A practical approach to prediction of internal multiples and ghosts

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ABSTRACT
Existing methods of internal multiple prediction are either computationally expensive or not automated. Here, based on stationary phase arguments, we introduce a method for predicting internal multiples that is not only fully automated but also computationally inexpensive. The procedure is completely data driven and requires no velocity information or reflector identification. An additional advantage of the proposed method is that it can also be used to predict source- and receiver-ghosts. The method, however, is limited to gently-dipping reflectors. Through synthetic examples and field data, we demonstrate the effectiveness of our methodology.

1 INTRODUCTION

In most stages of seismic data processing, it is assumed that the data is devoid of multiply scattered energy and contains only primaries. For example, the contribution of multiples to semblance panels (for velocity analysis) might result in erroneous picking of velocities. More importantly, most imaging algorithms are based on the Born approximation (single scattering). If not suppressed, the multiples might show up as spurious events in the image or even interfere with the primaries resulting in a degraded image.

Suppressing surface-related multiples using SRME (Verschuur *et al.*, 1992) is a standard practice now. Internal-multiple suppression, on the other hand, is not prevalent either because it is not fully automated or is computationally expensive. Berkhout & Verschuur (1997) proposed an iterative algorithm that includes extrapolating the shot records to a reflecting boundary responsible for the generation of the internal multiples. On similar lines, Jakubowicz (1998) proposed isolating the primary events on data followed by a convolution and deconvolution process to predict the internal multiples. The above two methods are not computationally intensive but are not fully automated. The inverse scattering approach of Weglein *et al.* (1997) and ten Kroode (2002) overcomes the above drawback and can also predict all possible internal multiples. The method, however, is computationally expensive.

In marine acquisition, since sources and receivers lie under the water surface, the air-water interface acts as a mirror. So the source would have a mirror source (ghost) above the surface; the same argument applies for the receiver as well. The source- and receiver-ghosts act as filters on the data with zeros at many frequencies. Such notch filters result in poor data quality by limiting the usable bandwidth of the data.

Existing methods of source- and receiver-ghosts suppression are primarily confined to the acquisition stage. Ziolkowski (1971) suggested recording at two different depths so as to fill in the zeros in the spectra. Similar recommendations have been made by others including Ghosh (2000). Such an acquisition is termed as over/under streamer acquisition (Moldoveanu *et al.*, 2007). The extreme case of all hydrophones having different depths was recently proposed by Soubaras & Whiting (2011). Ghosts could also be attenuated using dual-sensors (pressure and velocity) in a streamer (Carlson *et al.*, 2007).

Here, we introduce a practical approach to predict internal multiples with the primary aim of making the process computationally tractable as well as automatic. We also demonstrate how the proposed method could also be used to predict source- and receiver-ghosts.

2 INTERNAL MULTIPLES

As proposed by Jakubowicz (1998), any first-order internal multiple can be represented as a combination of three primaries. For example, in Figure 1a, the internal multiple $\mathcal{M}(\omega; x_A, x_E)$ is given by a convolution of primaries $\mathcal{P}_{ABG}$ and $\mathcal{P}_{FDE}$ followed by a deconvolution with the third primary $\mathcal{P}_{FCG}$. To automate the process,

