First application of Green's theorem derived source and receiver deghosting on deep water Gulf of Mexico synthetic (SEAM) and field data

James D. Mayhan, Arthur B. Weglein*, and Paolo Terenghi*, M-OSRP/Physics Dept./University of Houston**

Summary

We report the first use of Green's theorem derived source and receiver deghosting on deep water Gulf of Mexico synthetic (SEAM) and field data. Green's theorem derived deghosting has several qualities which separate it from previous deghosting methods: (1) it accommodates a multi-dimensional earth, (2) it doesn't require a Fourier transform over space coordinates, (3) it works in every depth of water, (4) it allows for any shape of measurement surface (e.g., a corrugated water bottom), and (5) it is consistent with wave theory processing methods. The context of Green's theorem deghosting is placed within a single consistent Green's theorem preprocessing and inverse scattering series (ISS) processing chain. Green's theorem derived deghosting theory is presented, and an algorithm implementing the theory is discussed. The algorithm has been tested on field data and several kinds of synthetic data with positive and encouraging results.

Introduction

Deghosting is a long standing problem (see, e.g., Robinson and Treitel, 2008) and is important because (1) removing the downward component of the recorded field (receiver deghosting) enhances seismic resolution with removal of notches and boosts low frequencies, and (2) it is a prerequisite for many processing algorithms including multiple elimination (ISS free surface multiples and internal multiples and SRME) and model matching 'FWI' that benefits from enhanced low frequency data. Hence, deghosting has benefit for both traditional seismic processing as well as playing an important role in all ISS based processing.

Green's theorem derived deghosting (Weglein et al., 2002; Zhang and Weglein, 2005, 2006; Zhang, 2007) has characteristics not shared by previous methods and is consistent with ISS wave theory methods that don't require subsurface information (Weglein et al., 2003). In Mayhan et al. (2011), we reported the first use of Green's theorem derived receiver deghosting on deep water Gulf of Mexico synthetic and field data. In this Expanded Abstract we report the first application of Green's theorem derived source and receiver deghosting on the same data.

While the ISS is independent of subsurface velocity (and in fact of all subsurface properties), it makes certain assumptions about its input data. Weglein et al. (2003) describe how every ISS isolated task subseries requires (1) the removal of the reference wavefield, (2) an estimate of the source signature and radiation pattern, and (3) source and receiver deghosting and how the ISS has a nonlinear dependence on these preprocessing steps. The fact that the ISS is nonlinear places a higher bar on preprocessing requirements. An error in the input to a linear process creates a linear error in its output, but the same error in ISS input creates a combination of linear, quadratic, cubic, etc. errors in its output.

The freedom of choosing a convenient reference medium means Green's theorem offers a flexible framework for deriving a number of useful algorithms. Methods that can be derived from Green's theorem include: wavefield separation (reference and scattered), wavelet estimation, ghost removal, and one way and two way wavefield continuation (RTM). Green's theorem methods are multidimensional, work in the $(\omega, \mathbf{r})$ data space (and hence, are simple to apply to irregularly spaced data), fully consistent with ISS wave equation processing, and make no assumptions about the earth. Therefore, Green's theorem preprocessing methods and ISS isolated task subseries processing are fully consistent. The delivery of the former always benefits the latter.

A brief aside on our terminology. The total wavefield P consists of the reference wavefield P_0 (which for a homogeneous reference medium doesn't experience the earth) and the scattered wavefield P_s (which does experience the earth). Ghosts begin their propagation moving upward from the source (source ghosts) or end their propagation moving downward to the receiver (receiver ghosts) or both (source/receiver ghosts) and have at least one upward reflection from the earth. Primaries and multiples are defined after the reference wavefield and source and receiver ghosts are removed. Primaries have only one upward reflection from the earth. Multiples have more than one upward reflection from the earth. Free surface multiples have at least one downward reflection from the free surface (air-water interface). Internal multiples have all their downward reflections below the free surface.

