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An Effective Ghost Removal Method for Marine Broadband Seismic Data Processing

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SUMMARY

Ghost reflections are the main limiting factor of the resolution of marine seismic data. Several acquisition and processing techniques have been proposed to address this problem. Some of the recently introduced acquisition methods are over/under streamer, slanted streamer, geostreamer (hydrophone/geophone streamer). These methods adequately address the notch introduced by the ghost reflections but do not address the loss of the critical part of the injected source wavelet spectrum, the low frequencies.

Here we present a method of de-ghosting which not only addresses the notch problem introduced by the ghost reflections but also recovers the low frequency component of the source signature. Our method of recursive de-ghosting outputs seismic data is if recorded away from the ghost generating air/water contact. We demonstrate the effectiveness of the method on an over/under streamer seismic data.
Introduction

The wavefield initiated by the air gun explosion in marine seismic exploration initiates pressure wavefield in all directions, including upward. The upward traveling source wavefield reflects from the sea surface and follows the down-going wavefield with a certain delay. When these waves are recorded at the receivers, all the reflections appear as double image. This is known as the source ghost. Additionally, the wavefield that arrives at the receiver locations continues its upward travel and reflects from the sea surface and is recorded again. This is known as the receiver ghost. These delayed reflections from the sea surface are the main factors limiting the resolution of marine seismic data. Several acquisition (Day et. al., 2013, Sablon et. al., 2011) and processing (Aytun, 1999) techniques have been proposed to address this problem. Some of acquisition methods are over/under streamer, slanted streamer, geostreamer (hydrophone-geophone streamer). These methods adequately address the notch introduced by the ghost reflections but most of the time do not address the loss of the critical part of the wavelet spectrum; the low frequencies.

Here we present a method of de-ghosting which not only addresses the notch problem introduced by the ghost reflections, but it also recovers the low frequency components of the source signature. The output from this method is seismic data recorded as if the source and receiver are not placed near the air/water contact. We demonstrate the method on an over/under streamer data.

Deghosting Methodology

In conventional marine seismic surveys, the air-guns and streamer(s) are placed at certain predefined depths below the sea surface. The decision of source/receiver depths for any given survey is based on several parameters, such as weather conditions, desired frequencies, equipment type, etc. In addition to those conditions, the location of the notch in the frequency spectrum created by the surface ghost reflections is something that must be considered. Ghosting is a direct result of placing the source and receivers below a sharp discontinuity, which is the water/air contact in marine acquisition. Figure (1) is an illustration of the primary and ghost reflections due to source, receiver and their combination ghost reflections.

Figure 1 Illustration of marine seismic ghost reflections. Event and ray path marked 1 is an illustration of the primary reflection, 2 is an illustration of the source ghost, 3 is an illustration of the receiver ghost and 4 is an illustration of the ghost reflection recorded due to source and receiver ghost interaction.

Ghosts on seismic data exhibit themselves as notches in the frequency domain (Figure 2). Notice that the addition of a ghost reflection is not only impacting higher frequencies by introducing notches but also causes loss of amplitudes at the lower frequencies. The impact of two ghost reflections, one for the source side and one for the receiver side further complicate the spectrum that by adding notches in the spectrum at the appropriate harmonics. As show in Figure (1), the presence of two ghost reflections introduces a third event that is the interaction of the two ghosts and it is recorded in the same polarity as the primary reflection. The train of reflections in the illustration in Figure (1) can be formulated as:

\[ W(t) = U(t) + \alpha U(t - \tau_s) + \beta U(t - \tau_R) + \alpha \beta U(t - (\tau_s + \tau_R)) \]  (1)

where \( W(t) \) is the total wavefield as a function of time, \( U(t) \) is the ghost free upgoing wavefield as a function of time, \( \alpha \) and \( \beta \) are the source and receiver side reflection coefficient at the surface plus the
exponential decay due to the delayed path, \( \tau_S \) is the source ghost (delay time), \( \tau_R \) is the receiver ghost (delay time). We can rewrite equation (1) as:

\[
U(t) = W(t) - \alpha U(t - \tau_S) - \beta U(t - \tau_R) - \alpha \beta U(t - (\tau_S + \tau_R))
\]

(2)

Equation (2) is the classical definition of a 3 pole recursive filter (Akaike, 1969). Notice that equation (2) is a combination of \( W(t) \), total wavefield (including ghost reflections) and \( U(t) \), the upgoing wavefield (ghost free). If we know the ghost parameters (\( \alpha, \beta, \tau_S, \tau_R \)), we can obtain the upgoing wavefield starting via a recursive filter. This will result in seismic data output as if recorded away from the ghost generating interface.

The problem of obtaining the unknown ghost parameters in equation (2) can be formulated as a non-linear inversion process. We implemented two minimization criteria, minimum energy and minimum absolute amplitude. Since the process is recursive, it is very sensitive to the non-reflective noise in the seismic data. Direct arrivals, swell noise etc. will be amplified by this process and an additional step of removing such noise before the recursive de-ghosting process described in equation (2) is necessary. The results of ghost removal will depend on how successful data preconditioning step is.