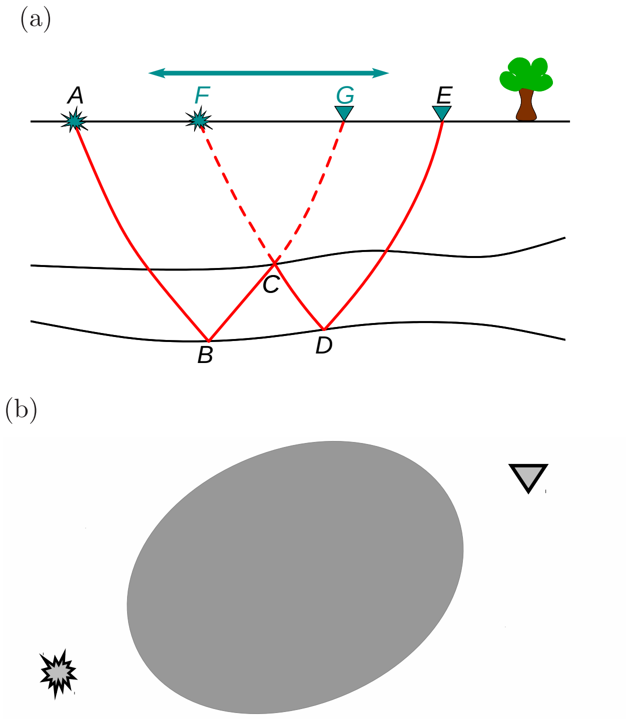

Figure 1. (a) Illustration of the computation of the internal multiple for a 2D acquisition. The summation zone (two-sided arrow) spans between the source at x_A and the receiver at x_E. The dashed red line denotes the primary that is common to the two other primaries and needs to be deconvolved in equation 1. (b) Plan view of a 3D surface-seismic acquisition. The grey area represents the proposed summation zone for a given source-receiver pair.

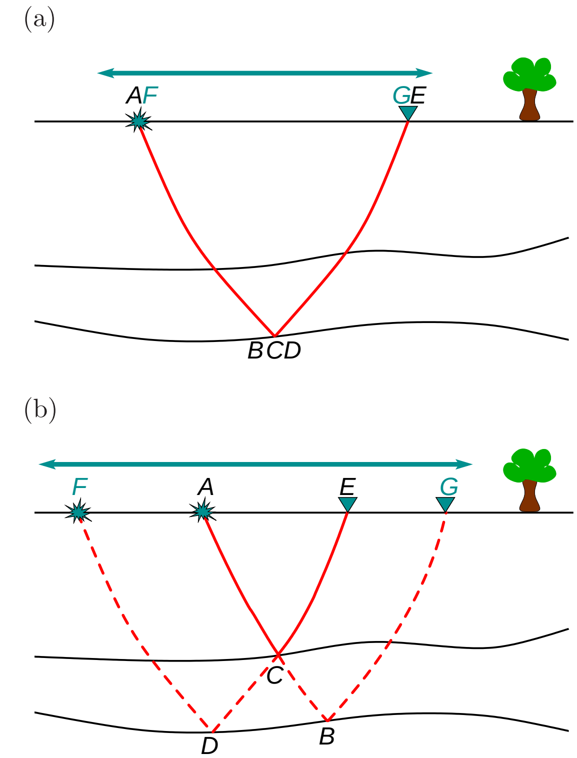

Figure 2. (a,b) Illustration depicting the need for limiting the zone of stationary phase integration to the interior of points A and E.

we replace the windowed primaries (Jakubowicz, 1998) with the full Green's function between the source and receiver. In practice, the internal multiple is obtained by following dual-summation over the locations of F and G:

$$\mathcal{M}(\omega; x_A, x_E) = \sum_{x_F} \sum_{x_G} \frac{\mathcal{U}(\omega; x_A, x_G)\,\mathcal{U}(\omega; x_F, x_E)}{\mathcal{U}(\omega; x_F, x_G)}, \quad (1)$$

where x represents the coordinate location, $\mathcal{U}$ is the recording between any source and receiver and ω is the frequency. Equation 1 predicts all orders of internal multiples at the same time. The above procedure is akin to seismic interferometry (Lobkis & Weaver, 2001; Wapenaar & Fokkema, 2006) that retrieves the Green's function between a virtual source and a receiver. The maximum contribution to the summation 1 comes from the stationary points at x_F and x_G. Note that the source signature inherent in $\mathcal{U}$ is retained in $\mathcal{M}$ because of the deconvolution operation in equation 1.

