Green's theorem derived deghosting: fundamental analysis, numerical test results, and impact on ISS free-surface multiple elimination

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SUMMARY

Ghosts distort the data spectrum and affect the results of many seismic processing algorithms (e.g., multiple elimination, imaging, and inversion). Green's theorem derived deghosting is a wave theoretic method defined in the frequency-space domain with demonstrated capability, accuracy and flexibility. In this abstract, we present an analytic example and numerical test results of Green's theorem derived receiver and source side deghosting, and its impact on the inverse scattering series (ISS) free-surface multiple elimination.

INTRODUCTION / BACKGROUND

In marine seismic exploration, a source ghost is an event starting its propagation upward from the source, and a receiver ghost ends its propagation moving downward at the receiver. Ghosts have the same frequency content as their primaries and usually arrive shortly after them. The interference of the primaries and their ghosts reduces the low frequency content of the data, lowers the resolution, produces notches in the spectrum, and sometimes generates multiple images of the subsurface. The effective removal of ghosts has been a long standing problem in exploration seismology (Schneider et al., 1964; Amundsen et al., 1995).

The deghosting method derived from Green's theorem (Weglein et al., 2002; Zhang and Weglein, 2005, 2006; Zhang, 2007) is a wave theoretic algorithm defined in the frequency-space domain and can easily accommodate cables of any shape (e.g., slanted or ocean bottom). A complete Green's theorem derived deghosting procedure consists of two steps: receiver side deghosting in common shot domain and source side deghosting in common receiver domain, performed in any order. The receiver side deghosting method was first applied to synthetic datasets in Zhang (2007) and then a field dataset in Mayhan et al. (2011). In this Expanded Abstract, we first provide a brief introduction to the algorithm and then present an analytical example which provides a clear and transparent understanding of the method. Finally, numerical test results for deghosting and its impact on the ISS free-surface multiple elimination algorithm are shown and analysed.

THEORY

The equation for Green's theorem derived receiver side deghosting is

$$P_R'(\mathbf{r_g'},\mathbf{r_s},\omega)=\int_{m.s.}[P(\mathbf{r},\mathbf{r_s},\omega)\nabla G_0^+(\mathbf{r},\mathbf{r_g'},\omega) - G_0^+(\mathbf{r},\mathbf{r_g'},\omega)\nabla P(\mathbf{r},\mathbf{r_s},\omega)]\cdot\hat{\mathbf{n}}\,dS \qquad (1)$$

(Weglein et al., 2002, Equation 5). For all wavefield quantities in this abstract, e.g., $P(\mathbf{r_1},\mathbf{r_2},\omega)$, the leftmost spatial locator $\mathbf{r_1}$ represents the receiver coordinate and the rightmost $\mathbf{r_2}$ the source coordinate. $P(\mathbf{r},\mathbf{r_s},\omega)$ and $\nabla P(\mathbf{r},\mathbf{r_s},\omega)$ are the hydrophone measurement and its derivative, $P_R'(\mathbf{r_g'},\mathbf{r_s},\omega)$ is the receiver side deghosted wavefield, $G_0^+(\mathbf{r},\mathbf{r_g'},\omega)$ is the causal Green's function of the reference medium (chosen as water), and $\int_{m.s.} dS$ is an integration over the measurement surface. Note that the use of $\nabla P(\mathbf{r},\mathbf{r_s},\omega)\cdot\hat{\mathbf{n}}$ requires the availability of the field and its normal derivative on the measurement surface, which can be acquired from measurements using dual sensor cable or over/under cables, or derivation using the source wavelet and P on the measurement surface (Zhang, 2007, pp. 33-39). The former method allows deghosting for an arbitrary source distribution without needing to know the source and is the one we will use for the numerical tests in this abstract. The expression does not contain an integration along the source coordinates of the measured field. Hence, the Green's theorem receiver side deghosting only requires the data from a single shot experiment and can be applied independently to each shot gather.

