Extinction theorem deghosting method using towed streamer pressure data: Analysis of the receiver array effect on deghosting and subsequent free surface multiple removal

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Summary

In seismic exploration, acquiring full surface coverage with point receiver data is generally consistent with wave theoretic processing requirements. It is important to characterize the receiver array effect on any wave theory based seismic processing method. Deghosting is a prerequisite for free surface multiple removal (FSMR), internal multiple attenuation/elimination, and the imaging and inversion of primaries. The effectiveness of deghosting directly affects the performance of these methods. We propose a new method for deghosting towed streamer data that modifies and extends the Weglein et al. (2002) algorithm and make use of the wavelet method presented by Guo et al. (2005). We test the method for a simple 1D acoustic model and conclude that very accurate deghosting results can be obtained when using point receiver data. Useful but less accurate results can also be obtained when using receiver array data.

Introduction

In marine seismic exploration, the wavefield is recorded by receivers located on the towed streamer beneath the free surface. Wave theory calls for recording the wavefield and hence, well sampled point receiver data. However, in order to improve the signal/noise ratio, receiver arrays are widely used in practice. A receiver array is a set of receivers whose records are summed together so that the signal can be enhanced and the random noise suppressed. Since this summation will inevitably damage the actual wavefield, it is important to characterize its effect on any wave theoretical method. A common sequence of data processing is source wavelet estimation, deghosting, free surface multiple removal (FSMR), internal multiple attenuation/elimination, imaging and inversion. The order of these operations is important since the later stages require the earlier steps for their input. Hence, the performance of the later operations are directly affected by the performance of the earlier ones. Some recently developed processing techniques for imaging without the velocity (e.g., Weglein et al., 2000 and Shaw et al., 2003) and nonlinear inversion (Zhang and Weglein, 2005) put a very high bar on the data preprocessing (wavelet estimation, deghosting and multiple removal) since those techniques are nonlinear in the data. For example, in imaging without the velocity method, the amplitude of events in the data are used as well as arrival times. In this paper, assuming the source wavelet is available, we study the effect of the receiver array on the new deghosting method and the subsequent free surface multiple removal algorithm. Only point sources are considered in this paper. The generalization of this method and analysis to a source array is currently underway.

In the following, we briefly review our deghosting and FSMR procedures, and then we present the numerical point receiver and array test results followed by concluding remarks.

Theory

There is an extensive literature in the area of deghosting seismic data with papers that provide background, motivation and novel and effective methods (e.g., Schneider, 1964; Robertsson and Kragh, 2002; Weglein et al., 2002 and Amundsen et al., 2005). The deghosting method presented here provides certain advantages and begins with the relationship between the total field P, its vertical derivative $\frac{dP}{dz}$ and receiver deghosted data P^{up} (Weglein et al., 2002). The steps in this new proposed method are (1) Calculate the source wavelet from the pressure measurements on the towed streamer using the algorithm presented by Guo et al. (2005); (2) calculate the field P and its vertical derivative on the new surface (PMS) (Tan, 1992 and Osen et al., 1998) and (3) predict the up-going field on the receiver side (Weglein et al., 2002). The above steps can be formulated into a single algorithm:

$$
\begin{aligned}
P^{\mathrm{up}}(\mathbf{r},\mathbf{r}_s,\omega) = A(\omega)\int\limits_{PMS}\Big(&G_0^{DD}(\mathbf{r}',\mathbf{r}_s,\omega)\frac{\partial G_0^{+}(\mathbf{r},\mathbf{r}',\omega)}{\partial z'}\\
&-G_0^{+}(\mathbf{r},\mathbf{r}',\omega)\frac{\partial G_0^{DD}(\mathbf{r}',\mathbf{r}_s,\omega)}{\partial z'}\Big)d\mathbf{S}'\\
+\int\limits_{PMS}\int\limits_{MS} P(\mathbf{r}'',\mathbf{r}_s,\omega)\Big(&\frac{\partial G_0^{DD}(\mathbf{r}'',\mathbf{r}',\omega)}{\partial z''}\frac{\partial G_0^{+}(\mathbf{r},\mathbf{r}',\omega)}{\partial z'}\\
&-G_0^{+}(\mathbf{r},\mathbf{r}',\omega)\frac{\partial G_0^{DD}(\mathbf{r}'',\mathbf{r}',\omega)}{\partial z' z''}\Big)d\mathbf{S}'d\mathbf{S}'',
\end{aligned}
\tag{1}
$$

where,

$$
\begin{aligned}
A(\omega) = \int\limits_{MS}\Big[&P(\mathbf{r}'',\mathbf{r}_s,\omega)\frac{\partial G_0^{D}(\mathbf{r}'',\mathbf{r}_b,\omega)}{\partial z''}\\
&-G_0^{D}(\mathbf{r}'',\mathbf{r}_b,\omega)\int\limits_{MS}P(\mathbf{r}'',\mathbf{r}_s,\omega)\frac{\partial G_0^{DD}(\mathbf{r}'',\mathbf{r}''',\omega)}{\partial z'''\partial z''}d\mathbf{S}''\Big]d\mathbf{S}''\\
&/\Big(-G_0^{D}(\mathbf{r}^{b},\mathbf{r}_s,\omega)+\\
&\int\limits_{MS}G_0^{D}(\mathbf{r}'',\mathbf{r}_b,\omega)\frac{G_0^{DD}(\mathbf{r}''',\mathbf{r}_s,\omega)}{\partial z'''}d\mathbf{S}''\Big).
\end{aligned}
\tag{2}
$$

