Multiple removal and prerequisite satisfaction: current status and future plans

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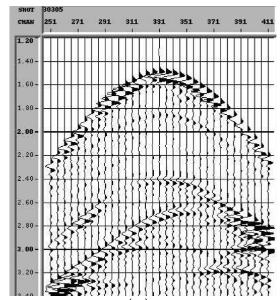
Summary

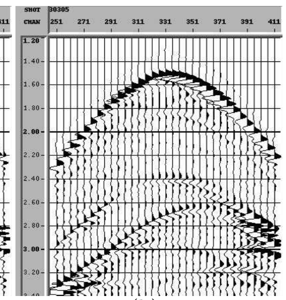
In exploration seismology, as the geology probed by seismic waves becomes more complex, untangling multiples and primaries becomes more challenging. The inverse scattering series (ISS) has provided distinct algorithms for eliminating free-surface multiples and attenuating internal multiples without needing any subsurface information. To deliver their promise it is important to satisfy the prerequisites of these two algorithms. The free-surface-multiple-elimination algorithm assumes that its input has had the source wavelet deconvolved and ghosts removed. The internal-multiple algorithm requires deghosting and source-wavelet deconvolved and further assumes that its input data has had free-surface multiples removed. Fortunately, Green's theorem provides algorithms for estimating the source wavelet and removing ghosts that are consistent with the ISS algorithms, *i.e.*, they need no subsurface information and are multidimensional. The effects of meeting and not meeting the prerequisites of the demultiple algorithms are exemplified, and the current and future status of demultiple algorithms are discussed.

Introduction

The two purposes of this paper are (1) to review and exemplify the influence of prerequisite satisfaction for free-surface-multiple and internal-multiple algorithms with synthetic data corresponding to offshore plays, and (2) to motivate onshore methods for prerequisite satisfaction and describe early efforts to reach that goal.

As exploration for hydrocarbons has moved into areas with more complex geology, there are more instances in which multiples are proximal to or even overlapping primaries. Hence, demultiple algorithms are challenged to remove multiples without damaging proximal primaries. The inverse scattering series (ISS) can achieve all processing objectives directly and without subsurface information. In particular, the ISS free-surface-multiple-elimination method has the ability to accurately predict the phase and amplitude of free-surface multiples, if its prerequisites (source signature and deghosted data) are satisfied (Carvalho et al., 1992; Weglein et al., 1997, 2003). The current ISS internal-multiple-attenuation algorithm can predict the exact phase (time) and approximate amplitude of all internal multiples, at once, automatically, and without subsurface information (Araújo et al., 1994; Weglein et al., 2003), as has been demonstrated on marine field data (Carvalho and Weglein, 1994; Matson et al., 1999; Terenghi et al., 2011; Ferreira, 2011). Those ISS properties are what all other current demultiple methods (*e.g.*, Feedback loop methods, modeling and subtracting multiples, and filter methods) do not possess and cannot deliver (Weglein and Dragoset, 2005).


(a)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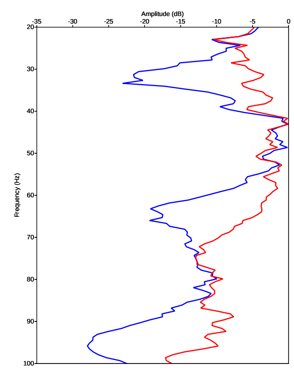

(c)

Fig. 1: *SEAM Phase I data, shot 130305: (a) recorded pressure wavefield at 17 m, (b) receiver-deghosted pressure wavefield at the air-water boundary using Green's theorem. The horizontal axis is trace number, and the vertical axis is time (s). Note the collapsed wavelet in the right panel. (c) Frequency spectra of 2D field data, shot 841: input hydrophones at 25 m (blue), receiver-deghosted pressure wavefield at the air-water boundary using Green's theorem (red). The receiver notches around 30 Hz, 60 Hz, and 90 Hz have been filled in. Input data courtesy of PGS. (Mayhan et al., 2011)*

The prerequisites for ISS demultiple algorithms can be met by Green's-theorem-based algorithms (Weglein and Secrest, 1990; Weglein et al., 2002; Zhang and Weglein, 2005, 2006; Zhang, 2007). The ability of Green's theorem to meet prerequisites has been tested on SEAM and field data (Mayhan and Weglein, 2013; Mayhan, 2013); we show examples in Figure 1. When prerequisites are satisfied, the prediction improves, as shown in Figures 2 and 4.

