Literature review and discussions of inverse scattering series on internal multiple prediction

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Summary

Internal multiple attenuation is an increasingly high priority in seismic data analysis in the wake of increased sensitivity of primary amplitudes in quantitative interpretation, due to more information intend to be squeezed from seismic data. Removal of internal multiple is still a big challenge even though several various methods has been proposed. Inverse scattering series (ISS) internal multiple attenuation algorithm, with great potential, developed by Weglein and collaborators in the 1990s, indicated that all internal multiples can be estimated by combining those sub-events satisfying a certain schema,which is the lower-higher-lower criterion. One key feature for implementing the ISS prediction on land is the search parameter selection to avoid the generation of artifacts. In this paper, we comprehensive review inverse scattering series internal multiple attenuation algorithm both in theoretical and its applications in various domains and pursue two related ways of mitigating artifacts and increase the precision of single and multicomponent internal multiple prediction: (1) ISS prediction with a non stationary ε, (2) implementing ISS with stationary ε in variant domains.

Introduction

Multiples attenuation and identification remains to be an indispensable procedure in seismic data processing and its quality will directly affect the accuracy of quantitative interpretation. When the influence of free-surface is considered, multiples can be identified as two major classes, surface-related multiple and interbed multiple. Due to its periodic characteristic in $\tau - p$ domain, surface-related multiples can be eliminated in a comfortable manner and many innovative technologies have been developed in different domains, such as predictive deconvolution (Taner 1980), inverse approach using feedback model (Verschuur 1991), embedding technique (Liu, Sen, and Stoffa 2000), inverse data processing (Berkhout 2006; Berkhout and Verschuur 2005; Ma, Sen, and Chen 2009). However, the attenuation of the other classical multiple, internal multiple, is still a giant challenge, especially on land data, even though much considerable progresses have been made recently.

Kelamis et al. (2002) introduced a boundary-related/layer-related approach to remove internal multiples in the post-stack data (CMP domain). Berkhout (2006) extended the inverse data processing to attenuate internal multiples by considering them as the suppositional surface-related multiples through the boundary-related/layer-related approach in common-focus-point (CFP) domain. The common ground of those algorithms is that, as it were, extensive knowledge of subsurface is required; thus if the possibility exists that multiple removal will have to take place with incomplete knowledge of the velocity structure and generators, the ISS approach will be optimal. By analysing the mechanical context of forward scattering series, Araujo et al. (1994) and Weglein et al. (1997) demonstrated that all possible internal multiples can be reconstructed, in an automatic way, as the combination of those sub-events satisfying a certain criterion, and the processing can be achieved by implementing the inverse scattering series in an appropriate manner. Many research on ISS prediction algorithm have been made (Hernandez and Innanen 2014; Innanen and Pan 2015; Pan 2015; Sun and Innanen 2015;). In this paper, to better understand the specification and innovative working mechanism of inverse scattering series internal multiple prediction algorithm and improve the accuracy of prediction, we retrospect ISS prediction algorithm and discuss its implementation with variant parameters in different domains.

Theory

The ISS prediction in wavenumber-pseudo depth domain

Araujo et al. (1994) and Weglein et al. (1997) showed that all internal multiples can be predicted by summing over events which satisfy the lower-higher-lower relationship. In the pseudo-depth domain, the attenuation term is

$$b_{IM}(k_g,k_s,\omega)=\frac{1}{(2\pi)^2}\iint dk_1 e^{-i\upsilon_1(z_g-z_s)}dk_2 e^{-i\upsilon_2(z_g-z_s)}\int_{-\infty}^{+\infty}dz_1 e^{i(\upsilon_g+\upsilon_1)z_1}b_1(k_g,k_1,z_1) \times\int_{-\infty}^{z_1-\varepsilon}dz_2 e^{-i(\upsilon_1+\upsilon_2)z_2}b_1(k_1,k_2,z_2)\int_{z_2+\varepsilon}^{+\infty}dz_3 e^{i(\upsilon_2+\upsilon_s)z_3}b_1(k_2,k_s,z_3) \quad (1)$$

where

$$\upsilon_X=\frac{\omega}{c_0}\sqrt{1-\frac{k_X^2c_0^2}{\omega^2}} \quad (2)$$

and where υ_X , are vertical wavenumbers associated with the various lateral wavenumbers and the reference velocity.

