Deghosting Method

When source and/or receivers are placed near a sharp discontinuity, such as the air/water contact, secondary reflections occur which follow the primary reflections with certain delays. These ghost reflections not only distort the waveform by introducing notches in the spectrum but also result in attenuating the low frequency component of the recorded wavefield. The decision to place the source and/or receivers at a certain depth is governed by several factors, including the notch in the frequency spectrum of the recorded wavefield, caused by the proximity to the discontinuity. Placing the source and/or receivers close to the surface pushes the notches in the spectrum to higher frequencies but at the same time attenuates more of the low frequencies. A deghosting method should not only fill in the missing frequencies at the notches but should also recover the low frequencies. In essence, when there is ghost reflections in a system, no frequency component of the source waveform is correct. While low and notch frequencies are being strongly attenuated, everywhere else they are amplified via constructive interference.

Yilmaz et al (2015) presented a method of deghosting via recursive filters where the ghost parameters are estimated via least squares and the ghosting mechanism is run with reverse polarity to cancel them. The total wavefield recorded at a surface for a plane wave source and a point receiver can be formulated as given in equation (1). In this equation, $U(t)$ is the ghost free upgoing wavefield, $W(t)$ is the total wavefield recorded due to upgoing wavefield plus the source and receiver ghost reflections. In equation (1), $\tau_s, \tau_R, \alpha$ and $\beta$ are the unknown ghost generating system parameters. Rewriting equation (1) by reordering gives us a method of deghosting (equation 2) which is running the ghost mechanism with the reverse polarity, thus canceling the effects of the ghost on the total wavefield. Dethosting via equation (2) requires the estimation of the ghost generating system parameters.

$$W(t) = U(t) + \alpha U(t - \tau_S) + \beta U(t - \tau_R) + \alpha \beta U(t - \tau_S + \tau_R)$$  \hspace{1cm} (1)$$

$$U(t) = W(t) - \alpha U(t - \tau_S) - \beta U(t - \tau_R) - \alpha \beta U(t - \tau_S + \tau_R)$$  \hspace{1cm} (2)$$
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Strictly speaking, equation (2) is only valid for plane sources, where all the data is sorted into arrival angles and the delay between the primary upgoing wavefield $U(t)$ and the ghost reflection times $(\tau_S, \tau_R)$ is constant. This is not true for x-t domain since each sample has a slightly different arrival angle and thus the delay is slightly different. Despite this limitation, equation (2) can be used in deghosting x-t gathers, by designing a new operator at each trace (Yilmaz et al 2015). Particularly in the presence of deep water column surveys, the assumption of constant arrival angle is “nearly” true.

Deghosting in X-T domain

Equation (2) as described by Yilmaz et al (2015) is valid for tau-p domain, in the strictest sense. Plane wave simulation, i.e., linear tau-p transform includes summation of the traces with certain delays to emulate plane waves with different dips. The resulting gather is a simulation of a recording system where the receiver is at the former source location and the sources are cylindrical (2D) or planar (3D) sources as long as the receiver aperture. For 2D cases, the sampling in the inline direction is dense enough to allow a proper synthesis of plane waves but usually the streamer separation in 3D is too large to allow proper plane wave simulation. The limited aperture of the receiver arrays creates undesired edge effects close to the source which further degrades the quality of the simulated plane waves (Yilmaz et al, 1994). Additional constraints are needed for usable simulations which may lead to artifacts that may degrade the results of the recursive filter in equation (2).

Furthermore, the receivers are not always at the same depth but includes small deviations. On top of these deviations, the wave heights during the duration of the recording can have an impact on the ghost parameters in equation (2). Slanted summation for plane wave simulation will result in defocused primary and ghost reflections due to the small scale deviations from the perfect horizontal cable. Thus the deghosting process may not be able to recover the ghost free wavefield completely.

Therefore, an implementation in the x-t domain presents advantages regarding the precise estimation of the ghost parameters but the fact that they change with time needs to be accounted for. Instead of the time-invariant ghost parameters defined in equation (2), we can redefine them as $\tau_S(t)$, $\tau_R(t)$, $a(t)$ and $\beta(t)$. With the introduction of a time component, equation (2) can be rewritten to include the time varying ghost system parameters:

$$ U(t) = W(t) - a(t)U(t - \tau_S(t)) - \beta(t)U(t - \tau_R(t)) $$

Equation (3) is a highly underdetermined system since 4 parameters are required for each recorded value. Still, this can be solved by assuming constant values across a group of traces or alternatively constant gradients for a limited range of samples. It must be pointed out that the time-varying estimation of these parameters will account for the variation of these parameters as a function of time but will not account for arrivals at the same time from different angles.

