The inverse scattering series approach towards the elimination of land internal multiples

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Summary

The estimation and subsequent elimination of internal multiples in land seismic data is one of the most challenging steps in data processing. Although marine multiple elimination techniques, such as the SRME technology, are well established, in land their implementation is not straightforward and in many cases poor results are obtained. In this paper we use theoretical concepts from the Inverse Scattering Series (ISS) formulation and develop computer algorithms for land internal multiple elimination. The key characteristic of the ISS-based methods is that they do not require any information about the subsurface, i.e., they are fully data driven. Internal multiples from all possible generators are computed and adaptively subtracted from the input data. These methodologies can be applied pre- and post-stack and their performance is demonstrated using realistic synthetic and field datasets from the Arabian Peninsula. These are the first published results of the application of the ISS internal multiple attenuation method to the daunting challenge of land internal multiples.

Introduction

Radon-based methods are commonly employed for multiple reduction in land seismic data processing. However, in land data, the lack of velocity discrimination between primaries and multiples results in unacceptable results. Thus, wave equation based schemes have to be introduced. The research articles of Verschuur *et al.* (1992), Berkhout (1997), Weglein *et al.* (1997), Carvalho and Weglein (1994), Dragoset and Jericevic (1998), Jakubowicz (1998), Berkhout (1999), and Verschuur and Berkhout (2001), to mention a few, offer theoretical insights to wave equation surface and internal multiple elimination along with several applications to synthetic and marine datasets.

Kelamis *et al.* (2002) used concepts from the Common Focus Point (CFP) technology and developed algorithms for internal multiple elimination applicable in land. Luo *et al.* (2007) and Kelamis *et al.* (2008) have also showed successful applications of land internal multiple suppression. They employed the layer/boundary approaches introduced by Verschuur and Berkhout (2001). In these schemes the user has to define phantom layers/boundaries which correspond to the main internal multiple generators. Thus, some advanced knowledge of the main multiple generators is required. In land, as shown by Kelamis *et al.* (2006), the majority of internal multiples are generated by a series of complex, thin layers encountered in the near surface. Thus, the applicability of the CFP-based layer/boundary approach is not always straightforward since it requires the definition of many phantom layers. In contrast, the ISS theory does not require the introduction of phantom layers/boundaries. Instead, it computes all possible internal multiples produced by all potential multiple generators. Therefore, automated internal multiple elimination algorithms can be developed in the pre- and post-stack domains.

The ISS method and background

The ISS-based formulation for internal multiple attenuation (Araújo *et al.*, 1994; Weglein *et al.*, 1997) is a data-driven algorithm. It does not require any information about the reflectors that generate the internal multiples or the medium through which the multiples propagate, and it does not require moveout differences or interpretive intervention. The algorithm predicts internal multiples for all horizons at once. This ISS internal multiple attenuation scheme is basically the first term in a subseries of the ISS that predicts the exact time and amplitude of all internal multiples without subsurface information. The ISS attenuation algorithm predicts the correct travel-times and approximate amplitudes of all the internal multiples in the data, including converted wave internal multiples (Coates and Weglein, 1996). Carvalho *et al.* (1992) pioneered the free-surface ISS method and applied it to field data. Matson *et al.* (1999) were the first to apply the ISS internal multiple algorithm to marine towed streamer field data, and Ramírez and Weglein (2005) extended the theory from attenuation towards elimination by including more terms in the subseries, thereby improving the amplitude prediction. Matson (1997) and Weglein *et al.* (1997) extended the ISS methods for removing free surface and internal multiples to ocean bottom and land data.