The ISS prediction in slowness-pseudo depth domain

In addition to the lower-higher-lower relationship, three sub-events in combination to reconstruct the ray-path of internal multiple are also interrelated through wavenumber on source and receiver sides. The ray-path relationships between primaries and predicted internal multiples can be labeled according to their contributing wavenumbers, i.e., k_g, k_s, k_1, and k_2 in Eq.(1). As is well-known, horizontal slowness shares the same direction as the wavenumber, which means Eq.(1) can also be written into slowness component.Therefore, the ISS prediction algorithm in slowness-pseudo depth domain can be written as,

$$b_{IM}(p_g,p_s,\omega)=\frac{1}{(2\pi)^2}\iint dp_1 e^{-i\omega q_1(z_g-z_s)}dp_2 e^{-i\omega q_2(z_g-z_s)}\int_{-\infty}^{+\infty}dz_1 e^{i\omega(q_g+q_1)z_1}b_1(p_g,p_1,z_1) \times\int_{-\infty}^{z_1-\varepsilon}dz_2 e^{-i\omega(q_1+q_2)z_2}b_1(p_1,p_2,z_2)\int_{z_2+\varepsilon}^{+\infty}dz_3 e^{i\omega(q_2+q_s)z_3}b_1(p_2,p_s,z_3) \quad (3)$$

where

$$q_X=\sqrt{\frac{1}{c_0^2}-p_X^2} \quad (4)$$

q_X , are vertical slownesses associated with the carious horizontal slownesses and the reference velocity. Here, the input is obtained by $b_1(p_g,p_s,z)=-i2q_sD(p_g,p_s,z)$.

The ISS prediction in plane wave domain

Based on the relationship between pseudo-depth and intercept time (Nita and Weglein 2009; Sun and Innanen 2015):

$$k_z z=\omega\tau \quad (5)$$

where, $k_z=\upsilon_g+\upsilon_s$, z is the pseudo-depth, and τ is the intercept time.

The plane wave domain ISS prediction algorithm can be achieved by substituting Eq.(5) into Eq.(1), delineated as (Coates et al. 1996),

$$b_{IM}(p_g,p_s,\omega)=\frac{1}{(2\pi)^2}\iint dp_1 e^{i\omega(\tau_{1s}-\tau_{1g})}dp_2 e^{i\omega(\tau_{1g}-\tau_{1s})}\int_{-\infty}^{+\infty}d\tau_1 e^{i\omega\tau_1}b_1(p_g,p_1,\tau_1) \times\int_{-\infty}^{\tau_1-\varepsilon}d\tau_2 e^{-i\omega\tau_2}b_1(p_1,p_2,\tau_2)\int_{\tau_2+\varepsilon}^{+\infty}d\tau_3 e^{i\omega\tau_3}b_1(p_2,p_s,\tau_3) \quad (6)$$

The ISS prediction in time-offset domain

The intention of re-formulating the ISS-IMs attenuation in time-offset domain is originated from seeking a non-stationary search parameter to identify the lower-higher-lower criterion. For a 1.5D case, replacing the products of integrals over time by modified convolutions and correlations, and substituting the products in wavenumber by the convolution in space, Innanen (2017) presented the ISS prediction with a nonstationary ε in time-offset domain,

$$b_{IM}(x,t) = \int dx_1 \int dt_1 d(x-x_1, t-t_1) \int dx_2 \int_{\alpha(t,t_1)}^{\beta(t)} dt_2 d(x_1-x_2, t_1-t_2) D(x_2,t_2) \quad (7)$$

where,

$$\alpha(t,t_1) = t-(t-\varepsilon)$$
$$\beta(t) = t-\varepsilon \quad (8)$$

However, due to time consuming, the ISS prediction with a nonstationary ε is implemented in wavenumber-time, instead of Eq.(7), written as,

$$b_{IM}(k_g,t) = \int_{-\infty}^{+\infty} dt_1 D(k_g, t-t_1) \int_{\alpha(t,t_1)}^{\beta(t)} dt_2 D(k_g, t_1-t_2) D(k_g,t_2) \quad (9)$$

