Premigration deghosting for marine towed streamer data using a bootstrap approach

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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 for preprocessing steps such as multiple suppression and velocity analysis. We propose a bootstrap approach that self-determines its own parameters for receiver deghosting. The recorded data in shot domain are first used to create mirror data through a 1D ray tracing based normal moveout correction method; then both the recorded and mirror data are used to jointly invert for the receiver-ghost-free data. We demonstrate with both synthetics and real data that our deghosting method can, in many situations, reliably remove the receiver ghost for marine towed streamer data in the premigration stage (as opposed to the more generally applicable postmigration joint deconvolution).

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 close to -1, the downgoing wavefield has similar amplitude as but opposite polarity of the upgoing wavefield. Thus some frequencies in the recorded signal are attenuated near the ghost notches. Removing the receiver ghost can potentially infill the ghost notches and thus 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 carried out 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 since the acquired data are often too coarsely sampled in the crossline direction for high frequencies.

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 which 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: Kemal 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.

In this paper we propose a method in F-XY domain that uses recorded (Figure 1a) and mirror data (created from recorded data, Figure 1b) to jointly invert for the receiver-ghost-free data (Figure 1c). Our method largely overcomes the limitations encountered by the above-mentioned methods and is applicable to various types of marine towed streamer acquisition.

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). We create the mirror data using a 1D ray tracing-based normal moveout correction method which approximately redatums the receiver ghost (black ray in 1a) in the recorded data to the primary timing (red ray in 1b). Therefore the primary in the recorded data becomes the mirror ghost (black ray in 1b) which arrives earlier than primary.

In a given T-XY (time-space) window the recorded data \( n(t,x,y) \) and mirror data \( m(t,x,y) \) are first transformed to
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Frequency domain as \( N(f, x, y) \) and \( M(f, x, y) \) (simplified as \( N \) and \( M \) hereafter), which then can be expressed by multiplying the primary (receiver-ghost-free data) \( P \) with a receiver ghost filter \( F_N \) and its dual \( F_M \) respectively:

\[
\begin{align*}
N &= F_N P, \\
M &= F_M P.
\end{align*}
\]  

(1)

Ideally, the primaries in the recorded and mirror data (the red rays/events in Figure 1a,b) are aligned in timing. If this were true, then

\[
F_M = F_N^*.
\]  

(2)

However, in practice there is always a time shift, albeit a small one, due to 1) redatuming using 1D approximation; 2) velocity inaccuracy; and 3) receiver depth error. We address this error by adding a phase coefficient to match the timing. Equation 2 becomes

\[
F_M = e^{i\omega \Delta t} F_N^*.
\]  

(3)

Combination of Equation 1 and 3 forms a system which can be used to determine receiver-ghost-free data \( P \) through a least square process in the presence of noise. With this primary as the starting point, we start the following iterative process (4-7) by first obtaining the ghost

\[
G_t = N - P_0.
\]  

(4)

The optimal average ghost-delay time \( T_t \) for the given window can then be obtained by minimizing

\[
O = \left| P + G e^{i\omega \Delta t} \right|.
\]  

(5)

Thus the optimal ghost filter can be expressed as

\[
F_{t,i} = 1 - e^{-i\omega \Delta t}.
\]  

(6)

The primary is derived as

\[
P_{t,i} = F_{t,i}^* N,
\]  

(7)

where \( F_{t,i} \) is self-determined, or bootstrapped, from the \( i \)th iteration. We tested this algorithm on both synthetic and real data and found that this process often converges in only a few iterations. Note that mirror data are not used for the final deghosting (Equation 7).

Our method works in a localized \( T-XY \) window in which we expect all events to have a similar ghost-delay time. The delay-time difference satisfies

\[
|\Delta t| < \frac{1}{f_{\text{max}}}
\]  

(8)

where \( f_{\text{max}} \) is the maximum frequency of the data.

Application to synthetic data

We first apply our algorithm to synthetic data modeled from 2.5D Sigsbee2a model using a constant receiver depth of 25 ft.

To demonstrate that our method does not depend on accurate receiver depth, we intentionally add random error with standard deviation of 2 ft to the true receiver depths when generating the mirror data for the results shown in this section. Shown in Figure 2a is an input shot gather with the receiver ghost. Every individual event consists of a black peak and a red trough, with peak after trough or vice versa depending on the polarity of the event. The data in 2b is after receiver deghosting, hereafter called deghosted data. The ghost data, that is, the difference between deghosted data and input data, are shown in 2c. You can see that after receiver deghosting, two black events around 5.1 seconds (2b, 2c) are well-separated when they were otherwise overlapping with each other prior to receiver deghosting. This proves that our receiver deghosting works properly, even when the receiver depth error is present and events interfere with each other.