Free-surface-multiple removal with and without first removing ghosts is shown in Figure 2. Using the model shown in Figure 2(a), Figures 2(b) and 2(c) are the input data with and without ghosts, respectively. Inputting them into the ISS free-surface-multiple-elimination algorithm, Figures 2(d) and 2(e) are their corresponding free-surface-multiple predictions. After subtracting from the input data, Figures 2(f) and 2(g) show the corresponding results after free-surface-multiple removal. If the input data are not deghosted, the ISS free-surface-multiple-removal method can predict the exact phase but only an approximate amplitude of free-surface multiples. After deghosting the data, we can see that all free-surface multiples are predicted exactly, and, through a simple subtraction, all are well eliminated, and, most importantly, primaries are not touched, as shown in Figure 2(g). Other examples of removing free-surface multiples with and without deghosting for simple synthetic data are given in Zhang (2007) and Wang et al. (2012) (Figure 3).

Free-surface-multiple elimination and internal-multiple attenuation with and without first removing the source wavelet are shown in Figure 4. Each column is plotted to the same scale. The left column uses the model in Figure 2(a), and the right column uses a model with no free surface and two reflectors. Figures 4(a), 4(c), and 4(e) show the input data and the predicted free-surface multiples using the free-surface-multiple-elimination algorithm with and without source wavelet deconvolution, and Figures 4(b), 4(d), and 4(f) show the input data and the predicted internal multiples using the internal-multiple-attenuation algorithm with and without source wavelet deconvolution. Figures 4(d) and 4(f) show that the internal-multiple-attenuation algorithm predicts the correct travel times but different amplitudes and shapes for the internal multiples. In Figure 4(d), the amplitude of the predicted internal multiple is comparable with the internal multiple in the input data, while the amplitude is totally different from that of the internal multiple in the input data in Figure 4(f). Deconvolving the source wavelet, as required by the internal-multiple-attenuation algorithm, significantly improves the amplitude and shape of the predicted internal multiple.

Current status

The current status of multiple removal for marine seismic data is summarized in Table 1. Row (1): Satisfying the prerequisites of the ISS (using Green's theorem) is relatively mature. Estimating the source wavelet and removing ghosts have been tested on simple synthetic data, SEAM data, and field data (Zhang, 2007; Mayhan, 2013). Row (2): Free-surface-multiple elimination is also mature. In principle, the ISS free-surface-multiple prediction algorithm gives the exact amplitude and phase of the free-surface multiples. Row (3): Internal-multiple attenuation is also mature; it was tested on field data by Matson et al. (1999), Terenghi et al. (2011), and Ferreira (2011). Work is underway to eliminate spurious events (Ma and Weglein, 2014) and move attenuation to elimination (Zou and Weglein, 2014a,b). Row (4): Adaptive subtraction using energy minimization is inconsistent; if multiples and primaries are separated, it works, but not if multiples are

