Analysis and application of data-driven approaches for internal-multiple elimination

Chao Ma, Manhong Guo, Zhaojun Liu and James Sheng, TGS*

SUMMARY

Imaging artifacts caused by strong internal multiples can interfere with primary images, affecting structural interpretation and amplitude analysis. In such cases, internal multiples are often attenuated in either data domain or in the image domain. In this abstract, we study three data-driven approaches: Jakubowicz, Inverse Scattering Series (ISS) and Marchenko for internal-multiple removal and analyze their performances. Each method has its unique advantages due to the differences among them. This knowledge, in turn, helps users to choose the appropriate method. Following the analysis, we show field data applications of these methods on towed steamer data.

INTRODUCTION

Although the use of multiples to help subsurface imaging (e.g., Lu et al, 2011) has gained a lot of interest and developments in recent years, multiple removal remains an essential step in seismic data processing for velocity model building and imaging primaries. Many multiple-removal methods have been developed based on the assumption that primaries and multiple have different characteristics. For example, multiples can be attenuated based on the difference in Radon transformed space. These methods are often an effective and appropriate choice when the assumptions are satisfied. Wave-equations based methods are another set of methods used to attenuate multiples by first predicting multiple models using wave equations and then adaptively subtracting the models from the data. Methods using wave equations for predicting multiple models fall into two categories: (1) multiples are forward modeled with the subsurface information, and (2) multiples are predicted by data-driven approaches without the subsurface information.

Among the data-driven approaches, Surface-Related Multiple Elimination (SRME) (Berkhout, 1985; Verschuur and Berkhou, 1992) and ISS Free-surface multiple elimination (Carvalho et al. 1991 and Weglein et al. 1997) algorithms were developed for surface-related multiples. Araujo et al. (1994) and Weglein et al. (1997) developed the ISS internal multiple removal algorithm. Jakubowicz (1998) extended the approach of SRME to predict and remove internal multiples. Most recently, van der Neut and Wapenaar (2016) proposed a Marchenko-based internal multiple removal algorithm.

In this abstract, we study and compare three data-driven approaches (Jakubowicz, ISS and Marchenko) for internal multiple removal and analyze their similarities and differences. These data-driven approaches for internal-multiple removal share the idea of combining events in the data to predict an internal-multiple model. However, they differentiate from each other by each method's unique way to select and combine the events. In the following two sections, we first study those similarities and differences, understand each method's unique advantages and disadvantages, and then we share some field data applications.

METHOD

Like the data-driven approaches for predicting surface-related multiples, internal multiples can be predicted by combining different reflections in the data domain, but it involves convolving two outer events and cross-correlating the middle event (see Figure 1). Different ways of selecting the events that are convolved and cross-correlated distinguish the different methods we discuss in this abstract.

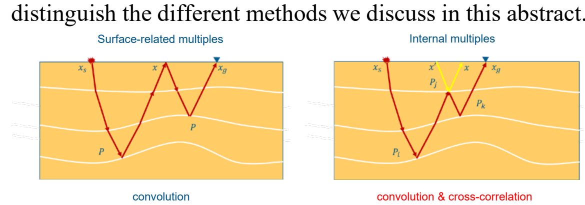

Figure 1: Illustration of the general idea of using data-driven approaches for predicting surface-related (convolution) and internal multiples (convolution and cross-correlation) by combining events in the data.

In the Jakubowicz (1998) method, to predict an internal multiple, an internal-multiple generator (the reflector at which the downward reflection occurs) is identified first. Then, the input data are separated into two parts: one part contains the reflection corresponding to the generator, the other part contains all the reflections below the generator. The two parts are combined to predict the internal multiples as follows:

$$\boldsymbol{M_j}(\boldsymbol{x_s},\boldsymbol{x_g},\boldsymbol{\omega}) = -\sum_{\boldsymbol{x}',\boldsymbol{x}} \boldsymbol{P}_{i_{(>j)}}(\boldsymbol{x_s},\boldsymbol{x},\boldsymbol{\omega})\boldsymbol{P}_j^*(\boldsymbol{x},\boldsymbol{x}',\boldsymbol{\omega})\boldsymbol{P}_{i_{(>j)}}(\boldsymbol{x}',\boldsymbol{x_g},\boldsymbol{\omega}), \quad (1)$$