The ISS internal multiple attenuation algorithm in 2D starts with the input data, $D(k_g, k_s, \omega)$, that is deghosted and has all free-surface multiples eliminated. The parameters, k_g, k_s and ω, represent the Fourier conjugates to receiver, source and time, respectively. The ISS internal multiple attenuation algorithm for first order internal multiple prediction in a 2D earth is given by (Araújo, 1994; Weglein *et al.*, 1997):

$$\begin{aligned} &b_{3IM}(k_g, k_s, \omega) \\ &= \frac{1}{(2\pi)^2}\int_{-\infty}^{\infty} dk_1 e^{iq_2(z_g-z_s)} \int_{-\infty}^{\infty} dz_1 b_1(k_g, k_1, z_1) e^{i(q_g+q_1)z_1} \\ &\times \int_{-\infty}^{\infty} dk_2\, e^{-iq_1(z_g-z_s)} \int_{-\infty}^{z_1-\varepsilon} dz_2 b_1(k_1, k_2, z_2) e^{-i(q_1+q_2)z_2} \\ &\times \int_{z_2+\varepsilon}^{\infty} dz_3 b_1(k_2, k_s, z_3) e^{i(q_2+q_s)z_3} \end{aligned} \tag{1}$$

The quantity $b_1(k_g, k_s, z)$ corresponds to an un-collapsed migration (Weglein *et al.*, 1997) of an effective incident plane-wave data which is given by $-2iq_s D(k_g, k_s, \omega)$. The vertical wavenumbers for receiver and source, q_g and q_s, are given by $q_i = sqn(\omega)\sqrt{\frac{\omega^2}{c_0^2} - k_i^2}$ for $i = (g, s)$; c_0 is the constant reference velocity; z_s and z_g are source and receiver depths; and z_i $(i = 1,2,3)$ represents pseudodepth. Note that the obliquity factor, $-2iq_s$, is used to transform an incident wave into a plane wave in the Fourier domain (Weglein *et al.*, 2003).

The construction of a first order internal multiple is illustrated in Figure 1. The first order internal multiple is composed of three events that satisfy $z_2 < z_1$ and $z_2 < z_3$. The traveltime of the internal multiple is the sum of the traveltimes of the two deeper events minus the traveltime of the shallower one. The parameter ε introduced in equation (1) to preclude $z_2 = z_1$ and $z_2 = z_3$ in the integrals. For band limited data, ε is related to the width of the wavelet. The output of equation (1), b_{3IM}, is divided by the obliquity factor and transformed back to the space-time domain. When we subtract the estimated internal multiples from the original input data, all first order internal multiples are suppressed and higher order internal multiples are altered.

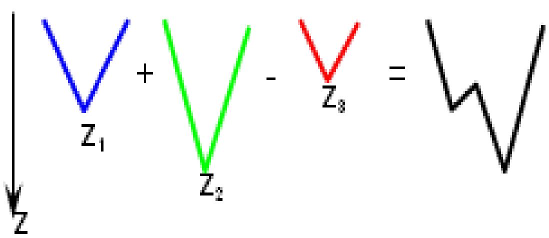

Figure 1: The sub-events of an internal multiple. The internal multiple (in black) is constructed by three arrivals (blue, green and red) that satisfy the lower-higher-lower relationship in pseudodepth z_i $(i = 1,2,3)$.

Synthetic & Field Data

Figure 2 shows a synthetic CMP gather obtained from an 18-layer velocity model. The data contains only primary reflections and internal multiples. The results of our 1.5D ISS algorithm are shown in the middle panel and compared with the true primaries-only gather on the right. Note that almost all internal multiples are attenuated considerably. There is some degradation of the primaries and is due to the adaptive least-squares subtraction. The results of Figure 2 are obtained without any user intervention, i.e., are fully automated and are very encouraging. More full pre-stack tests are currently underway.

Next the application of ISS-based internal multiple attenuation is shown on post-stack data. One of our goals is to study if ISS can successfully predict internal multiples generated by thin layers. Figure 3 depicts the ISS performance on a realistic zero-offset synthetic dataset. The model is composed of a large number of layers with 1 foot thickness and is obtained from a field sonic log. The data (primaries and internal multiples) are modeled using the acoustic wave equation. The 1D ISS internal multiple elimination result is shown on the right, while the primaries-only traces are also depicted in the middle panel. The performance of the 1D ISS algorithm is very good. Despite the post-stack application note the complete internal multiple elimination obtained in the zone of interest between 1.0 and 1.4 secs. At the same time the main primary events are preserved.