**Figure 2** The spectrum of a single reflection and the addition of a receiver ghost and source ghost reflections. Notice that the notches fore receiver ghost only are appearing at multiples of 62.5Hz, as described by \( n f = V_{\text{water}} / \lambda \) where \( n = 1, 2, 3 \ldots \), \( f \) is the notch frequency, \( \lambda \) is twice the receiver depth and \( V_{\text{water}} \) is the water velocity.

**Over/Under streamer example**

Our example is from an over/under cable acquisition, one of the field methods specifically designed to address the issue of notches in the spectrum due to ghost reflections. Two cables are towed at two depth levels directly above one another. The over cable in this survey is placed at 8 m depth and the under cable is placed at 15 m depth. The under cable length is 8 km and the over cable is 6 km. A close up view of the water bottom reflections from the two streamers is given in **Figure (3a)**. As expected, frequencies from the over cable can be used to supplement the receiver notch seen at about 50 Hz on the under cable (**Figure 3**). Along with the clear notches in the spectrum, notice the lack of low frequencies in both spectrums. Therefore the availability of two level recording will not help resolve the loss of the low frequencies. In fact, the loss of low frequency will be an issue for any acquisition method, including slanted cable and geostreamer.

This seismic data was acquired with a 3 dB low cut analogue filter at 6 dB/oct slope, with the aim of recording the low frequencies as much as possible. With the introduction of the ghost reflections into the wavefield, not only the low frequencies are attenuated, but also the mid-range frequencies have amplitude and phase values that are quite different from the undisturbed ghost free waveforms. In essence, the discontinuities near the source and receiver suppresses some of the frequencies and at the same time amplifies other, but all with wrong phase values. A least squares derivation of the ghost parameters in equation (2) for each trace followed by deghosting lead to the images given in **Figure (3b)**. The sections and the traces were processed independently from one another. Notice the close similarity of the over and under prestack sections after the deghosting process.

Full process of the field data was carried out in to workflows, deghosting being the only difference. In both cases we did not include any wavelet shaping since we wanted to have a one to one undisturbed comparison. The sections are displayed after static shift correction due to depth differences. Notice the discrepancy between the over and under streamer sections before deghosting and the similarity of
the two after deghosting. There was not any matching applied between the sections, only independent ghost parameter estimation for each trace. The high degree of similarity of the two sections is a confirmation of the success of the deghosting process and in fact, the presence of an additional level recording does not add any value.

**Figure 3** Water bottom reflections from the over and under streamers (a) before and (a) after deghosting. Notice the clear presence of the source, receiver and their combination ghost reflection train as illustrated in (a). The waterbottom and source ghost remain constant between the over/under cables records whereas the receiver and the combination ghost is located at different times. The average spectrum of the range of traces is given at the bottom.

**Figure 4** Close up display of the brute stacks from the under cable before and after deghosting. Sections are scaled globally. Notice the less ringy nature of deghosting and the impact on the interpretation of the event marked with the red arrows.

**Tau-P versus X-T domain deghosting**

In the strict sense, equation (2) is only valid for Tau-P domain where the reflections are sorted by their arrival angles and thus the source and receiver ghost delay times are constant for the duration of the trace. But the same equation can be applied to the X-T data, as long as there are not many complex arrivals from different angles, which is the case for most of the deep water surveys.

Implementation of deghosting in the X-T domain has some advantages over deghosting in the Tau-P domain. Equation (2) represents a 3 pole recursive filter in the case of a continuous data. Pole filters are very sensitive to the location and amplitude of the pole coefficients. That is why in our opinion the statistical filters are not successful, because the correlation analysis does not have the necessary sensitivity. On the other hand, small scale deviations from the exact location in recursive filter
application may lead to unstable results. This property that may seem like a handicap is in fact an advantage which can be used to pick the small scale deviations of the cable and even the impact of the wave heights at the time of the arrivals. These small scale variations cannot be incorporated into the Tau-P transform, which, in some cases, may lead to dispersing the ghost reflection. Additionally, equation (2) can be expanded to include an angle term and the analysis can be carried in sliding windows. This expansion will still not address the multiple primary arrivals at the same time sample from different angles. The direct arrival, which maps in a unique slope trace in the Tau-P domain, is one of the events that does not obey equation (2) and needs to be removed before the application of deghosting process in the X-T domain.

Figure 5 The stack of (a) over, (b) under cable datasets and their (c) average and the stacks after deghosting process of the (d) over, (e) under cable datasets and their (e) average. Notice that the over, under and average sections before deghosting exhibit significant differences whereas after deghosting process, they are virtually identical. Static time shifts have been applied to bring the over and under sections to the same reference depth beforehand.

Conclusions

The presence of discontinuity near the source and receivers in marine processing creates ghost reflections which greatly reduce the resolution of seismic data. The greatest impact of the ghost reflections is in the low frequency part of the wavelet, which is the most sought after part in FWI and inversion algorithms. We presented a method of deghosting which is capable of removing the effects of ghost reflection on the seismic spectrum by recovering the ghost free wavefield. The method is equally applicable in the x-t domain and tau-p domain. We demonstrated the validity and applicability of the method for on an over/under cable dataset.

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References


