Elimination of land internal multiples based on the inverse scattering series

Yi Luo, Panos G. Kelamis, Qiang Fu, ShouDong Huo, and Ghada Sindi, Saudi Aramco
Shih-Ying Hsu and Arthur B. Weglein, University of Houston

Despite the explosion of new, innovative technologies in the area of multiple identification and subsequent attenuation, their applicability is mostly limited to marine environments especially in deep water. In land seismic data sets however, the application of such multiple-elimination methodologies is not always straightforward and in many cases poor results are obtained. The unique characteristics of land seismic data (i.e., noise, statics and coupling) are major obstacles in multiple estimation and subsequent elimination. The well-defined surface multiples present in marine data are rarely identifiable in land data. Particularly in desert terrains with a complex near surface and low-relief structures, surface multiples hardly exist. In most cases, we are dealing with so called "near-surface-related multiples." These are primarily internal multiples generated within the complex near surface.

In this paper, we employ 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 prestack and poststack and their performance is demonstrated using realistic synthetic and field data sets from the Arabian Peninsula. These are the first published field data examples of the application of the ISS-based internal multiple-attenuation technology to the daunting challenge of land internal multiples.

Introduction

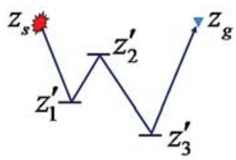
Radon-based methods are commonly employed for multiple reduction in land seismic data processing. However, in land data, the lack of velocity discrimination between primaries and multiples causes unacceptable results. Thus, wave-equation-based schemes have to be introduced. The research articles of Verschuur 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 data sets.

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 presented 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. On 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 because 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, fully automated internal multiple-elimination algorithms can be developed in the prestack and poststack domains.

Basic principles of ISS technology

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, in principle, it does not require moveout differences or interpretive intervention. The algorithm predicts internal multiples for all horizons at once.

$$b_{3IM}(k_g, k_s, q_g + q_s) = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} dk_1 e^{-iq_1(z_g - z_s)} \int_{-\infty}^{\infty} dk_2 e^{iq_2(z_g - z_s)} \times \int_{-\infty}^{\infty} dz'_1 b_1(k_g, k_1, z'_1) e^{i(q_g+q_1)z'_1} \times \int_{-\infty}^{z'_1-\epsilon} dz'_2 b_1(k_1, k_2, z'_2) e^{-i(q_1+q_2)z'_2} \times \int_{z'_2+\epsilon}^{\infty} dz'_3 b_1(k_2, k_s, z'_3) e^{i(q_2+q_s)z'_3}$$



$\epsilon > 0$ ensures $z'_1 > z'_2$ and $z'_3 > z'_2$

Figure 1. *ISS internal multiple prediction formulation.*

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 traveltimes 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 toward elimination by including more terms in the subseries, thereby improving the amplitude prediction.