where, P_j is the reflection corresponding to the j-th generator (* means the complex conjugate in the frequency domain), $P_{i_{(>j)}}$ are the reflections below the j-th generator with travel times larger than the travel time of the reflection in P_j. M_j is the predicted internal-multiple model reflected downward at the j-th generator for a source at x_s and a receiver at x_g. To predict internal multiples generated by a sequence of generators using this method, a top-down approach is usually carried out (see e.g., Ramírez, 2013). As a data-driven approach, this method doesn't require any subsurface information. However, accurately picking the internal-multiple generators in a complex Geology can be challenging.

Araujo et al. (1994) and Weglein et al. (1997) developed an internal-multiple-removal algorithm based on the inverse scattering series theory. This algorithm first transforms the input data to the wavenumber-pseudo-depth domain through an uncollapsed constant-velocity F-K migration (Stolt, 1978). Events that satisfy the "lower-higher-lower" relationship in the pseudo-depth domain are automatically selected and combined to predict internal multiples (see Equation 2).

$$b_3(k_s,k_g,\omega)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}dk_1\int_{-\infty}^{\infty}dk_2e^{iq_1(z_g-z_s)}e^{iq_2(z_g-z_s)}\int_{-\infty}^{\infty}dz_1b_1(k_g,-k_1,z_1)e^{i(q_g+q_1)z_1}$$
$$\times\int_{-\infty}^{z_1-\varepsilon}dz_2b_1(k_1,-k_2,z_2)e^{-i(q_1+q_2)z_2}\int_{z_2+\varepsilon}^{\infty}dz_2b_1(k_2,-k_s,z_2)e^{i(q_2+q_s)z_3}\ . \quad (2)$$

ω is the temporal frequency, k_s and k_g are the horizontal wavenumbers for the source and receiver coordinates x_s and x_g, respectively. q_s and q_g are vertical source and receiver wavenumbers defined as $q_i=sgn(\omega)\sqrt{\frac{\omega^2}{c_0^2}-k_i^2}$ for $i\in(g,s)$. z_s and z_g are source and receiver depth; and z_j $(i\in\{1,2,3\})$ represents pseudo-depth using reference velocity (c_0) migration; $b_1(k_s,k_g,z)$ is the uncollapsed F-K migration of the input data. Weglein and Matson (1998) have demonstrated that Equation (2) can be interpreted as the subevents prediction of internal multiples shown in Figure 1. Notice that, the "lower-higher-lower" relationship in real depth is retained in pseudo-depth domain for most cases. Therefore, using this "lower-higher-lower" relationship in pseudo-depth domain will predict internal multiples with reflections corresponding to "lower-higher-lower" relationship in real depth (Nita and Weglein, 2007).

Equation 2 doesn't require identification of internal-multiple generators and can predict all possible internal multiples (for all possible generators) at once. This unique advantage makes this algorithm a suitable choice when the subsurface is complex (and it is difficult to pick internal-multiple generators) and when all possible internal multiples need to be predicted. However, its computational cost is much higher compared to the Jakubowicz method.

Recently, van der Neut and Wapenaar (2016) proposed a Marchenko-based internal-multiple-removal method. It can be expressed as follows:

$$M_{f1}(\mathrm{x_g},\mathrm{x_s},\omega)=-\left\{\Theta_{t_H}^{\infty}R\left[\Theta_{t_0}^{t_H}R^*\left(\Theta_{t_0}^{t_H}R\right)\right]\right\}(\mathrm{x_g},\mathrm{x_s},\omega), \quad (3)$$

$$M_{f2}(x_g,x_s,\omega)=-\left\{\left[\Theta_{t_0}^{\infty}R\left(\Theta_{-t_H}^{-t_0}R^*\right)\right]\Theta_{t_H}^{\infty}R\right\}(x_g,x_s,\omega). \quad (4)$$

where, R is the input data,

$$\Theta_{t_1}^{t_2}(t)=\begin{cases}1 & if\ t_1<t<t_2\\ 0 & otherwise\end{cases}$$