Theory—Receiver deghosting

Green's theorem derived deghosting establishes an integral relationship between the total wavefield P excited by a source located at $\mathbf{r}_s$ and its ghost free version P'. The relationship is valid within a region of space V (which must include $\mathbf{r}_s$) bounded by a closed surface S (Figure 1). For convenience, the region is chosen such that its lower boundary coincides with the measurement surface defined by the location of the active receivers.

To facilitate solving the problem at hand, a whole space of water is selected as a reference medium (where the

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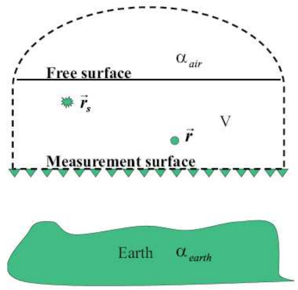

Fig. 1: *Configuration for deghosting using Green's theorem (Zhang, 2007, Fig. 2.10). α_{air} and α_{earth} are perturbations, the differences between the actual medium (air, water, earth) and reference medium (water).*

Green's function is known analytically). A perturbation operator, α, is introduced to characterize the difference between earth and reference properties. For this choice of reference medium, the perturbation may be seen as a quantity describing the capability of the earth to cause scattering (reflections, transmissions, diffractions, etc.) of the reference wave produced by the physical source located in the water column. For our choice of reference medium, the scattering potential is non-zero at and above the free surface and at and below the sea bottom. Therefore, scattering contributions to the wavefield P are expected, which may be interpreted as the product of secondary sources located in the reference medium.

If G_0^d is the Green's function for the reference medium, it can be shown (Weglein and Secrest, 1990) that the integral equation

$$P'_R(\mathbf{r}'_g, \mathbf{r}_s, \omega) = \int_{\mathrm{m.s.}} dS\, \hat{\mathbf{n}} \cdot \tag{1}$$
$$[P(\mathbf{r}, \mathbf{r}_s, \omega) \nabla G_0^+(\mathbf{r}, \mathbf{r}'_g, \omega) - G_0^+(\mathbf{r}, \mathbf{r}'_g, \omega) \nabla P(\mathbf{r}, \mathbf{r}_s, \omega)]$$

(Weglein et al., 2002, equation 5) identifies the contribution to P recorded inside V caused by sources located outside V. Here $\mathbf{r}'_g$ is the prediction point and $\mathbf{r}$ is the measurement point. If the region V is chosen to include water and air, as shown in Figure 1, the only sources are passive scattering sources at and below the water bottom. Hence, evaluating equation 1 with $\mathbf{r}$ in V (above the measurement surface and below the free-surface) provides the portion, P', of P traveling upwards from the subsurface to the receivers.

The implementation of the above theory is done in a straightforward manner. The Green's theorem algorithm computes the surface integral in equation 1. The method requires two wavefields as input, the pressure measurements P and their normal derivatives $\partial P/\partial z'$. The latter requires dual sensor cables or dual streamer cables.

Theory—Source deghosting

The last section has shown how Green's theorem can be applied to select the portion of the seismic wavefield that is up-going at a field position above the cable. The algorithm uses data from a single shot gather and the receiver coordinate as the integration variable. This section shows how the theory can be similarly applied for source deghosting, where the portion of the wavefield that is down-going at the source is sought. An application of reciprocity to the entire set of shot records allows the original receiver ghost removal to become a source ghost removal. Then a second application of Green's theorem over receivers results in source and receiver deghosted data. The direct Greens theorem based method for completely removing source and receiver ghosts requires a collection of single shot experiments where P and dP/dz_g are recorded on the measurement surface (in 2D along a towed streamer). The procedure of receiver deghosting produces the up-going wavefield at $\mathbf{r}$. If $\mathbf{r}$ is chosen shallower than the source ($\mathbf{r}_s$), applying the source-receiver reciprocity principle (i.e., swapping the source and receiver x, y, z coordinates) brings the problem back to the same setup as in receiver deghosting, where the total wavefield and its derivative are known on the receiver side and the up-going portion is sought. The analogous integral is

$$P'_{SR}(\mathbf{r}'_g, \mathbf{r}'_s, \omega) = \int_{\mathrm{sources}} dS\, \hat{\mathbf{n}} \cdot \tag{2}$$
$$[P'_R(\mathbf{r}'_g, \mathbf{r}, \omega) \nabla G_0^+(\mathbf{r}, \mathbf{r}'_s, \omega) - G_0^+(\mathbf{r}, \mathbf{r}'_s, \omega) \nabla P'_R(\mathbf{r}'_g, \mathbf{r}, \omega)].$$