Implementation of ISS prediction

Many incentive research and discussions of inverse scattering series on internal multiple attenuation have been made depending on the variant purposes, (1) correcting predicted amplitude of internal multiples (Zou and Weglein 2014), and (2) refining the algorithm for certain high priority acquisition styles and environments (Sun and Innanen 2016a,b,c). In this paper, using a 1.5D synthetic data, we investigate and discuss the influence of search parameter and implementation domains. Figure 1 shows a three-layer geological model with velocity varies in depth only (top: 1500m/s, middle: 2800m/s, bottom: 4200m/s), which is utilized to investigate the implementation of ISS prediction. A single shot record is created using finite difference method with all four boundaries set as ‘absorbing' to suppress the creation of free-surface multiples., shown in Figure 2. Two primaries are indicated in yellow at zero-offset traveltime and red lines denote the two-way zero offset traveltime for 1st- and 2nd- order internal multiples, respectively.

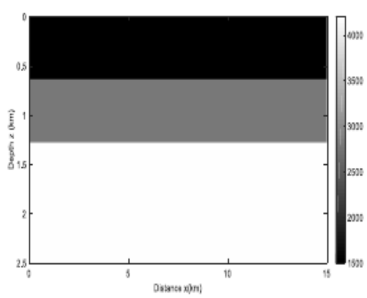

FIG. 1. Synthetic model with velocity varies in depth only: 1500m/s, 2800m/s, 4200m/s.

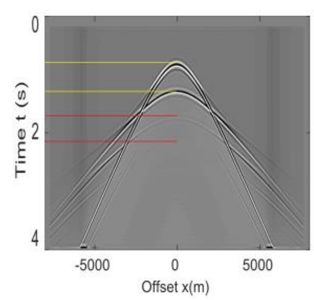

FIG. 2. Synthetic data created using model in Figure 1. Two primaries in yellow, and two internal multiples in red.

Search parameter and Inputs

One reason, increasing the trouble of land ISS-IMs prediction, is that the previous noted limitations integrate sub-events uncertainly in the combination of internal multiple prediction. The key ingredient of separation of sub-events, either in pseudo-depth or in intercept time, is the search parameter applied in prediction algorithm. A suitable ε must has the capacity to separate subevents of combination as the trace changes. Figrue 3 illustrates the inputs of ISS prediction in (k_g, z), (p_g, z), (k_g, t), and (p_g, τ) domains, respectively. Compared the spread distribution as the wavenumber increasing in Figure 3a and 3c, horizontal slowness has a critical superiority in centralizing amplitude of each subevent, which allows a relative stationary ε. To examine the difference between domains and selection of ε, the ISS prediction is implemented in all four domains with variant ε shown in Table 1.