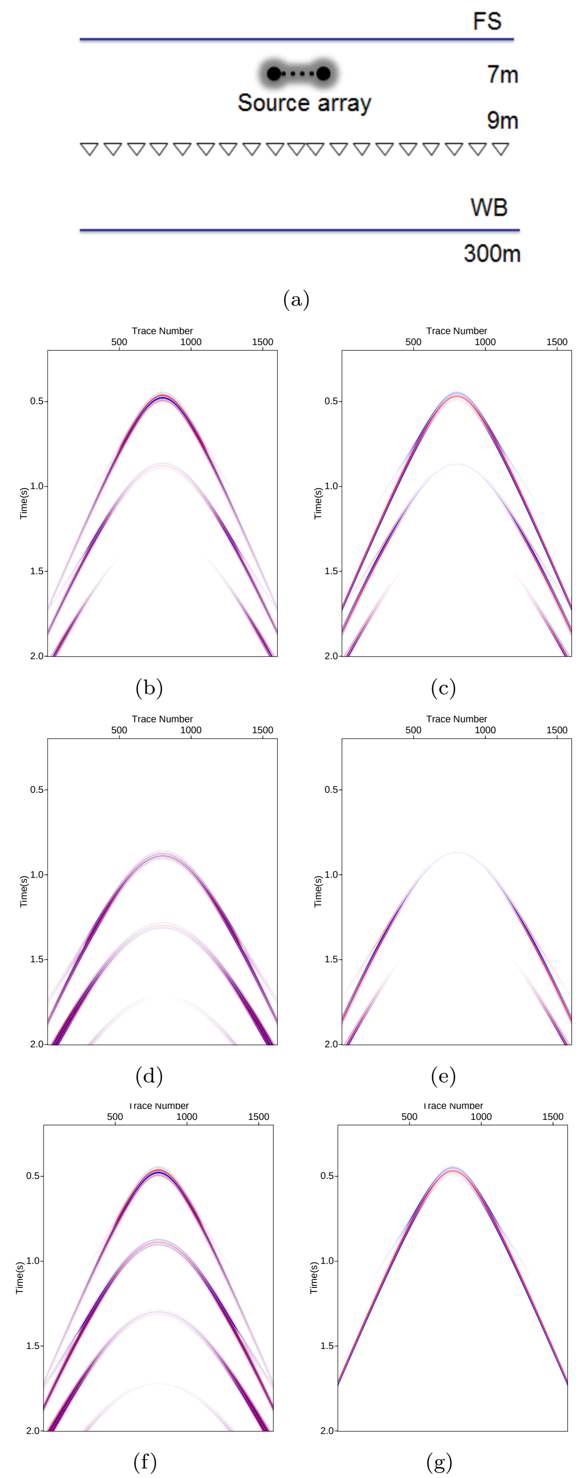

Fig. 2: *Free-surface-multiple removal with and without first removing ghosts: (a) model used to create input data; (b) & (c) input data with and without ghosts; (d) & (e) corresponding ISS free-surface-multiple prediction; (f) & (g) after free-surface-multiple removal through a simple subtraction. (Tang et al., 2013)*

