; and 2) emergence-angle variations.

Receiver deghosting using data acquired with concurrently towed shallow and deep streamers was proposed by Posthumus (1993). For such configuration: Özdemir et al. (2008) proposed an optimal deghosting approach in the $f - k$ domain to jointly deghost the shallow and deep data; Gratacos (2008) proposed a 3D least-square-based data-merging algorithm in $f - xy$ domain to obtain the upgoing wavefield. However, the former suffers from sparse crossline sampling and both require accurate receiver positioning for high frequencies.

Wang and Peng (2012) proposed a bootstrap deghosting approach which removes both shot and receiver ghosts and works for both NAZ and WAZ geometries. However, it is less accurate when the variation of emergence angles is large in a given $t - x$ window (e.g., at shallow large offsets where different arrivals converge). In this paper we propose a new method that combines the bootstrap approach with anti-leakage $\tau - p$ transform and is able to better handle large variations of emergence angles.

Methodology

The concept of using recorded and mirror data for premigration receiver deghosting is similar to that of using a migration and a mirror migration for postmigration receiver deghosting proposed by Soubaras (2010). Wang and Peng (2012) proposed to use the recorded data and the mirror data which is created from the recorded data to remove both shot and receiver ghosts in the premigration stage. It uses a bootstrap iteration to determine the ghost-delay time for a local $t - x$ window. In this paper we modify this algorithm to better handle a large variation of emergence angles. The new method uses a bootstrap iteration to invert ghost-delay time for a local $\tau - p$ window and reconstructs the ghost-free data through least squares using the inverted ghost-delay times.
The recorded 2D shot gather \( N(t,x_i) \) and its mirror \( M(t,x_i) \) \((i=1,2,...,n)\) are first transformed to \( \tau - p \) domain, then divided into different \( \tau - p \) windows and transformed to \( f - p \) domain as \( N(f,p^j_i) \) and \( M(f,p^j_i) \) \((j=1,2,...,m)\) and \( p^j_i \) is the \( j \)th slowness in \( x \) direction. A deterministic deghosting filter can be applied to each slowness trace when slowness in \( y \) direction \( p_y \) is zero (e.g., in 2D case). The ghost-free data \( P(f,p^j_i) \) can be written as

\[
P(f,p^j_i) = N(f,p^j_i)(1 - e^{\imath \omega f t^j_i p^j_i})^{-1}
\]

with \( d \) as the receiver depth and \( v \) as the water velocity. For a 3D case, the problem is complicated for two reasons: 1) \( p_y \) may not be zero, and 2) \( p_y \) may be different for different events with the same \( p_x^j \). To address this issue, instead of using a deterministic dehosting filter, we implement a bootstrap approach (Wang and Peng, 2012) to invert the ghost-delay times for a \( \tau - p \) window.

We first determine receiver-ghost-free data \( P(f,p^j_i) \) through a least square process:

\[
\begin{align*}
N(f,p^j_i) &= F_x P(f,p^j_i) \quad (1) \\
M(f,p^j_i) &= F_y P(f,p^j_i) 
\end{align*}
\]

where \( F_x \) is ghost filter and \( F_y \) is its dual. With this primary as the starting point, \( P_0(f,p^j_i) \), we start the following iterative process (3-6) by first obtaining the ghost

\[
G_k(f,p^j_i) = N(f,p^j_i) - P_0(f,p^j_i),
\]

where \( k \) stands for the \( k \)th iteration. The ghost-delay time \( \tau^k_j \) can then be obtained by minimizing

\[
O = \left| P_k(f,p^j_i) + G_k(f,p^j_i) e^{\imath \omega f \tau^k_j} \right|
\]

Thus the optimal ghost filter can be expressed as

\[
F_{k+1} = 1 - e^{-\imath \omega f \tau^k_j}.
\]

The primary is derived as

\[
P_{k+1}(f,p^j_i) = F_{k+1}^* N(f,p^j_i),
\]

where \( F_{k+1} \) is self-determined, or bootstrapped, from the \( k \)th iteration.

Once the ghost-delay times are determined, we can perform a least square inversion in \( f - p \) domain

\[
\begin{bmatrix}
N(f,x_1) \\
N(f,x_2) \\
\vdots \\
N(f,x_n)
\end{bmatrix} =
\begin{bmatrix}
(1 - e^{\imath \omega f \tau^j_1}) e^{-\imath \omega f p^j_1} \\
(1 - e^{\imath \omega f \tau^j_1}) e^{-\imath \omega f p^j_1} \\
\vdots \\
(1 - e^{\imath \omega f \tau^j_1}) e^{-\imath \omega f p^j_1}
\end{bmatrix}
\begin{bmatrix}
P(f,p^j_1) \\
P(f,p^j_1) \\
\vdots \\
P(f,p^j_1)
\end{bmatrix}
\]