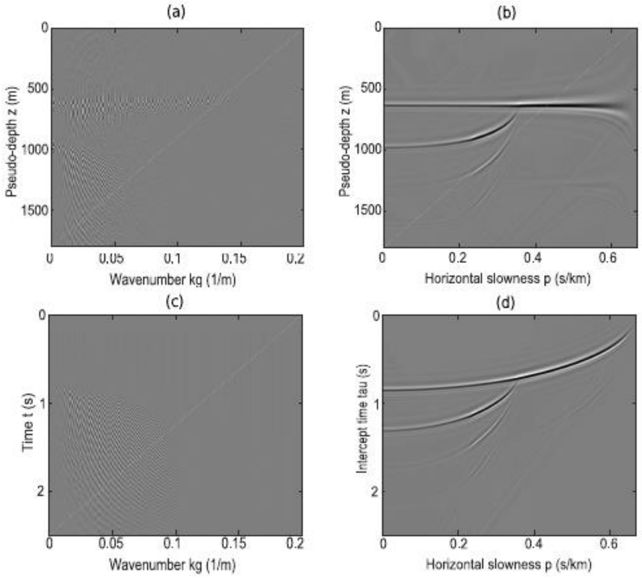

FIG. 3. Inputs of ISS prediction. (a) (k_g, z) domain, (b) (p_g, z) domain, (c) (k_g, t) domain, (d) (p_g, τ) domain.

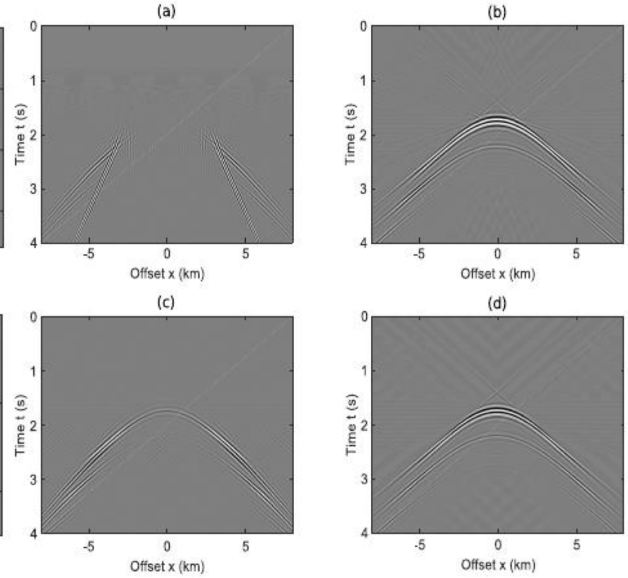

FIG. 4. ISS internal multiple prediction in related domains as Figure 3 illustrated.

Table 1. The corresponded limits of integrals implementing prediction in different domains, and related inputs are shown in Figure 3.

Domains	Equations	Limits of integrals applied
(k_g, z)	Eq.1	$\epsilon = 0.3km$
(p_g, z)	Eq.3	$\epsilon = 0.3km$
(k_g, t)	Eq.9	$\alpha(t, t_1, \epsilon(k_g))$ and $\beta(t, \epsilon(k_g))$
(p_g, τ)	Eq.6	$\epsilon = 0.3s$

Predicted results and discussion

Figure 4a shows the internal multiple prediction using ISS in wavenumber-pseudo depth domain with a stationary ε. As illustrated previous, a fixed search parameter in such domain brings large-dip artifacts when the offset beyond the interacted point between primaries and internal multiples. Compared with Figure 4a, implementing ISS algorithm in horizontal slowness-pseudo depth domain (Figure 4b) provides a preciser result though dispersion occurr at high angle set near surface. A wavenumber-time dependent ε selected in (k_g, t) domain (Figure 4c) can mitigate the aritifacts and improve the precision of result. However, implementing in this domain is computational expensive. The ISS prediction in plane wave domain allows a stationary ε without generating artifacts, shown in Figure 4d. Beyond that, impementation of ISS prediction in plane wave domain is very efficient.

Conclusions

Inverse scattering series internal multiple attenuation algorithm is a powerful and promising way to eliminate multiples on land, even though many challenges to be solved when comes in practice. In this paper, we literature review the progresses, have been made on internal multiple prediction based on inverse scattering series. The selection of search parameter is a key characteristic to eliminate high angle artifacts and to achieve preciser prediction of internal multiple. Two way to access, (1) using a non-stationary search parameter, (2) implementing prediction in plane wave domain which allows a relative stationary search parameter. Plane wave algorithm is more considerable option to implementing the ISS prediction on 2D/3D land data.

Acknowledgements

We thank the sponsors of CREWES for continued support. This work also funded by NSERC through the grant CRDPJ 461179-13.

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