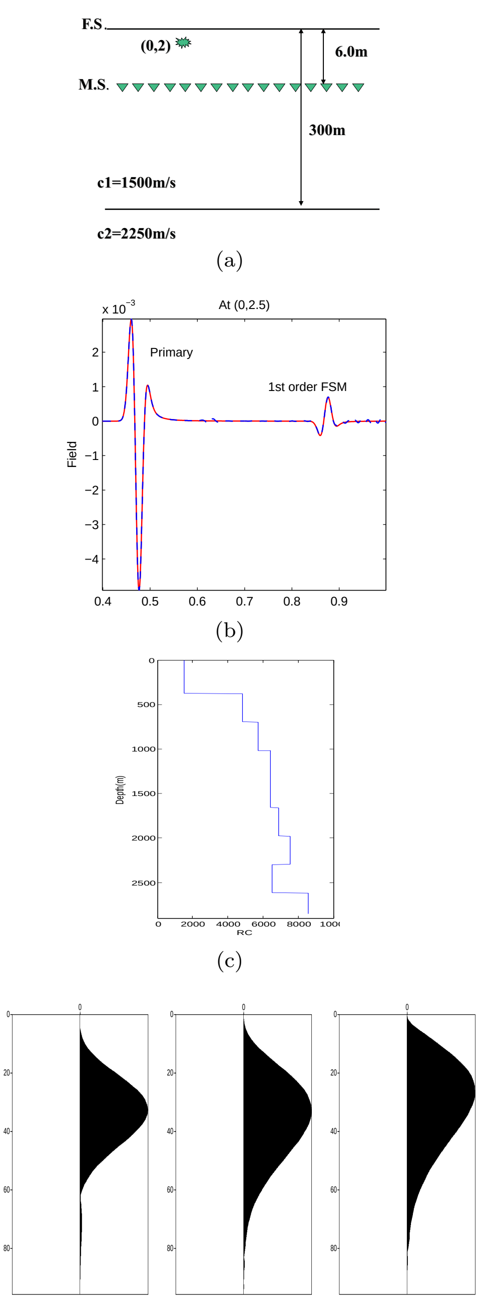

Fig. 3: *(a) The constant-density acoustic model used for panel (b). (b) Using receiver-array data, the calculated deghosting results (blue dash) are compared to the exact deghosting results (red solid). The direct wave has been removed before deghosting. Notice the small errors in amplitude. (Zhang, 2007) (c) The velocity model (provided by Total) used for panel (d). (d) Spectrum plots of their wavelets: The left panel is before deghosting, the middle panel is receiver deghosted, and the right panel is source and receiver deghosted. Both receiver deghosting and source deghosting recover more low-frequency information. (Wang et al., 2012)*

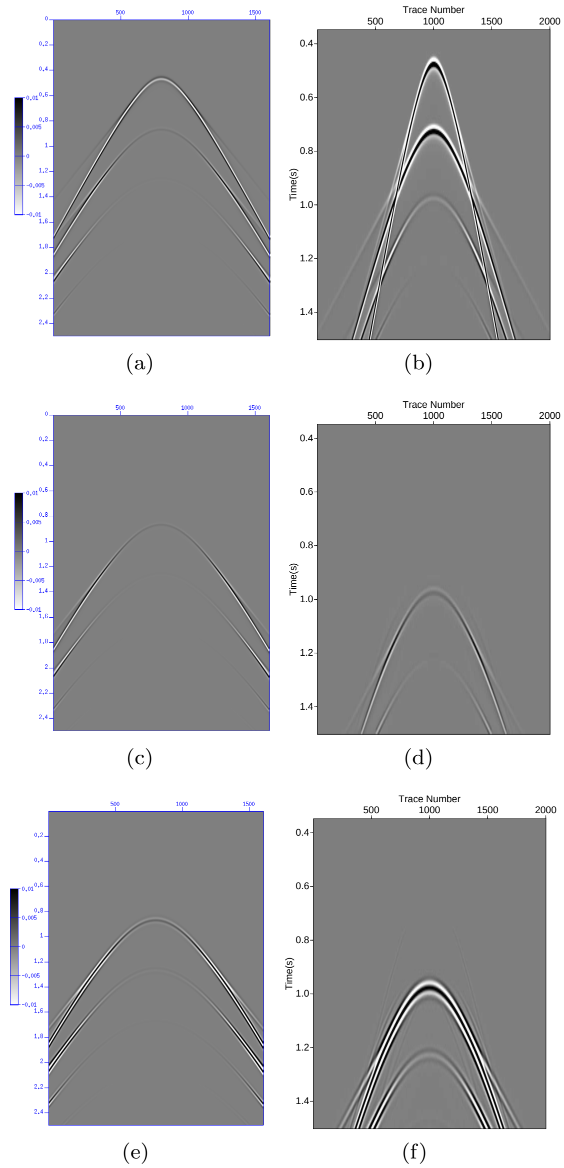

Fig. 4: *Impact of source wavelet on ISS free-surface-multiple removal: (a) input data, (c) and (e) predicted free-surface multiples with and without source wavelet deconvolution, respectively (Yang and Weglein, 2012). Impact of source wavelet on ISS internal-multiple attenuation: (b) input data, (d) and (f) predicted internal multiples with and without source wavelet deconvolution, respectively (Yang and Weglein, 2014).*

proximal to or overlapping primaries. A possible replacement for energy-minimization adaptive subtraction has been proposed for free-surface-multiples (Weglein, 2012).