The source and receiver deghosting steps described below essentially follow the method described and exemplified in Zhang, 2007, pp. 33-39. The one difference is that for each shot we input dual measurements of P and dP/dz_g along the towed streamer whereas in J. Zhang the source wavelet and P along the cable are used. The advantage of having the wavefield P and its normal derivative along the towed streamer is to allow deghosting for an arbitrary source distribution without needing to know or to determine the source.

In practice the algorithm in equation 1 is reused via the following steps: (1) Receiver deghosting is performed in the common shot gather (CSG) domain. The Green's theorem algorithm removes down going waves at the receivers, i.e., receiver ghosts and source-receiver ghosts. (2) Source deghosting is performed in the common receiver gather (CRG) domain. We sort the receiver deghosted data from CSGs to CRGs and swap the coordinates of the sources and receivers. The Green's theorem algorithm again removes down going waves at the receivers. Source deghosting assumes reciprocity between sources and receivers. Calculations and numerical tests (Mayhan et al., 2012) support this conclusion. Additional theory and complementary test results are reported in a companion paper by Wang et al. (2012).

Example: Flat layer model

In Figure 2, the upper left panel is the input data from a 1D layer model, designed so that deghosting is easy

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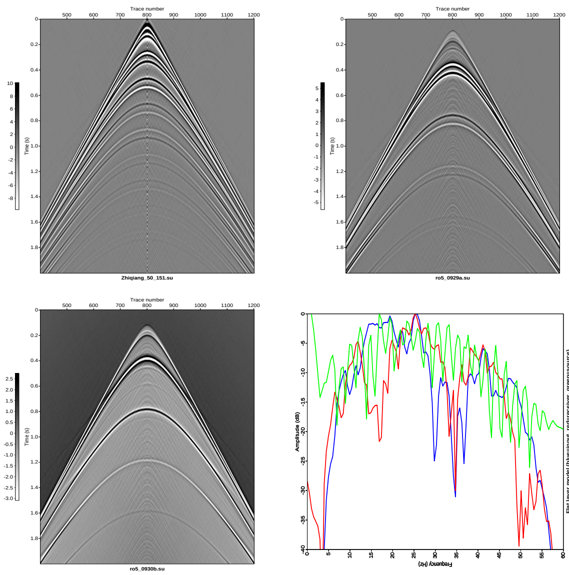

Fig. 2: *Flat layer model (sources at 50m and 52m, cables at 150m and 151m, water bottom at 300m): input data at 151m (upper left), receiver deghosted at 20m (upper right), source and receiver deghosted at 10m (lower left). Frequency spectra (lower right): input data (blue), receiver deghosted (red), source and receiver deghosted (green). The receiver notches (at intervals of 5Hz) and source notches (at intervals of 15Hz) have been filled in.*

to demonstrate. The depth of the receivers is chosen such that primaries and ghosts appear as distinct seismic events. We compute the event times for the data in the upper left panel of Figure 2, upper right panel, and lower left panel. We see that: (1) The events in the upper left panel of Figure 2 are (from the top) the direct wave G_0^d and its free surface (FS) reflection G_0^{FS}, the water bottom (WB) primary and its source ghost, the WB primary's receiver ghost and source/receiver ghost, the first free surface multiple (FSM) and its source ghost, and the first FSM's receiver ghost and source/receiver ghost. (2) In the upper right panel of Figure 2, all events are attenuated except the WB primary and its source ghost and the first FSM and its source ghost. (3) In the lower left panel of Figure 2, all events are attenuated except the WB primary and the first FSM. All source and receiver ghosts are removed.