To predict only multiples, we limit the summation over locations x_F and x_G to a specific spatial location and aperture. It is crucial that points x_F and x_G lie in between the source at x_A and the receiver at x_E. If F and G lie outside this region (Figure 2b) or are close the points A and E (Figure 2a), respectively, then $\mathcal{M}(\omega; x_A, x_E)$ would contain primaries in addition to multiples. For example, in the special case of F coinciding with A and G coinciding with E, equation 1 would reduce to $\mathcal{M}(\omega; x_A, x_E) = \mathcal{U}(\omega; x_A, x_G)$, i.e. the 'predicted multiple' would be the Green's function between source at x_A and receiver at x_E and contain all primaries and multiples. A significant advantage of limiting the summation to a small aperture (determined by the source and receiver locations) is the reduction in computational cost. Summing over all possible locations of F and G would not only be prohibitively expensive, but also would not yield the internal multiples. In 3D, the summation can be carried over all surface points in a region (grey area in Figure 1b) that would likely contain the stationary points F and G. In the inverse scattering approach (Weglein *et al.*, 1997; ten Kroode, 2002), on the other hand, the summation is over all possible locations of F and G which adds to its computational cost.

The above modifications (using the Green's function in equation 1 and limiting the region of summation), however, result in other drawbacks and limitations. Usage of the full Green's function in equation 1 results in spurious events that have been extensively studied in seismic interferometry (Snieder *et al.*, 2006; Forghani & Snieder, 2010). However, since there is no stationary phase contribution to the spurious events, including more traces into the summation can suppress these events. Another drawback is that the near-offset prediction would not be accurate because of the proximity of F and G to A and E, respectively and also because of the limited number of traces going into the summation in equation 1. The limitation imposed on the region of summation assumes that the stationary points x_F and x_G lie in between x_A and x_G. This might not be the case for complicated geology and steeply dipping reflectors. For example, in Figure 2, since G lies outside the zone of integration (between x_A and x_E), the internal multiple would not be predicted accurately. So the method proposed here would work well for gently dipping layers and non-complicated subsurfaces. This is the primary limitation of our methodology compared to the methods of Berkhout & Verschuur (1997); Jakubowicz (1998); Weglein *et al.* (1997); ten Kroode (2002).

Synthetic examples: The synthetic test demonstrated here is that for a 1D velocity model comprising of 3 layers. A shot gather for this test is shown in Figure 3a. The predicted internal multiples are shown in Figure 3b. As explained above, the near-offset prediction is not accurate; however, the mid- and far-offsets clearly show the first- and second-order internal multiples.

3 GHOSTS

The geometry of a source+receiver ghost (Figure 4) is similar to that of an internal multiple (Figure 1a). So the same algorithm, that is used for predicting internal multiples, can be exploited for predicting source+receiver ghosts. The source+receiver ghost $g(\omega; x_A, x_G)$ between the source at x_A and the receiver at x_G is given by the dual-summation:

$$g(\omega; x_A, x_G) = \sum_{x_C} \sum_{x_E} \frac{\mathcal{U}(\omega; x_A, x_E)\,\mathcal{U}(\omega; x_C, x_G)}{\mathcal{U}(\omega; x_C, x_E)}. \quad (2)$$

Viking Graben data: The above ghost-prediction algorithm is tested on a 2D seismic line from North Sea, acquired over the Viking Graben (Keys & Foster, 1998). The shallow seafloor results in strong source and receiver ghosts. The data also contains strong reverberations most likely because of guided waves in the subsurface. A set of common-offset gathers from the field data and the predicted ghosts is shown in Figure 5. The common-offset sections (Figures **??** and **??**) are dominated by a few mono-frequency signals. In addition to the presence of guided waves, note the presence of surface-related and internal multiples in Figures **??** and **??**.