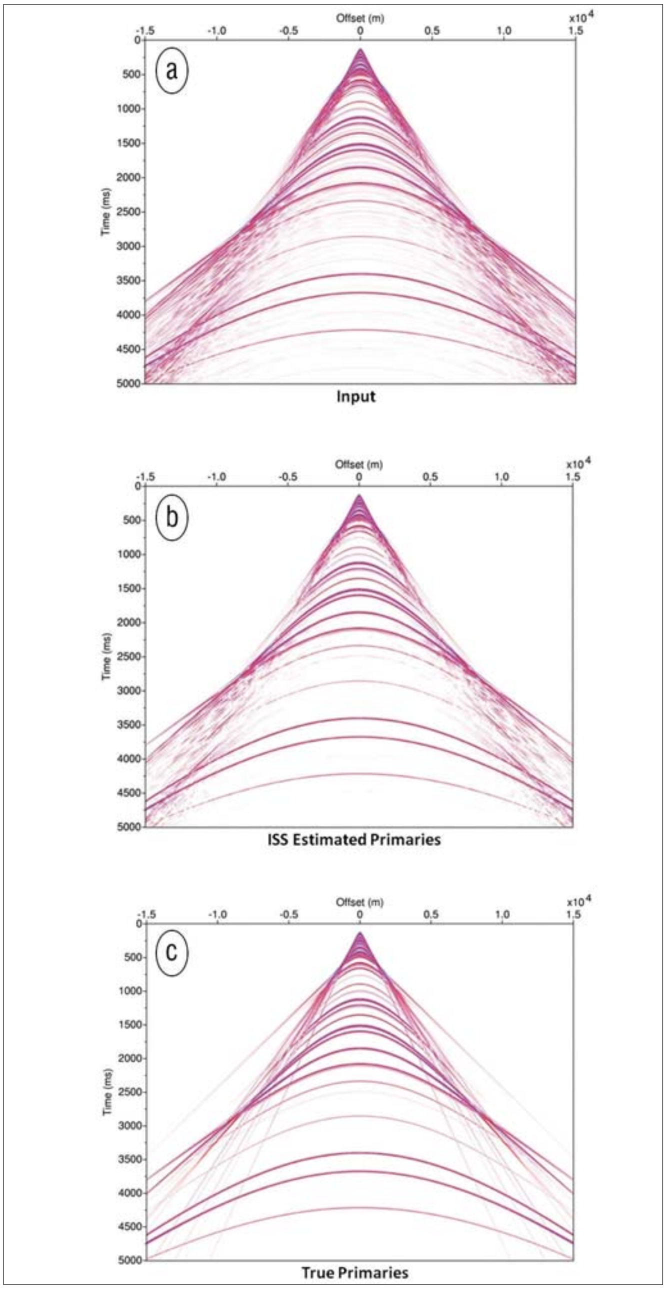


Figure 2. *(a) Synthetic CMP gather from 18-layer velocity model. (b) ISS-estimated primaries. (c) True primaries.*

Matson (1997) and Weglein et al. (1997) extended the ISS methods for removing free-surface and internal multiples from 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 are deghosted and have 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) and Weglein et al. (1997). Figure 1 depicts the mathematical formulation along with a pictorial construction of a first-order multiple. The quantity $b_1(k_g, k_s, z)$ corresponds to an uncollapsed migration (Weglein et al., 1997) of an effective incident plane-wave data which is

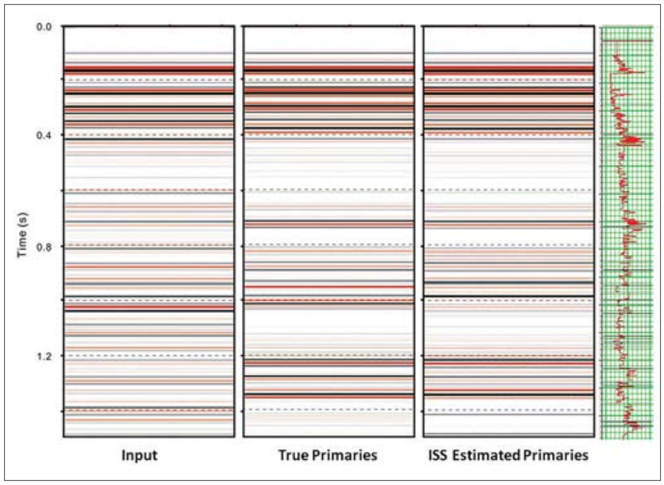


Figure 3. *(left) 1D synthetic with primaries and internal multiples modeled from the field sonic log (right). (center left) True primaries. (center right) ISS-estimated primaries.*

given by $-2iq_sD(k_g, k_s, \omega)$ The vertical wavenumbers for receiver and source, q_g and q_s, and are given by

$$q_i = sgn(\omega)\sqrt{\frac{\omega^2}{c_0^2} - k_i^2} \quad \text{for } i = (g,s);$$

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 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 is introduced in the equation of Figure 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 the equation, 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.

Synthetic and field data

Figure 2 shows a synthetic CMP gather obtained from an 18-layer velocity model. The data contain only primary reflections and internal multiples (Figure 2a). The results of our 1.5D ISS-based algorithm are shown in Figure 2b and compared with the true-primaries-only gather (Figure 2c). Note that almost all internal multiples are attenuated considerably. There is some degradation of the primaries which is due to the adaptive least-squares subtraction. The results of Figure 2 are obtained without any user intervention (i.e., are fully automatic) and are encouraging. More full prestack tests are currently underway in both the shot and CMP domains.

Next the application of ISS-based internal multiple attenuation is shown on poststack data. One of our goals is to study