Example: SEAM application

We applied Green's theorem to the SEAM dataset generated based on a deepwater Gulf of Mexico earth model (The SEG Advanced Modeling Corporation, 2011). We used the special SEAM classic dataset modeled to simulate dual sensor acquisition by recording the pressure wavefield at two different depths, 15 and 17m respectively. This dual sensor data consisted of nine sail lines for an equivalent wide azimuth towed streamer survey. The source interval is 150m by 150m while the receiver interval is 30m in both inline and crossline directions. Given the low frequency of the data (less than 30Hz) and the source and receiver depths of 15m and 17m, the ghost reflections overlap/interfere with non-ghost events in contrast to the previous flat layer model where events and their ghosts were well separated. In this SEAM data test, successful deghosting would correspond to a change in the wavelet shape. The result is shown in Figure 3. In the bottom panel, a window of the first three panels, we see there is no source notch to fill; the first source notch is at 44Hz which lies above the source frequency range (1–30Hz).

Example: Field data

We also applied the deghosting approach to a field survey from the deep water Gulf of Mexico. The data were acquired using dual sensor streamers comprised of hydrophones and vertical geophones. The top panel in Figure 4 shows a zoom in of an input shot record, the second panel displays the same traces after receiver deghosting, and the third panel displays the same traces after source and receiver deghosting. Note the collapsed wavelet in the output images. In the bottom panel note the gradual recovery of the shape of the wavelet: first by receiver deghosting (middle trace) and then by both source and receiver deghosting (right trace).

Conclusions

We have implemented Green's theorem derived source and receiver deghosting for the first time on deep water Gulf of Mexico synthetic and field data. Testing to date has shown the algorithm works with positive and encouraging results. Green's theorem derived deghosting has several qualities which separate it from previous deghosting methods. Green's theorem preprocessing (e.g., source and receiver deghosting and wavefield separation) and ISS processing (e.g., multiple removal and imaging) are a consistent set of methods where the preprocessing works in cooperation with the methods they are meant to serve, do not require a Fourier transform over receivers, and accommodate a not flat measurement surface. The direct Greens theorem based method for completely removing source and receiver ghosts requires a collection of single shot experiments where P and dP/dz_g are recorded on the measurement surface (in 2D along a towed streamer).

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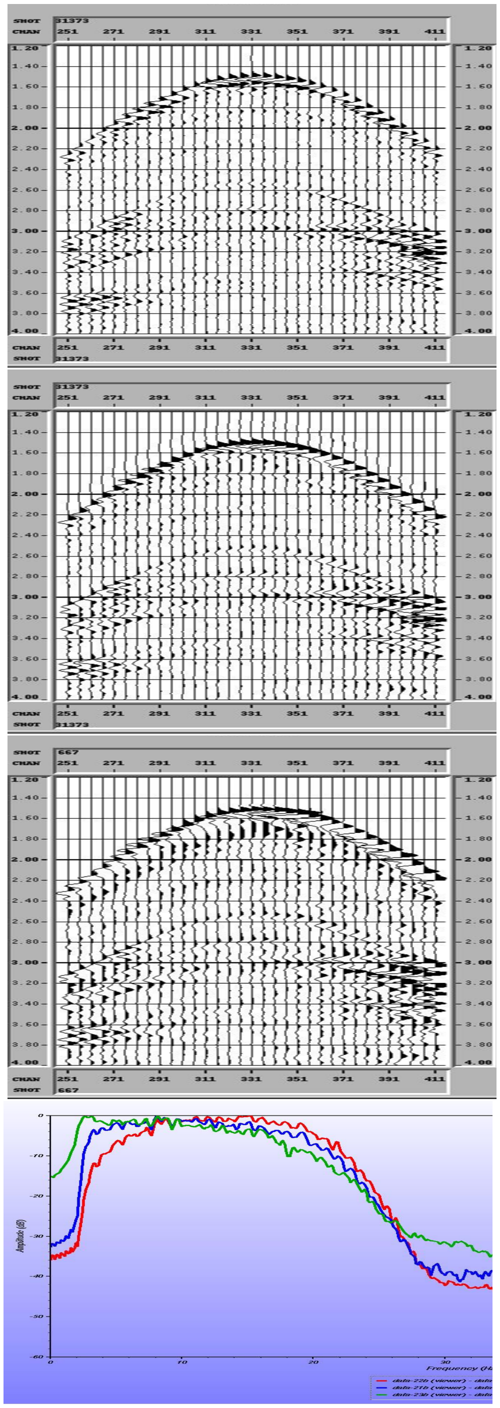