4 CONCLUDING REMARKS

Although not presented here, prediction of internal multiples should be followed by an adaptive subtraction method that eliminates these multiples from the data. The predicted ghosts could be suppressed in a similar fashion or using deconvolution techniques. Also, some interpretation of the predicted multiples might be necessary because of the generation of spurious events during the interferometry process. Additional processing steps might also be adopted to suppress these artifacts. The zone of summation (aperture) is an important variable in the algorithm. Too small an aperture would not predict any multiples and too large an aperture might lead to the presence of primaries in the prediction. Depending on the complexity of the subsurface, a few tests might be necessary to find this parameter.

The ability to predict internal multiples and ghosts using one single algorithm makes our methodology versatile and powerful. Although our method is limited to gently dipping interfaces, it should be applicable in numerous fields, especially in many onshore unconventional plays.

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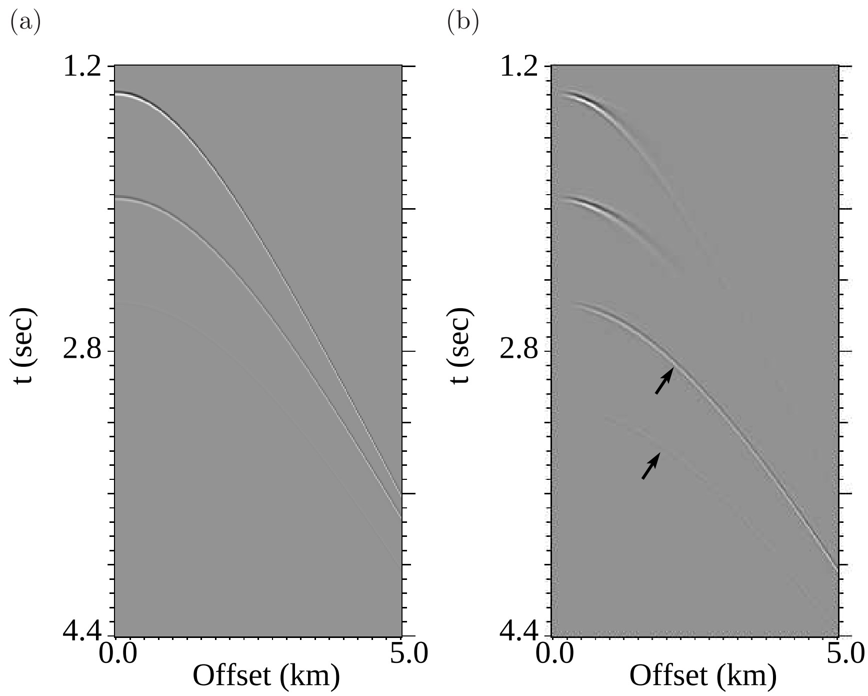

Figure 3. Shot-gather (a) and predicted internal multiples (b) for a layer-cake subsurface (three layers). The figures have been scaled to their respective maximum values. The internal multiples are too weak (compared to the primaries) to be seen in (a). An aperture equal to half the offset and centered about the mid-point was used in the prediction process. The arrows point to the predicted internal multiples.

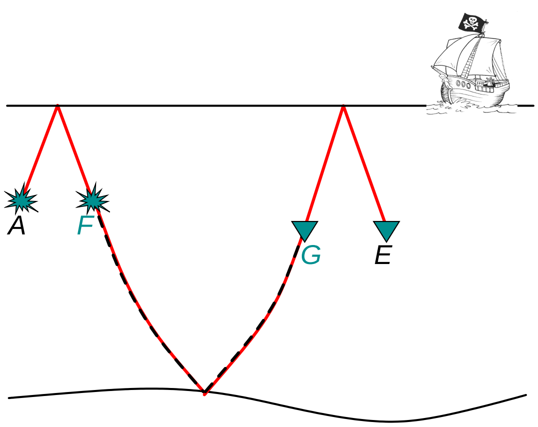

Figure 4. Illustration of the geometry behind source+receiver ghost computation.