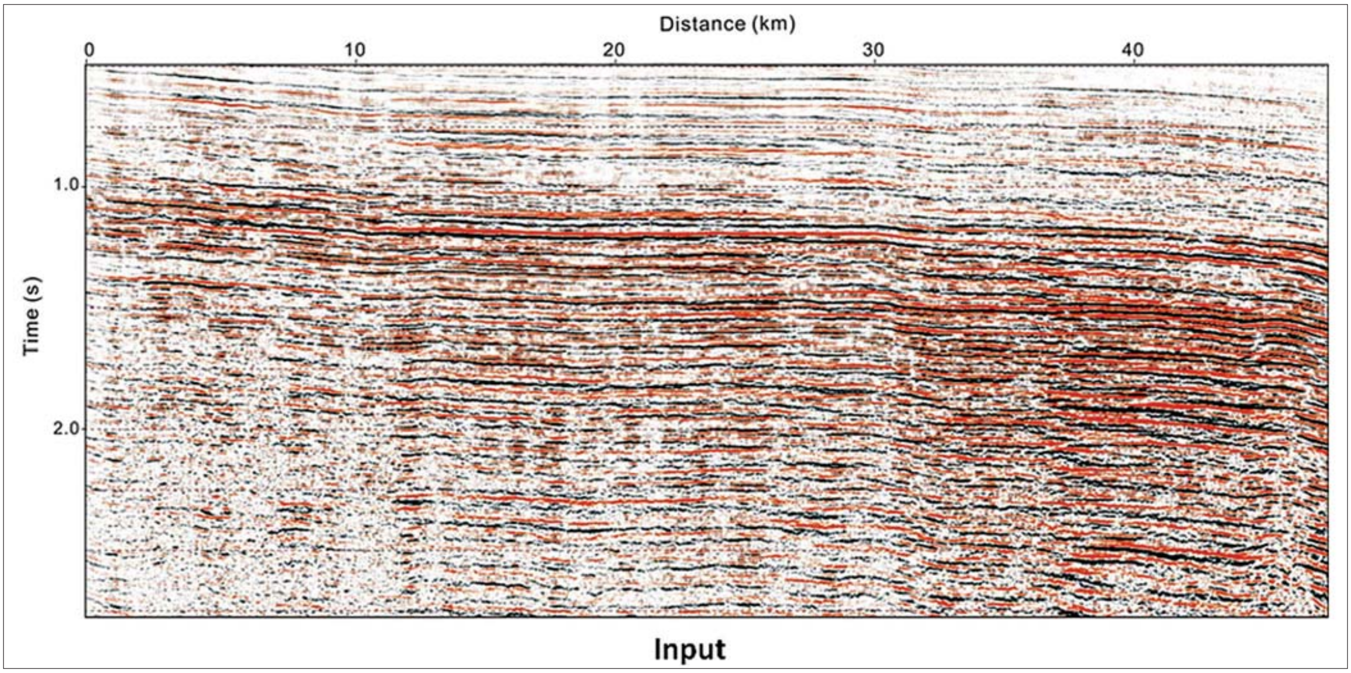


Figure 4. Stacked section from a land data set from Saudi Arabia. The presence of internal multiples is obvious.

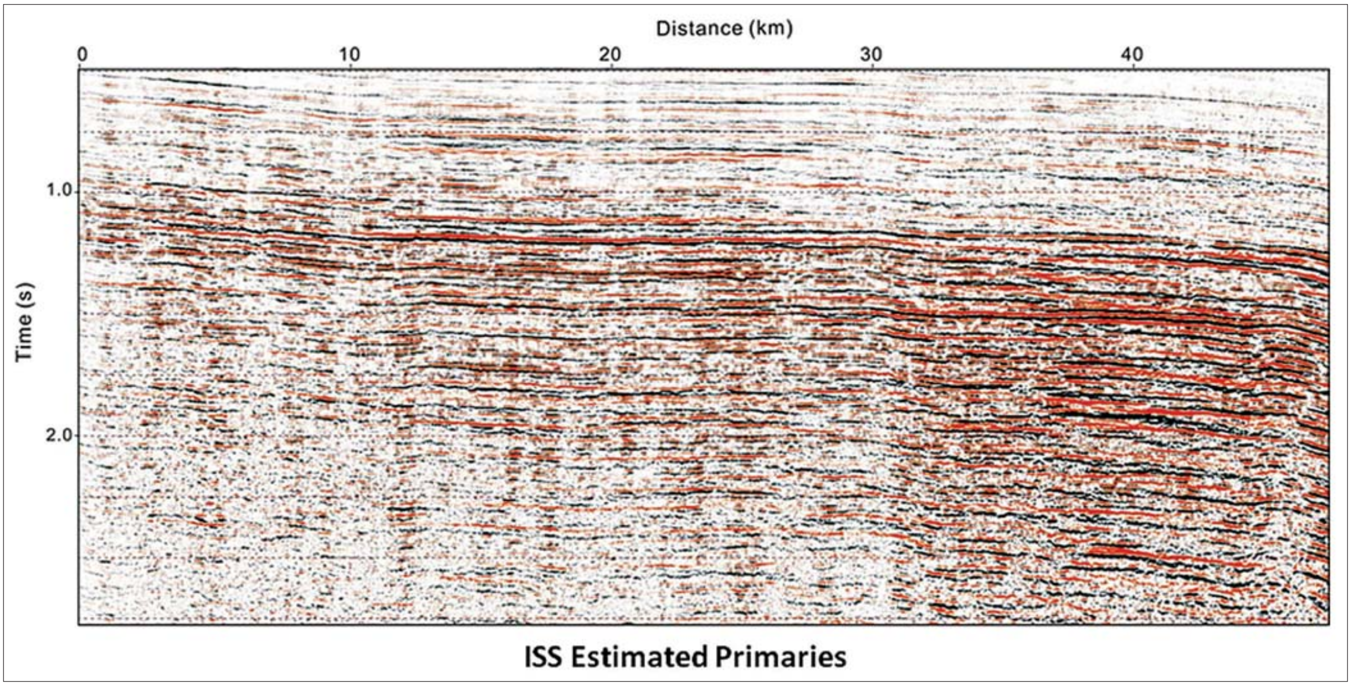


Figure 5. Same data as in Figure 4 after ISS internal multiple elimination.