The images shown in Figure 3a-e are stacked 3D RTM images (the receivers were positioned at negative receiver depth when migrating the ghost data). The images for modeled data with and without receiver ghost are shown in 3a and 3b. The images for deghosted data and ghost data are shown in 3c and 3d. You can see that, compared to the image with receiver ghost (3a), the images in 3b-3d appear to have a broader frequency spectrum which is consistent with the depth-domain spectrum comparison in 3f. The small difference (3e) between 3c and 3d and their high similarity to 3b mean that the primary and receiver ghost in the input data are accurately separated by our deghosting algorithm.

Figure 2: (a) Input data with receiver ghost; (b) deghosted data; (c) polarity-flipped ghost data (b-a). The blue lines serve as a time reference to better see the time shift between the primary (b) and ghost (c). The display amplitude is fixed.
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Application to field data
In this experiment we apply our bootstrap deghosting algorithm to a 3D data set from the Diana field in the East Breaks area of the Gulf of Mexico. The data set has constant shot and steamer depths at 7 m and 9 m respectively.

Figure 4 includes the input shot gather (4a), deghosted gather (4b), and ghost gather (4c) from an outer cable. The near-channel data from the outer cable are expected to carry strong 3D effects. However, the high similarity between dehosted gather (4b) and ghost gather (4c) indicates that our receiver dehosting works well in the presence of 3D effects. Figure 4d shows that the spectra of dehosted and ghost data are almost identical and are broader than that of original data.

The image shown in Figure 5a is the stacked 3D Kirchhoff prestack depth migration (PSDM) image of the input data without receiver dehosting and the image in 5b is the image after receiver dehosting. You can see that after receiver dehosting the wavelet appears more tightened which is an indication of broader frequency band. The spectrum comparison in 5c confirms that the receiver dehosting helps obtain images with broader frequency spectrum.

Figures 6a-6b show the 0-5 Hz images before and after receiver dehosting. The events can be better seen with less noise after receiver dehosting. The depth slice at 1600 m after receiver dehosting (6d) looks sharper with weaker side-lobes and thus the events are better delineated.

Conclusions and discussions
We have developed a self-sustaining, or bootstrap, dehosting algorithm that can effectively remove the receiver ghost in data from a variety of marine towed streamer configurations. The advantages of this method are twofold: 1) dense sampling is not required in either the inline or crossline direction; and 2) accurately-known receiver depths are not necessary. Because of receiver dehosting, the migrated images have better low and high frequency response 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 (Kemal et al., 2008) receiver dehosting which
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use two data recorded with different sensors, our method also uses two data. Yet, because our method creates the mirror data from recorded data, the data are cheaper to acquire. Additionally, our method requires no normalization between two data prior to deghosting since both data are recorded by the same sensor. Our method is also applicable to marine towed streamer data of most (if not all) acquisition methods, including variable-depth streamer methods. Our bootstrap approach does require a velocity model to create mirror data (Figure 1b), but we note that our method is insensitive to the inaccuracy of that velocity model (Equation 3). In addition, mirror data are not used for final deghosting (Equation 7).

Our method requires that the events in a chosen T-XY window bear similar ghost-delay time (Equation 8). In practice we often use a time window of 200-600 ms depending on the frequency content and sampling rate of input data. The space window can be fairly small but a larger space window (~10-30 traces per window) is used to stabilize the inversion when strong noise is present. In applications of this method to both narrow- and wide-azimuth conventional streamer data we found that our receiver deghosting is fairly robust with receiver depths varying from 6 m ($f_{max} = 120$ Hz) to 15 m ($f_{max} = 75$ Hz).

We observed that this method is less stable around the water bottom at large offsets (large emergence angles) where different seismic arrivals (primary/multiple/refraction) are recorded in a small time window. Data in that window are challenging for most existing deghosting methods. Fortunately, such data are less important as they are often muted before or after migration. While our method works well for deep water data, it may be less effective for shallow water data that have low S/N and contain abundant 3D diffractions, reflections and multiples of varying emergence angles within the same application window. In this case, a postmigration deghosting method, such as the joint deconvolution method proposed by Soubaras (2010), is more applicable.

We note that if we swap shots and receivers when generating mirror data our bootstrap deghosting algorithm can also be used for shot deghosting.

Acknowledgments

We would like to thank Jinjun Liu for his algorithm for mirror data generation, Qiaofeng Wu for tests on synthetic data, Min Yang and Bing Bai for tests on real data. Special acknowledgements go to Shuo Ji and Sheng Xu for constructive discussions. We also thank Kristin Johnston for editing this paper.
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