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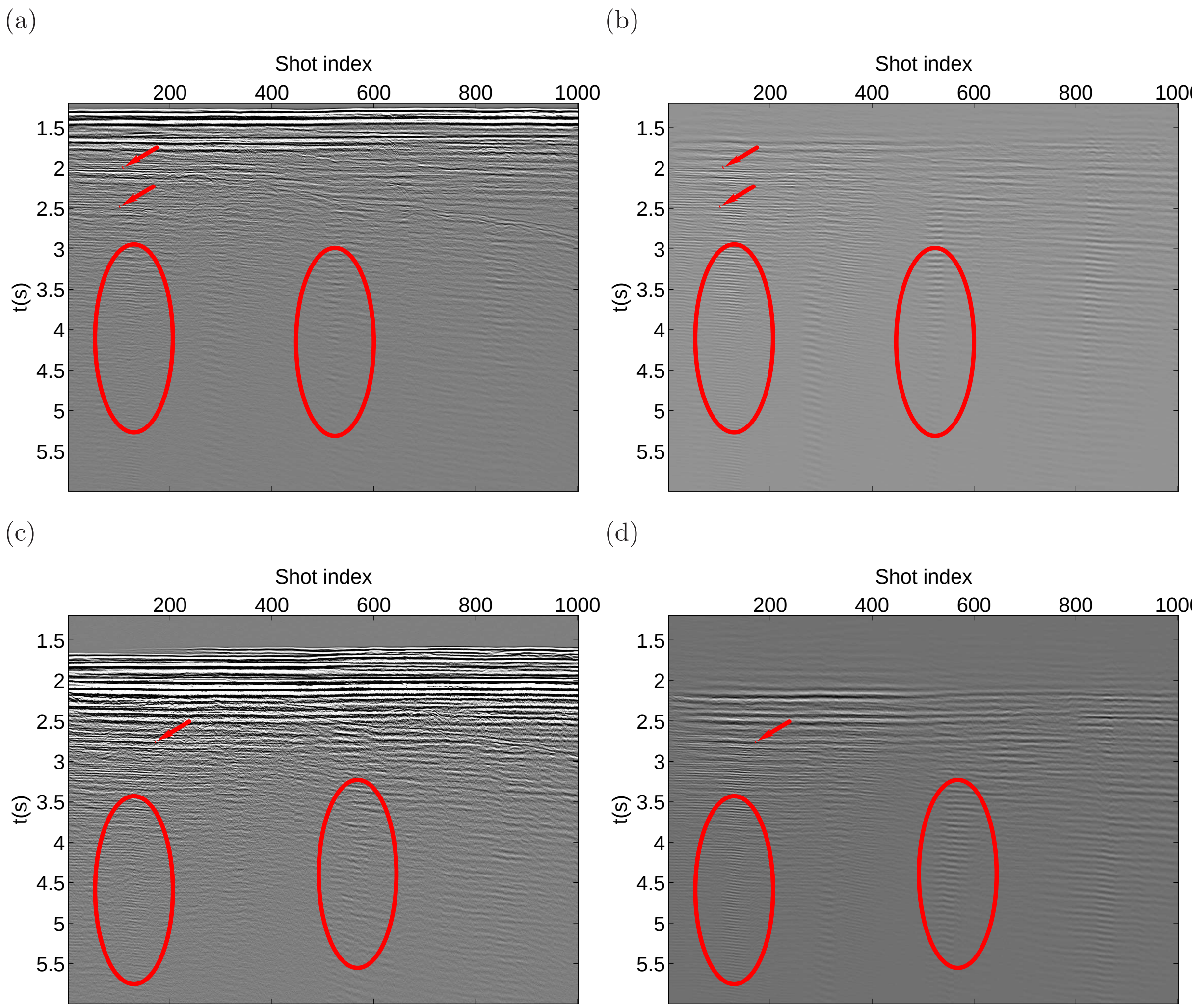

Figure 5. Mid (a) and far (c) common-offset sections of the Viking Graben data and corresponding predicted source+receiver ghost in (b) and (d), respectively. The arrow points to an interval containing internal multiples. The ovals highlight guided waves.

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