Fig. 3: *SEAM data, shot 131373: recorded data at 17m (top panel), receiver deghosted at 10m (second panel), source and receiver deghosted at 10m (third panel). Note the collapsed wavelets in the second and third panels. Frequency spectra (bottom panel): red=P at 17m, blue=receiver deghosted at 10m, green=source and receiver deghosted at 10m. The first source notch is at 44Hz which lies above the source frequency range (1–30Hz). Note the shift of the spectrum towards lower frequencies (which may be of interest to FWI).*

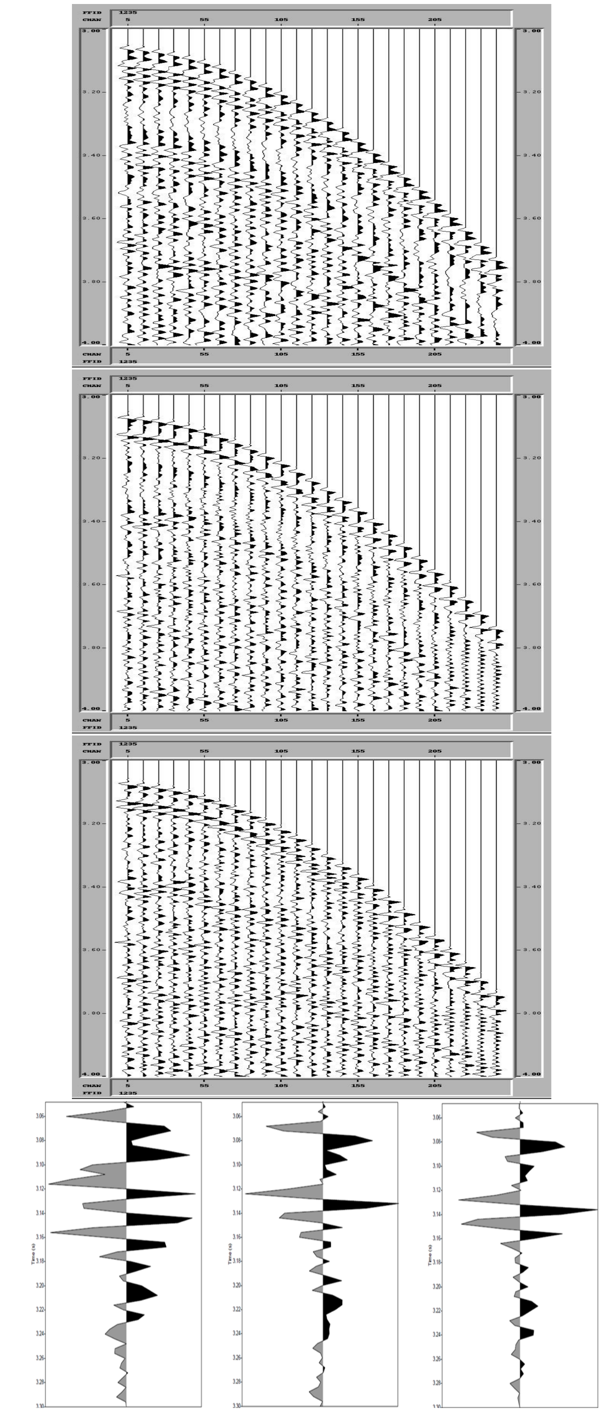

Fig. 4: *Field data: hydrophones at 22–25m (top panel), receiver deghosted at 10.5m (second panel), source and receiver deghosted at 8m (third panel). Note the collapsed wavelets in the second and third panels. Closeup of trace 5 in each of the above panels (bottom panel). Note the gradual recovery of the shape of the wavelet: by receiver deghosting (middle trace) then by both source and receiver deghosting (right trace). Input data courtesy of PGS.*

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