(7)

with \( 1 - e^{-\imath \omega f \tau^j_1} \) as the ghost operator for \( j \)th slowness, \( e^{-\imath \omega f p^j_1} \) as the inverse \( \tau - p \) transform operator for \( j \)th channel and \( f \)th slowness, and \( P(f,p^j_i) \) as the ghost-free data. After \( P(f,p^j_i) \) is inverted from Equation 7, an inverse \( \tau - p \) transform is applied to obtain the ghost-free data \( P(f,x_i) \) as

\[
\begin{bmatrix}
P(f,x_1) \\
P(f,x_2) \\
\vdots \\
P(f,x_n)
\end{bmatrix} =
\begin{bmatrix}
e^{-\imath \omega f \tau^j_1} & e^{-\imath \omega f \tau^j_1} & e^{-\imath \omega f \tau^j_2} & \cdots & e^{-\imath \omega f \tau^j_m} \\
e^{-\imath \omega f \tau^j_2} & e^{-\imath \omega f \tau^j_2} & e^{-\imath \omega f \tau^j_1} & \cdots & e^{-\imath \omega f \tau^j_m} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
e^{-\imath \omega f \tau^j_m} & e^{-\imath \omega f \tau^j_m} & e^{-\imath \omega f \tau^j_1} & \cdots & e^{-\imath \omega f \tau^j_2}
\end{bmatrix}
\begin{bmatrix}
P(f,p^j_1) \\
P(f,p^j_1) \\
\vdots \\
P(f,p^j_1)
\end{bmatrix}
\]

(8)

And we can then obtain the final primary \( P(t,x_i) \) via an inverse Fourier transform.

**Application to field data**

We apply our \( \tau - p \) bootstrap algorithm to a 2D data set from the Green Canyon area of the Gulf of Mexico. The data set has constant shot and steamer depths at 8 m and 27 m respectively.

Figures 1a and 1b show the input shot gather and the gather after receiver deghosting respectively. The insets are the zoom-in for red boxes. You can clearly see the primary and receiver ghost pairs in
Figure 1: a) input shot gather; b) after receiver deghosting; c) spectral comparison for the insets in a and b which are the zoom-in for red boxes; d) after $t - x$ bootstrap; and e) $\tau - p$ bootstrap receiver deghosting for data in the blue box in a.

1a and the receiver ghost is removed in 1b. Figure 1c shows the spectral comparison of input data and data after receiver deghosting. You can see that different orders of receiver-ghost notches are well filled-in. Figures 1d and 1e compare $t - x$ bootstrap method proposed by Wang and Peng (2012) with the $\tau - p$ bootstrap method proposed in this paper. The new method better copes with events with large variations of ghost-delay times at shallow large offsets (blue box in Figure 1a).

The image shown in Figure 2a is the stacked Kirchhoff prestack depth migration (PSDM) image of the input data without receiver deghosting. Because of the large receiver depth, the primary events are well-separated from their corresponding receiver ghosts with opposite polarity (indicated by red arrows); this poses difficulties in interpreting this data. In practice, people often high-cut filter the data at the first receiver-ghost-notch frequency to mitigate the confusion between primary and ghost (Figure 2b). Figure 2c shows the image using input data after receiver deghosting. The receiver ghost present in Figure 2a is properly removed and the resulting image appears cleaner with higher resolution. Figure 2d shows the spectral comparison among three images. The receiver-ghost notches present in the spectrum of raw input (red) are properly filled-in by our deghosting algorithm (blue).

Discussions and Conclusions

We have developed a self-sustaining, or bootstrapped, deghosting algorithm that effectively removes the receiver ghost in the premigration stage. The advantages of this method are twofold: 1) it works for 3D NAZ and WAZ geometry; and 2) accurately-known receiver depths are not necessary. We have successfully applied this algorithm to a deep-towed streamer data set with a receiver depth of 27 m. Because of the receiver deghosting, the migrated images have broader bandwidth as well as improved S/N which may be beneficial for the interpretation of geological structures and rock properties.

Similarly to both dual-senor (Carlson et al., 2007) and over-under (Özdemir et al., 2008) receiver deghosting that use two data sets recorded with different sensors, our method also uses two data sets. Yet, because our method creates the mirror data from the recorded data, it is applicable to all streamer data without the extra acquisition expense. Additionally, our method requires no normalization between two data prior to deghosting since both data are recorded by the same sensor.
While our proposed method largely overcomes the problems encountered by Wang and Peng (2012) when the variation of emergence angles is large (e.g., shallow large offsets), we observe that it’s still difficult to completely remove the receiver-ghost notches and flatten the spectrum, which is possibly due to: 1) noise contamination; 2) lack of notch diversity for flat-streamer data; and/or 3) the pseudo-3D algorithm. Obtaining the optimal spectrum still requires a true broadband acquisition solution.

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References

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Figure 2: Kirchhoff stacked images(unit in kilometers): a) raw input; b) raw input high-cut filtered at 27 Hz (first receiver-ghost-notch frequency); c) after receiver deghosting; d) spectral (blue box in b) comparison: red—raw input; green—high-cut input; blue—after receiver deghosting.