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In the above formula, the only input is hydrophone pressure measurements along the towed streamer. The source side deghosting procedure is to repeat step (2) and (3). The advantages provided by this method are (1) this method can predict the deghosted field directly from integration of the pressure along the towed streamer and (2) no finite difference method or frequency and depth relationship/assumption in computing the vertical derivative has been used. In this paper, we assume that the source wavelet has already been obtained through the stable algorithm given by Guo et al. (2005), which is also only from pressure only along the streamer.

After deghosting, we then perform FSMR. Various methods (e.g., Verschuur, 1991; Fokkema and van den Berg, 1993; Carvalho, 1992 and Weglein et al., 1997) provide approaches to FSMR. The FSMR procedure we use is derived from the inverse scattering series (Carvalho, 1992 and Weglein et al., 1997). The order of a free surface multiple is defined as the number of times the multiple has a reflection at the free surface. The first order FSMR exactly eliminates first order free surface multiples and at the same time alters the higher order free surface multiples so that they can be removed by higher order FSMR operations.

Numerical tests for towed streamer data

The numerical tests are based on a simple 1D acoustic model. Using the Cagniard-de Hoop method, we generate synthetic data for the model in Fig 1. The source wavelet is a Ricker wavelet. The advantage of the Cagniard-de Hoop method is that we can accurately calculate any specific event we are interested in so that we can compare it with the results predicted by our deghosting and FSMR algorithms.

Array effect on deghosting

The first test is to determine the accuracy of the deghosting result obtained from point receiver data. For this test, the receiver interval is 1m. The input data contains the direct wave, the primaries, multiples and their related ghosts. The reference wave (G_0) contains a component that travels directly from the source to the receiver (G_0^d) and its surface ghost (G_0^{fs}). Since the reference wave is downing-going at the receiver side, it should be eliminated after deghosting. The source and receiver deghosted results at several offsets are presented in Fig 2. Clearly, using point receiver data, the predicted deghosting results agree very well with the exact results.

For the array data test, the receiver array configuration we use is called Guardian and its parameters are shown in Fig 3. The records of the eight receivers are summed together with equal weights to produce one record at the center location of the array. The record/group interval is 12.5m. Through the numerical tests with receiver array data, we find that the direct wave cannot be removed at each of the four offsets. Since the reference wave can not be effectively removed using array data, it is necessary to remove it before deghosting. We can either mute it or predict the reference wave and subtract it from the original data. The deghosting results after we eliminate the direct wave are shown in Fig 4. We note that for the scattered field (1) at zero offset, both the amplitude and the phase of the primary and the first order free surface multiple are very accurate; (2) at large offsets, the phase of the scattered field is correct although there is a slight error in the amplitude.

For the scattered field, the results can be understood by considering how the receiver array changes the data at different offsets. At zero offset, for example, the receiver array is tangential to the wavefront. So the summation of the field produces less damage to the actual field. However, for large offset, the angle between the array and the wavefront is larger and thus, the field is more severely damaged. Therefore the results at zero offset are the most accurate.

For the reference wave, although the wavefront is tangential to the array at zero offset, the wave field at zero offset varies rapidly in space. Hence the damage of the array to the reference wave field is significant. However, at large offsets, the wavefront is almost orthogonal to the array. Hence the reference wave is much more affected in a negative way by the receiver array than the scattered field.

These numerical tests have demonstrated the effectiveness of the deghosting algorithm. When supplied with point receiver data, the results are very accurate. With receiver array data, the algorithm still produces useful results. Whether this usefulness is valuable or not depends on the objective. If the amplitude is not critical (structure mapping, for example), then this receiver array data is sufficient. For cases like inversion, where the amplitude is important, this angle/offset dependent error in the amplitude could produce serious errors in the prediction.

Array effect on free surface multiple removal

The point receiver deghosting results are substituted into the FSMR algorithm to remove the free surface multiple. Only the first order free surface multiple removal is performed. After the FSMR operation on the deghosted data, we obtain the first order FSMR results (Fig 5). As expected, the primary remains untouched and the first order free surface multiples have been eliminated.

For receiver array data, after eliminating the reference wave and deghosting, the FSMR is performed. Results are shown in Fig 6. As in the case of deghosting, the FSMR result is most accurate at zero offset. At larger offsets, there is a small error in the amplitude of the primary, which is reasonable since the small error already exists in the deghosting results. We can also see that the first order free surface multiple has been effectively reduced, although it has not been eliminated. This level of effectiveness is (once again) considered adequate or not depending on the objectives of the subsequent operations. For example, if the primary and the multiples are not

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overlapping and we want to separate the primary and multiples before interpretation, then this receiver array data result is probably adequate. It will not be adequate, however, if the primary event of interest happens to overlap with the free surface multiple.