In Figure 4 a stacked section of land seismic data from Saudi Arabia is shown. The presence of internal multiples is evident. Moreover, note the spatial variability of these multiples that follows the complex near surface. It's an indication that they are all generated within the complex, thin layers of the near surface. Figure 5 exhibits the data after 1D ISS internal multiple elimination, while Figure 6 shows the difference, i.e., the estimated internal multiples. The results are very encouraging. Note the overall reduction of internal multiples. Especially, at the zone of interest between 1.4 and 2.0 secs, the ISS internal multiple elimination has resulted in an improved definition of the primaries and thus increased the interpretability of the data. It is also interesting to examine the difference section where the estimated internal multiples are shown (Figure 6). The spatial variability of the internal multiples is quite obvious along with the "dull", character-free ringing appearance that represents no real geology.

Conclusions

We have developed and employed algorithms from the Inverse Scattering Series theory for the estimation of internal multiples. They can be applied pre-stack (1.5D) in the CMP domain and in zero-offset (1D) data. Their performance was demonstrated with complex synthetic and challenging land field datasets with encouraging results, where other internal multiple suppression methods were unable to demonstrate similar effectiveness. This paper presents the first series of onshore field data tests of the ISS-based internal multiple attenuation technology. ISS technology requires no velocity information for the subsurface or any advanced knowledge of the multiple generators. The main idea is to remove multiples without damaging primaries. In practice, a method like ISS can be used for high-end prediction, and then some form of adaptive subtraction is called upon to address issues omitted in the prediction. The improved multiple prediction offered by ISS is crucial in land seismic data where close interference between primaries and internal multiples occurs. 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. We will continue our research efforts for more accurate and complete prediction algorithms in order to produce effective, practical and automated internal multiple attenuation methodologies applicable for land seismic data.

Acknowledgements

We thank the Saudi Arabian Oil Company (Saudi Aramco) for support and permission to present this paper. We also thank Kevin Erickson for providing the synthetic datasets and Roy Burnstad for many discussions related to the processing of field data. Arthur B. Weglein and Shih-Ying Hsu thank Saudi Aramco for Shih-Ying's internship with the Geophysics Technology Group of EXPEC ARC. They also thank all M-OSRP sponsors for their support.

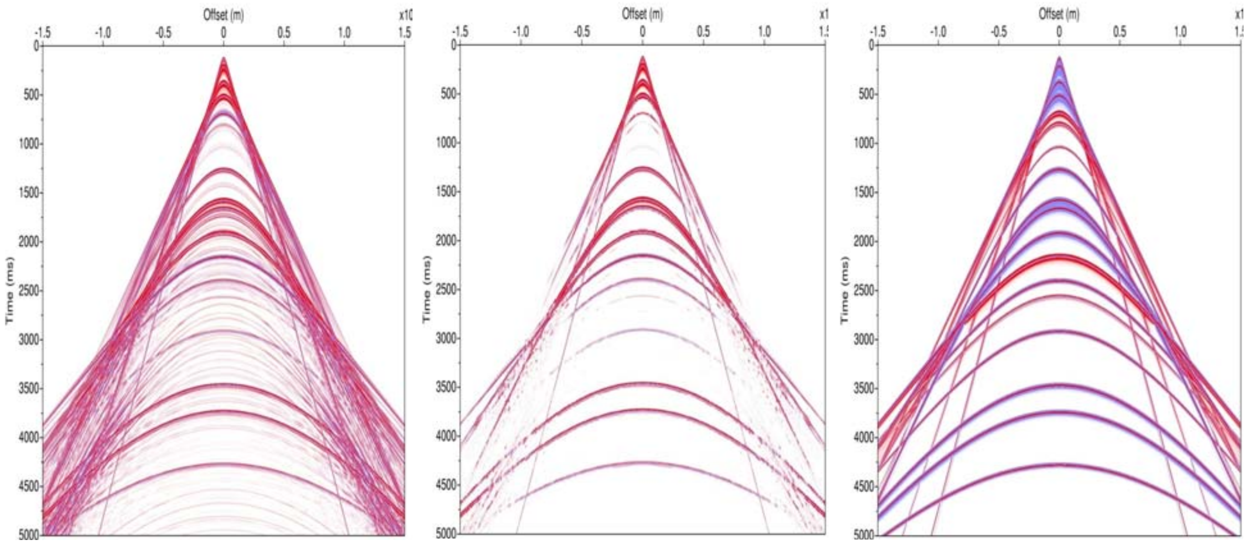

Figure 2: Pre-stack (1.5D) application of ISS internal multiple elimination. The input CMP gather (left) with primaries and internal multiples obtained from an 18-layer velocity model. In the middle, the result of the ISS-based internal multiple attenuation is shown. The true primaries are depicted on the right.