An additional complication will be due to the direct arrival. Direct arrival does not obey the assumptions made in equation (2) or (3), and therefore is a “noise” for this method and must be removed prior deghosting. There are several methods which can be used for eliminating the direct arrival, such as dip filter or Karhunen-Loewe transforms.

Deghosting of a Dual Cable Acquisition

The destructive impact of ghost reflections has been recognized since the early times of marine exploration. Solutions have been sought after both in the processing steps (Aytun, 1999, Amoussen et al 2013) and acquisition.

An example of acquisition broadband seismic is the utilization of over/under cable method. In this method, two cables are towed exactly above one another. Then, the traces at the same receiver position are first corrected for the depth differences and then added together (Jiao et al 1998). Because of the depth differences, the receiver notches of the two traces are at different frequencies, thus supplementing one another. A similar method can be utilized for the source ghost where sources are placed at two depth levels and shots are acquired by alternating these sources. Such acquisitions do indeed address the loss of information at the notch frequencies but do not help in recovering the low frequencies because they are attenuated in both recording levels, due to the ghost reflections.

Yilmaz et al (2015) presented examples of deghosting applied to dual cable recordings and showed that after deghosting the stacks from the two levels are virtually identical (Figure 1). Their examples were generated using the method in the x-t domain with the assumption of constant ghost generating parameters. Here we will take a closer look at the deghosting results and demonstrate the time varying ghost generating parameter estimation.

Our example is a shot gather from the seismic data used in Figure 1. The original shot gather before deghosting along with its average amplitude spectrum is given in Figure 2a and the deghosting result with equation (2), i.e. constant ghost parameters, is given in Figure 2b. Reversing the ghost mechanism recovers the source generated low frequencies Notice that the notches have also disappeared.
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During this process no assumption has been made about the spectrum of the source wavelet and no other process than equation (2) has been applied to the traces in Figure 2b.

The assumption of constant ghost parameters is not necessarily true for the duration of the record even in the plane wave domain. The long recording times of 9+ seconds will result in changes in the surface wave patterns, which in turn will impact both the ghost delay times and the reflected amplitudes from the air/water contact. Therefore, plane wave domain (linear tau-p) implementations may also benefit from the time-varying estimation of the ghost system (not considered here).

Since the system of equations for estimating time-varying ghost parameters (equation 3) is highly underdetermined, we will assume constant parameters within predefined time gates and vary them between these windows. An estimation and consequent ghost removal is given in Figure 4. Figure 4a is the original gather before deghosting and Figure 4b is after deghosting, with average amplitude spectrums given below the gathers. The average spectrums of the two deghosting methods of constant and time varying parameter estimation do not show much difference. In both cases the uplift of the low frequencies and the recovery of the notch frequencies is apparent.

The main difference between time-invariant and time-variant deghosting is seen when we analyse the amplitude spectrums of progressive windows rather than the averages for the entire gathers. When compared to the spectrums in Figure 3b, the spectrums of the time-variant deghosting exhibit a much better behaviour, with no signs of overcompensation.

Conclusions

Here we extended the original time-invariant ghost parameter estimation and deghosting method of Yilmaz et al (2015) to include a time-variant estimation and deghosting. We demonstrated with real marine data example the effectiveness of the method. The extension to time-varying parameter estimation may be beneficial even for the case of plane waves where the data is sorted into constant angle of arrivals. The dynamic nature of the recording environment, the changing waves etc. may have impact on the ghost parameters. A time-varying estimation will account for all those changes.

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Figure 1: 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 (After Yilmaz et al 2015).
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Figure 2: Portion of a (a) raw shot gather and its average amplitude spectrum and (b) deghosted gather and its average amplitude spectrum. Constant ghost generating system parameters are used for ghost removal. Notice the boost of the low frequencies and the removal of the spectrum notches.

Figure 3: Amplitude spectrums of progressive windows from the (a) original gather before deghosting and (b) after dehosting for the same part of the data in Figure 2. Notice the overcompensation of the deghosting process with increasing time.

Figure 4: Portion of a (a) raw shot gather and its average amplitude spectrum and (b) deghosted gather and its average amplitude spectrum. Time varying ghost generating parameters are estimated in the deghosting step. Compare to time invariant deghosting in Figure 2.

Figure 5: Amplitude spectrums of progressive windows from the (a) original gather before dehosting and after (b) dehosting for the same part of the data in Figure 2. Time varying ghost generating parameters are estimated in the dehosting step. Compare to time invariant dehosting in Figure 3.
EDITED REFERENCES
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REFERENCES