Conclusions

Based on the source wavelet estimation algorithm presented by Guo et al. (2005), we have proposed a new deghosting algorithm that only require the pressure measurements along the cable. And both point receiver and receiver array data for a simple 1D medium have been supplied to the deghosting and FSMR algorithm in order to test the new method, and the effect of the receiver array. Useful results can always be obtained for both data sets. It is shown that when point receiver data is used, both the deghosting and FSMR results agree very well with the exact ones.

When receiver array data is provided, the direct wave has to be removed separately before deghosting. Compared to the exact results, the phase of deghosted results of the scattered field are very good while a small error in the amplitude is observed. Instead of been eliminated, the first order free surface multiple has been significantly reduced after FSMR.

The impact of those small errors in the deghosting and FSMR results depends on the subsequent processing objectives. For the deghosted result, if the results are just used to do structure mapping, then those small error could be tolerable. Serious prediction error could occur for cases like inversion since amplitude fidelity is critical. The result of FSMR testing produces the same general conclusion.

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Extinction theorem deghosting and receiver array effect

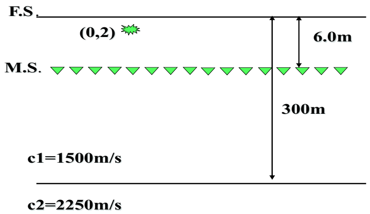

Fig. 1: One dimensional acoustic constant density medium

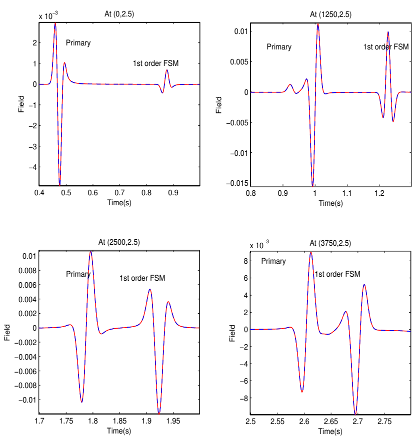

Fig. 2: Red solid: Exact source-receiver deghosted results; Blue dash: Calculated deghosting results (using point receiver data)

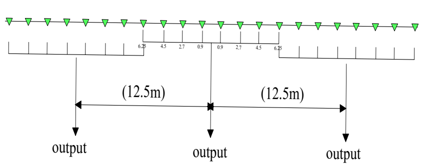

Fig. 3: Diagram of Guardian receiver array

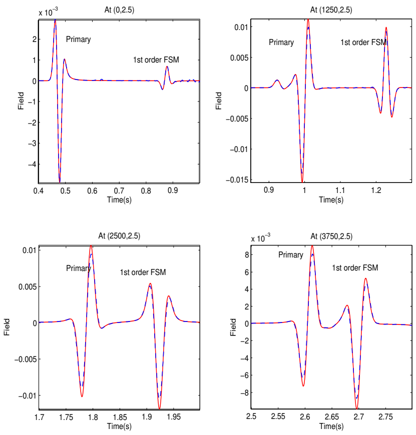

Fig. 4: Red solid: Exact source-receiver deghosted results; Blue dash: Calculated deghosting results (using receiver array data after the elimination of the reference wave)

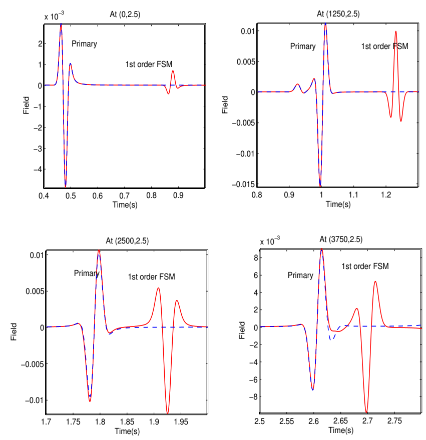

Fig. 5: Red solid: Exact source receiver deghosted data; Blue dash: After the first order FSMR (Using point receiver data).

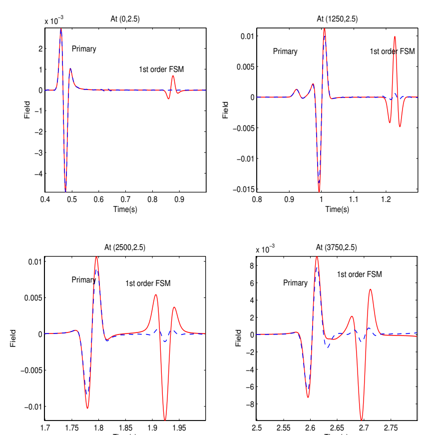

Fig. 6: Red solid: Exact source receiver deghosted data; Blue dash: After the first order FSMR (Using receiver array data).

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