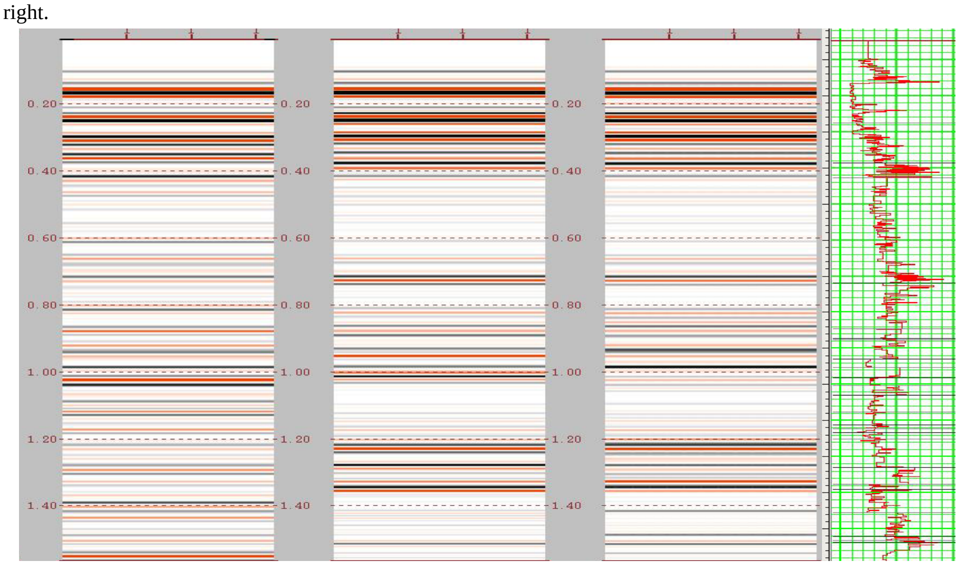

Figure 3: Post-stack application of ISS internal multiple elimination technology. The data is modeled from a field sonic log shown on the extreme right. The input data (left) has primaries and internal multiples only. The ISS result is shown on the right while the primaries-only section is in the middle.

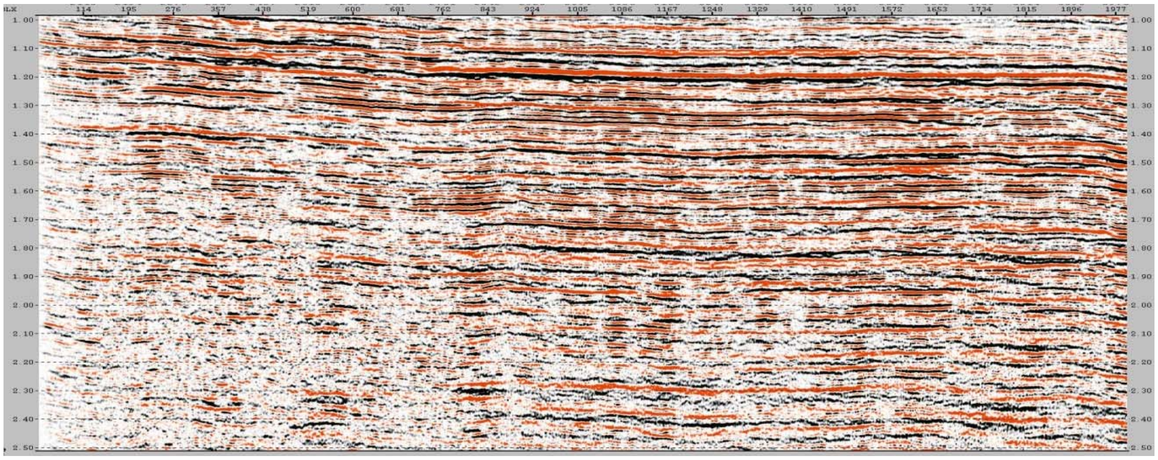

Figure 4: Stacked land seismic data with internal multiples.