Using arguments based on the reciprocity principle, a similar algorithm can be derived to address source side deghosting

$$P_{SR}'(\mathbf{r_g'},\mathbf{r_s'},\omega)=\int_{sources}[P_R'(\mathbf{r_g'},\mathbf{r},\omega)\nabla G_0^+(\mathbf{r},\mathbf{r_s'},\omega) - G_0^+(\mathbf{r},\mathbf{r_s'},\omega)\nabla P_R'(\mathbf{r_g'},\mathbf{r},\omega)]\cdot\hat{\mathbf{n}}\,dS. \qquad (2)$$

Here $\int_{sources} dS$ is an integration over the sources, P_R' is the receiver side deghosted data, and $\nabla P_R'\cdot\hat{\mathbf{n}}$ is its normal derivative over the sources. Our numerical testing uses over/under sources. However, this does not imply a need for two sources because following Zhang (2007) the second source line can be predicted using Green's theorem.

Further details behind the theory can be found in the companion paper by Mayhan et al. (2012).

1D ANALYTIC EXAMPLE

A simple 1D normal incidence analytic example can provide useful insights into the Green's theorem derived deghosting algorithm.

The causal whole space Green's function in the reference medium has the form

$$G_0(z,z_g',\omega)=\frac{e^{ik|z-z_g'|}}{2ik}, \qquad (3)$$

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and

$$P(z_g, z_s, \omega) = R\left[\frac{e^{ik(2z_{wb}-z_g-z_s)} - e^{ik(2z_{wb}-z_g+z_s)}}{2ik}\right.$$
$$\left.+\frac{-e^{ik(2z_{wb}+z_g-z_s)} + e^{ik(2z_{wb}+z_g+z_s)}}{2ik}\right]. \quad (4)$$

represents the water-bottom reflected primary and its source, receiver, and source and receiver ghosts respectively. Here $k = \omega/c_0$ is the wave number, R is the water-bottom reflection coefficient, z_g is the receiver depth, z_s is the source depth, z_{wb} is the water-bottom depth, and we suppose the free surface is at depth 0 and the sources and receivers are placed between free surface and water bottom ($0 < z_s < z_g < z_{wb}$).

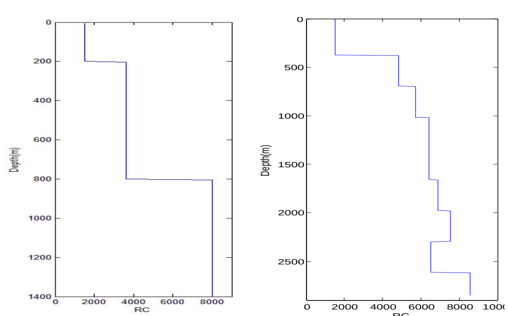
Substitute the Green's function G_0 and the wavefield P into Equation 1 to perform receiver side deghosting,

$$\begin{aligned} &P^{deghosted}_{receiver}(z'_g, z_s, \omega) \\ &= [P(z, z_s, \omega)\frac{dG^+_0(z, z'_g, \omega)}{dz} - G^+_0(z, z'_g, \omega)\frac{dP(z, z_s, \omega)}{dz}]|_{z=z_g} \\ &= R\left[\frac{e^{ik(2z_{wb}-z'_g-z_s)} - e^{ik(2z_{wb}-z'_g+z_s)}}{2ik}\right]. \end{aligned} \quad (5)$$

Here we assume $z'_g < z_g$, which means the predicted cable is shallower than the actual cable. The receiver side ghosts are removed and only the primary and its source side ghost remain in Equation 5. Further, we feed the receiver side deghosted data into Equation 2 for source side deghosting,

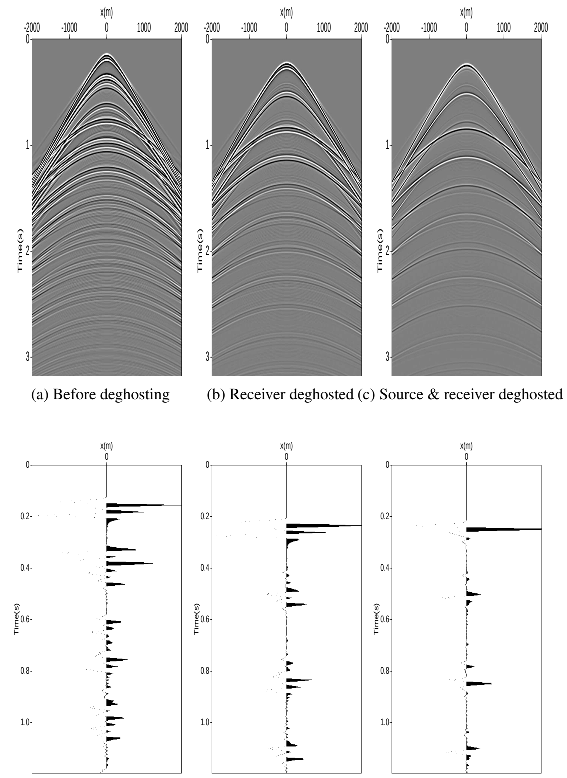
$$\begin{aligned} &P^{deghosted}(z'_g, z'_s, \omega) \\ &= [P^{deghosted}_{receiver}(z'_g, z, \omega)\frac{dG^+_0(z, z'_s, \omega)}{dz} \\ &\quad - G^+_0(z, z'_s, \omega)\frac{dP^{deghosted}_{receiver}(z'_g, z, \omega)}{dz}]|_{z=z_s} \\ &= \frac{Re^{ik(2z_w-z'_g-z'_s)}}{2ik}. \end{aligned} \quad (6)$$