if ISS can successfully predict internal multiples generated by thin layers. Figure 3 depicts the ISS performance on a realistic zero-offset synthetic data set. The model is composed of a large number of layers with thickness of 1 ft and is obtained from a field sonic log shown on the extreme right. 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-based algorithm is very good. Despite the poststack application, note the complete internal multiple elimination obtained in the zone of interest between 1.0 and 1.4 s. At the same time, the main primary events are preserved with a minimum degradation.

Figure 4 shows a stacked section of land seismic data from Saudi Arabia. The presence of internal multiples is evident in this data set. Moreover, note the spatial variability of these multiples that follows the complex near surface. It's a clear indication that they are all generated within the complex, thin layers of the near surface. Figure 5 exhibits the data after 1D

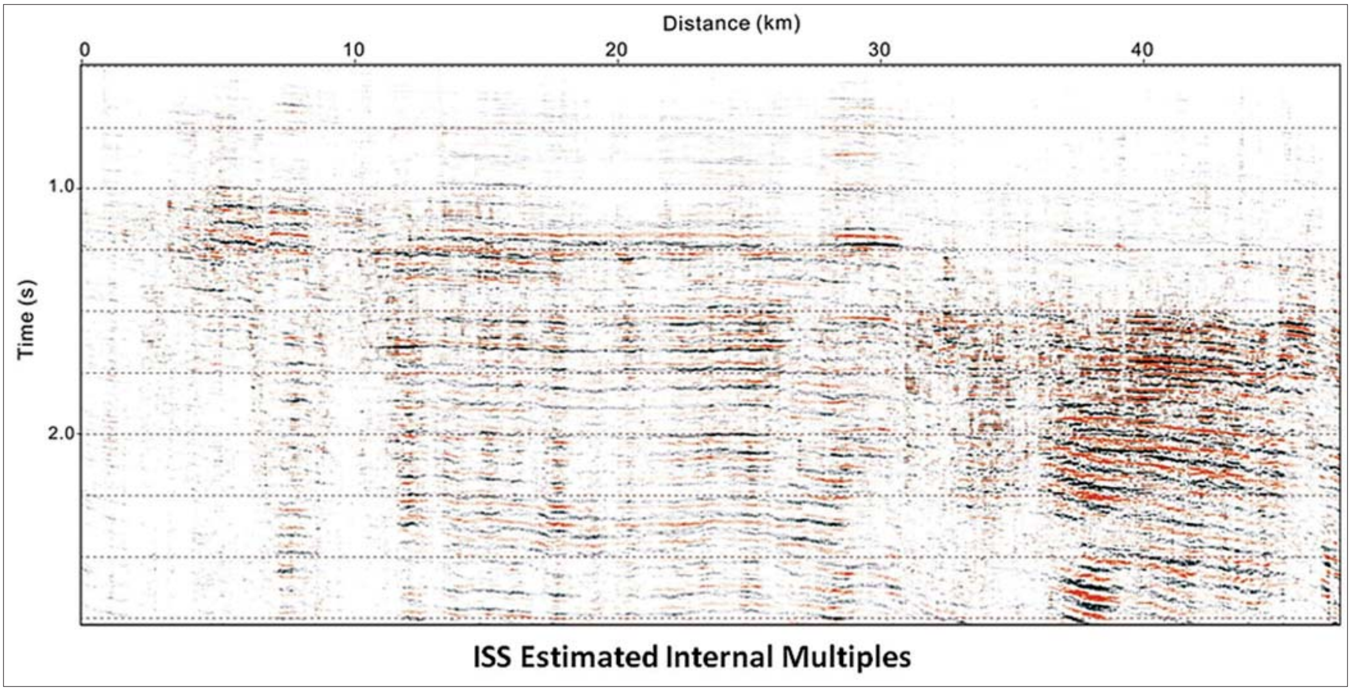


Figure 6. *Difference between Figure 4 and Figure 5 (i.e., the internal multiples).*

ISS internal multiple elimination, and Figure 6 shows the difference (i.e., the estimated internal multiples). The results are encouraging. Note the overall reduction of internal multiples. Especially, at the zone of interest between 1.4 and 2.0 s, 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 prestack (1.5D) in the CMP domain and in zero-offset (1D) data. Their performance was demonstrated with complex synthetic and challenging land field data sets with encouraging results; 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, because 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. TLE

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Corresponding author: panos.kelamis@aramco.com