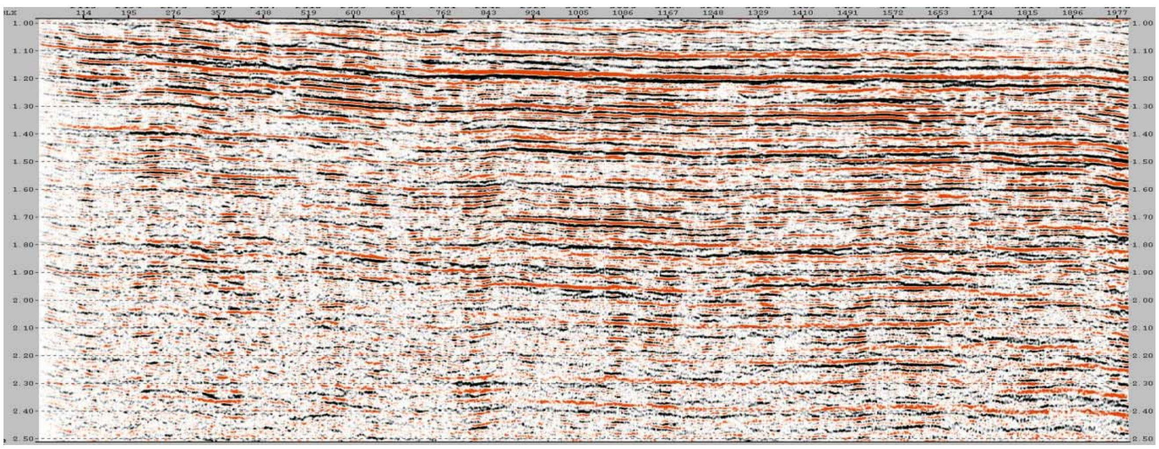

Figure 5: Primaries obtained after applying the 1D ISS internal multiple elimination algorithm.

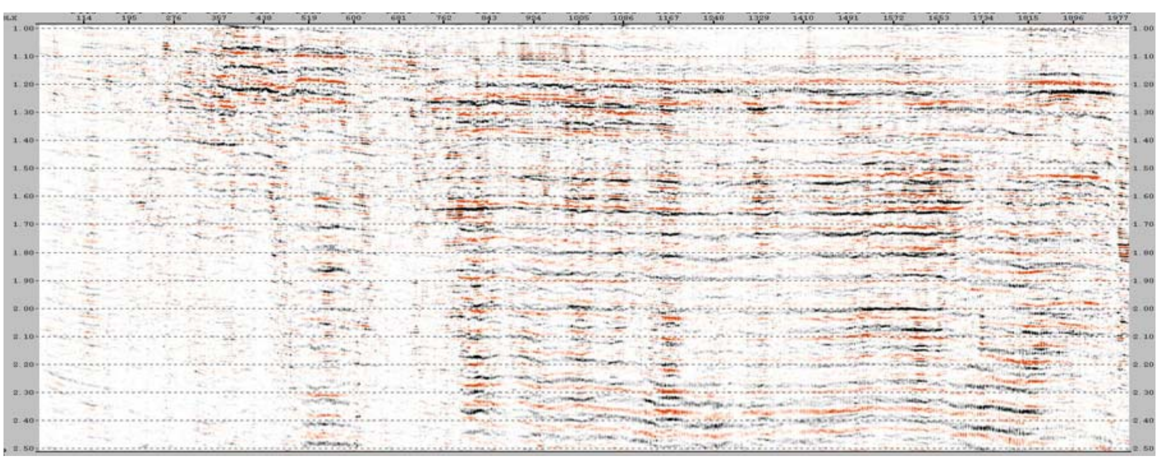

Figure 6: The estimated internal multiples, i.e., the difference between Figures 4 and 5.

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