Again we assume $z'_s < z_s$ (e.g., the predicted source is shallower than the actual source). The result of equation 6 is the water bottom reflected primary, without source, receiver, or source and receiver ghosts.



(a) Model one (b) Model two

Figure 1: Models for testing.



(a) Before deghosting (b) Receiver deghosted (c) Source & receiver deghosted

(d) Before deghosting (e) Receiver deghosted (f) Source & receiver deghosted

Figure 2: Deghosting for model one.

NUMERICAL TESTING

The code used to compute the results in this abstract is the receiver side deghosting code written by J. Mayhan and released in 2011 to the M-OSRP consortium. Changes were made to accommodate both receiver and source side deghosting. As mentioned above, we will use data with over/under sources and over/under receiver cables.

The first tested case (Figure 1a) is a three layer model with sources at 30m and 32m and receivers at 140m and 142m, such that the ghosts are not overlapping either with the corresponding primaries or among themselves. Figure 2b is the result after receiver side deghosting and Figure 2c is source and receiver side deghosting. Figures 2d, 2e, and 2f are the wiggle plots of the zero-offset traces. We can see the ghosts are mainly removed and the algorithm works with good accuracy.

The second tested case (Figure 1b) has 9 layers and is extracted from a velocity model provided by TOTAL. In this case, we choose the sources at 5m and 7m and receivers at 10m and 15m, so the events and their ghosts are overlapping. The data, its receiver side deghosted result, and both source and receiver side deghosted result are in Figures 3a, 3b, and 3c, respectively. Figures 3d, 3e, and 3f represent the wiggle plots of the zero-offset traces and Figures 3g, 3h and 3i are the spectrum plots of their wavelets. The notch at $c_0/(2d) = 1500/(2*12)hz = 62.5hz$ is removed after receiver side deghosting and

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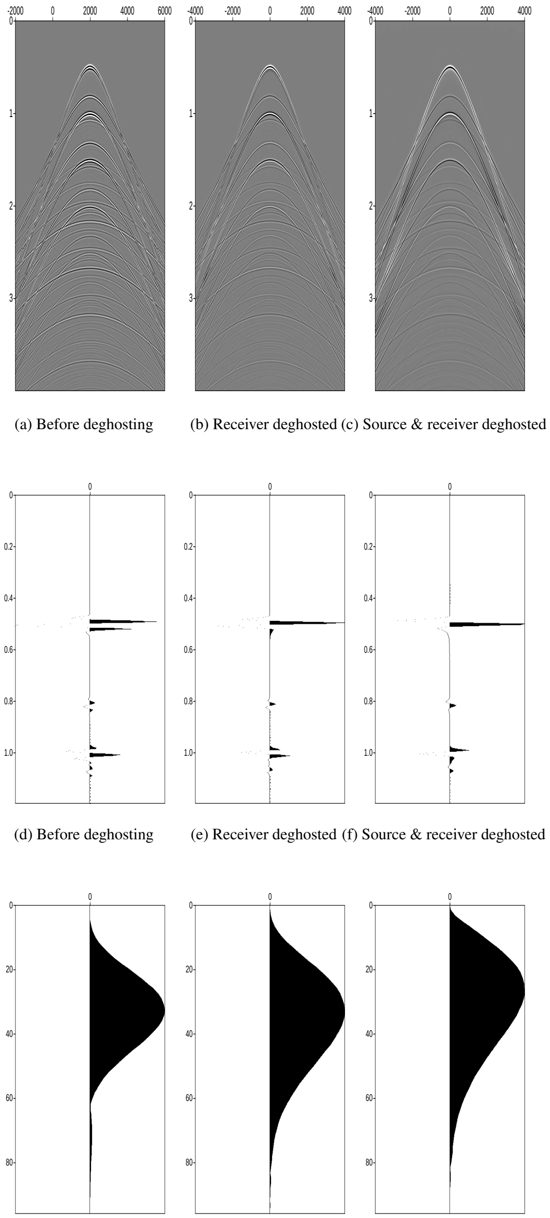