The current capability of multiple removal for onshore seismic data is summarized in Table 2. Row (1): Using Green's theorem to satisfy ISS prerequisites, as is cur-

	Method	Comment/status
1	Prerequisites (estimate wavelet, deghost)	Relatively mature
2	Free-surface multiples	Eliminate
3	Internal multiples	Attenuate
4	Adaptive	Energy minimization

Table 1: *The current status of multiple removal (marine seismic data).*

rently performed for marine seismic data, is discussed in Wu and Weglein (2014b), and a method for finding the reference velocity in the near surface is discussed in Tang and Weglein (2014). Row (3): The results of testing ISS internal-multiple attenuation on land are encouraging; its "performance was demonstrated with complex synthetic and challenging land field data sets with encouraging results, where other internal multiple suppression methods were unable to demonstrate similar effectiveness" (Fu et al., 2010). Row (4): "The examples of this paper point to the pressing need to improve the prediction and reduce the reliance on adaptive steps, since the latter can fail precisely when you have interfering events." (Fu et al., 2010)

	Method	Comment/status
1	Prerequisites (estimate wavelet, deghost)	Find reference velocity iteratively
2	Free-surface multiples	Eliminate
3	Internal multiples	Attenuate
4	Adaptive	Energy minimization

Table 2: *The current capability of multiple removal (onshore seismic data).*

Future plans

There is a three-pronged strategy to address the current outstanding issues listed in Tables 1 and 2 (Weglein, 2014a,b). (1) Develop the ISS prerequisites for predicting the reference wavefield (wavelet and radiation pattern) and producing deghosted data (in particular, for onshore and ocean-bottom acquisition) that are direct and do not require subsurface information; (2) Develop ISS algorithms to reduce/eliminate so-called spurious events and to eliminate (vs. attenuate) internal multiples; and (3) Develop a replacement for the energy-minimization criteria for adaptive subtraction, that derives from, and always aligns with and serves, the inverse-scattering-series free-surface and internal-multiple algorithms. This three-pronged strategy represents a consistent and aligned processing chain, with one single objective: providing a direct and practical solution to the removal of all multiples, without requiring any subsurface information, and without damaging primaries. All three prongs are being progressed: (1) in Wu and Weglein (2014a,b), (2) in Zou and Weglein (2014a,b) and Ma and Weglein (2014), and (3) in Weglein (2012). This ideal status of multiple removal (marine seismic data) is summarized in Table 3.

	Method	Comment/status
1	Prerequisites (estimate wavelet, deghost)	Mature
2	Free-surface multiples	Eliminate
3	Internal multiples	Eliminate
4	Adaptive	Consistent with 1-3

Table 3: *The ideal status of multiple removal (marine seismic data).*

The energy-minimization adaptive-subtraction criteria, while not derived as a property of the free-surface-multiple-elimination or internal-multiple-attenuation criteria, is useful for completing the matching between multiple prediction and multiple, when events are separated and there are no higher-order multiples in the vicinity, and only a first-order algorithm is being used. Part of the three-pronged strategy is to use the terms in the respective ISS subseries that can accommodate the order of multiple anticipated in the target region. Given deghosted and wavelet-deconvolved data, there is a stable closed form that eliminates all orders of free-surface multiples at once (Weglein and Dragoset, 2005). With proximal and/or interfering events the energy-minimization criteria fails, independently of how it's implemented (because of interfering proximal events), and a new set of criteria is sought for the adaptive step that derives from and aligns with and always supports the multiple subseries. (A candidate for a replacement for energy-minimization adaptive for free-surface multiples is given in Weglein (2012).)

Conclusions

This paper gives (1) an overview of removing multiples from marine data and (2) motivation and preview for removing multiples from onshore data. In principle, the ISS free-surface-multiple prediction algorithm gives the exact amplitude and phase of the free-surface multiples, and the ISS internal-multiple-attenuation algorithm is the high-water mark of current internal-multiple-attenuation capability. The quality of their output assumes their requirements are met, *i.e.*, source wavelet deconvolved and ghosts removed.

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