(a) Before deghosting (b) Receiver deghosted (c) Source & receiver deghosted

(d) Before deghosting (e) Receiver deghosted (f) Source & receiver deghosted

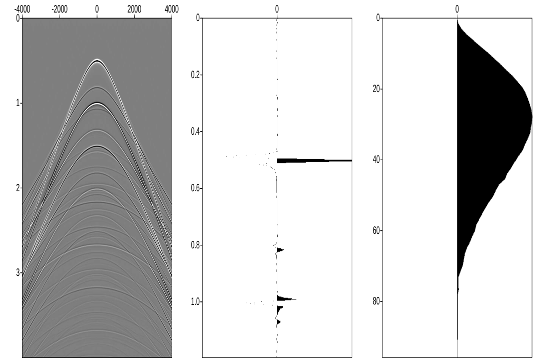
(g) Before deghosting (h) Receiver deghosted (i) Source & receiver deghosted

Figure 3: Deghosting for model two.

both receiver side deghosting and source side deghosting recover more low frequency information.

Results are positive and encouraging for both receiver side deghosting and source side deghosting when the data with dual sources and dual receiver cables are provided. Below we examine the consequences of two issues associated with the input data:

1. One issue is that in common practice, the derivative of the field (either through direct measurement or through dual cables) may not be available, especially on the source side. The industry trend has data with over/under streamers available today, and sometimes over/under sources, as well. However, Zhang (2007) uses Green's theorem to develop and exemplify a method that completely removes receiver and source ghosts with over/under streamers/receivers or with a single streamer and a source signature. The method does not require over/under sources. Another method that can be applied is based on the notion that the pressure field on the free surface D_{fs} is zero. This information can be used as another cable. Figure 4 shows the result when this property is used for model two. Comparing with the result using dual sources (Figures 3), the source ghosts are satisfactarily removed, although some high frequency information has been damaged. For low-frequency, this could be satisfactory.



(a) Shot plot (b) Wiggle plot (c) Spectrum plot

Figure 4: Source deghosting using $D_{fs} = 0$ for model two.

2. Another issue is the sensitivity to how accurate the depth of the cable is known due to a division if over/under cables are used. The Green's theorem method is robust to depth sensitivity (Zhang, 2007). Figure 5 compares the results when different depth intervals are used for receiver deghosting. The ghosts are well removed and not visible after deghosting when the cable intervals are 2 meters, 5 meters, or 10 meters. When the interval gets to 20 meters, the ghosts are still largely attenuated (comparing with Figures 2a and 2d).

IMPACT ON FREE-SURFACE MULTIPLE ELIMINATION

ISS free-surface multiple elimination method has the theoretical capability of predicting the exact phase and amplitude of multiples if its pre-requisites (source and receiver deghosting in particular) are satisfied. Figure 6 shows the result of applying the deghosted data into ISS free-surface multiple elimination algorithm. The right half is generated by directly subtracting the prediction from the input without any adaptive subtraction tool. We can see that all free-surface multiples are well attenuated and primaries are not touched.

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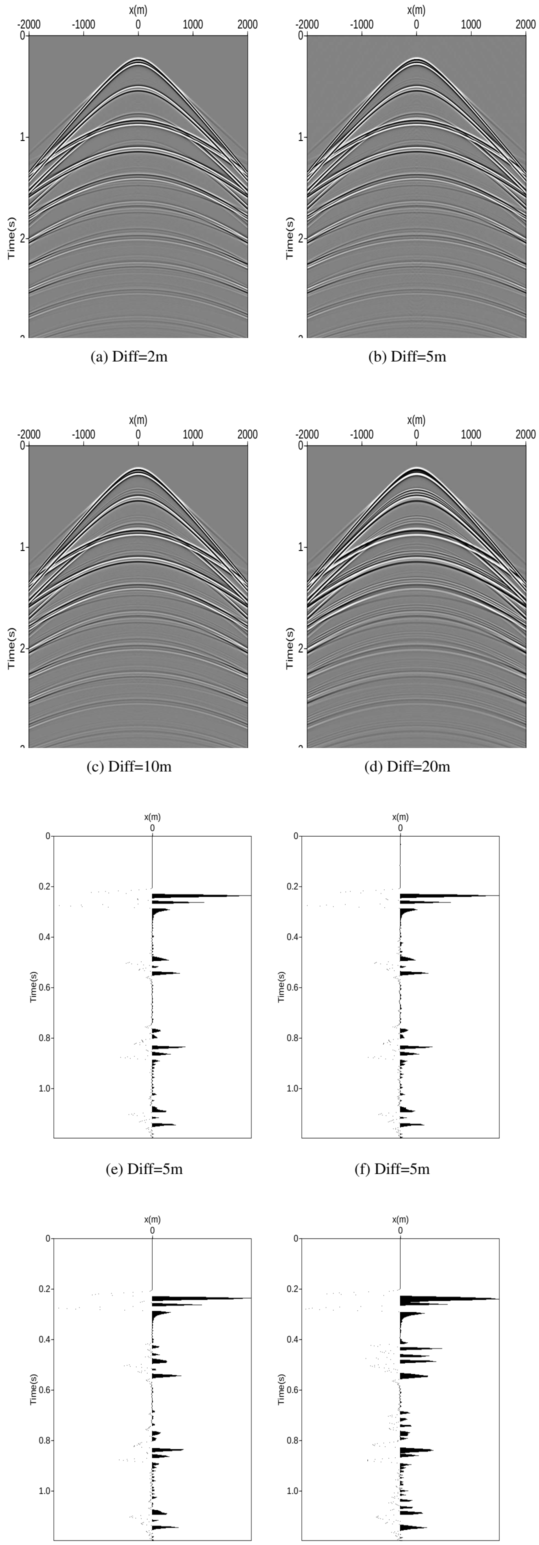


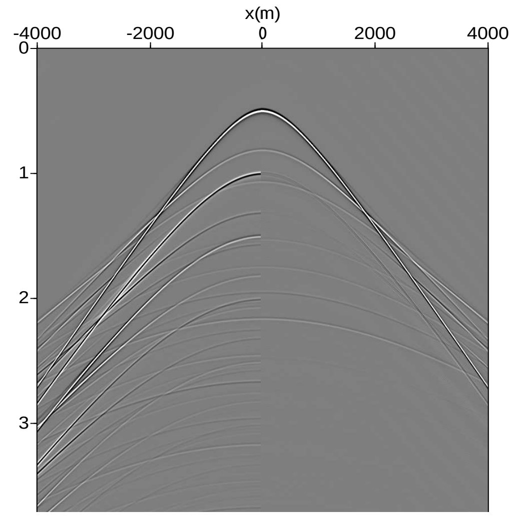
(a) Diff=2m (b) Diff=5m

(c) Diff=10m (d) Diff=20m

(e) Diff=5m (f) Diff=5m

(g) Diff=10m (h) Diff=20m

Figure 5: Compare different intervals between cables.



(a) (b)

Figure 6: ISS free-surface multiple elimination using deghosted data without adaptive subtraction for model two. (a) and (b) are the input (deghosted) and the output of the free-surface multiple elimination algorithm, respectively.

CONCLUSIONS

We tested Green's theorem derived source and receiver side deghosting algorithm using a 1D analytic example and two different sets of multi-offset 1D-earth synthetics with different source and receiver depth configurations. The complete source and receiver Green's theorem deghosting method (Zhang, 2007) exemplified in this paper requires either (1) a collection of shot records with over/under receivers or (2) a collection of shot records and the source signature. Over/under source lines are not needed. The companion paper Mayhan et al. (2012) complements the analysis and examples in this paper. Tests indicate that for most practical cases (less than 20 meters), the distance between over/under receiver cables would not be an issue. Green's theorem can predict the over/under source experiment required in Equation 2, without acquiring over/under source data. Alternatively, using the free surface can be a useful approach when the source depth is known. Tests of ISS free-surface multiple removal using the deghosted data confirms the good quality of the deghosted data. The results are positive and encouraging.

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