is a mute function to retain the data between the lower limit t_1 and upper limit t_2, t_0 is a positive number that is slightly larger than the wavelet length, t_H is the two-way travel time of a selected horizon, $\mathrm{M_{f1}}$ and $\mathrm{M_{f2}}$ are predicted internal multiples. We use a simple analytic example to better describe the Marchenko-based method for predicting internal multiples. Let's consider an experiment due to a normal incident plane wave on a three-reflector model. The primary data would be expressed as $D(\omega)=R_1e^{i\omega t_1}+R_2e^{i\omega t_2}+R_3e^{i\omega t_3}$. Notice that we have (1) used $(R_1,t_1),(R_2,t_2)$ and (R_3,t_3) to represent the amplitude and two-way travel times of three primaries, and (2) ignored internal-multiple reflections in $D(\omega)$. Consider a phantom horizon between the second and third reflector, which has two-way travel time t_H, thus, $t_2<t_H<t_3$. For the term M_{f1}:

$$M_{f1}(x_g,x_s,\omega)=-\underbrace{\left\{\Theta_{t_H}^{\infty}R\underbrace{\left[\Theta_{t_0}^{t_H}R^*\underbrace{\left(\Theta_{t_0}^{t_H}R\right)}_{1}\right]}_{2}\right\}}_{3}(x_g,x_s,\omega), \quad (3)$$

1. the truncation result of $\Theta_{t_0}^{t_H}R$ is $\left(R_1e^{i\omega t_1}+R_2e^{i\omega t_2}\right)$
2. Multiplying the first-step result with R^* and applying the truncation $\Theta_{t_0}^{t_H}$ gives: $R_1R_2e^{i\omega(t_2-t_1)}$
3. The last step in equation (3) is multiplying the second step's result with R and applying a final truncation. The result is $R_1R_2R_3e^{i\omega(t_3+t_2-t_1)}+R_1R_2^2e^{i\omega(2t_2-t_1)}$.

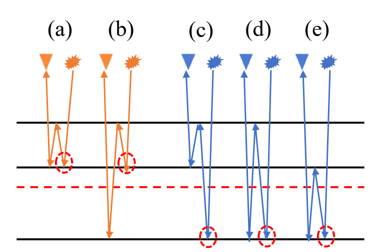

Figure 2: All first-order internal multiples in a three-reflector example.

Term M_{f1} can predict part of internal multiples which have the source-side upward reflection occurs above the selected horizon (see Figure 2 (a) and (b)). Same exercise can be carried out for term M_{f2} which predicts the *remaining* internal multiples where the source-side upward reflection occurs below the selected horizon (see Figure 2 (c), (d), and (e)). Notice that, the downward reflections of all predicted internal multiples in Marchenko method are above the selected horizon as shown by the analytic example. Together, M_{f1} and M_{f2} will predict all internal multiples with downward reflections occurring above the horizon and with travel times larger than the selected horizon. Hence, this method is a suitable choice when users are focusing on internal multiple removal for a target area. Depending on the area of interest, a horizon can be chosen just above the area, all internal multiples with travel times that fall into the area of interest would be predicted.

As we can see from the above analytic example, the Marchenko method works similarly to the Jakubowicz method, but the appropriate mute of the data occurs throughout the whole convolution and cross-correlation processing in Marchenko method, whereas the mute of data occurs before the convolution and cross-correlation in Jakubowicz method. In the ISS method, this "muting and selecting" of events is automatically done through three pseudo-depth integrals in Equation (2).

Notice that, events that are selected to predict internal multiples among these three data-drive approaches can also be internal multiples themselves. When internal multiples themselves are selected and combined, higher-order internal multiples are predicted (Zhang and Shaw, 2010). Under certain circumstances, spurious events can also be predicted (see Liang et al, 2013 for spurious events generation and its resolution).

FIELD DATA APPLICATIONS

In this section, we first show the 2D application of internal multiple removal using the three methods discussed in the last section. Then, we will show the application for 3D Marchenko-based internal multiple removal and its impact for migration.

For the 2D application, we use a line in the TableLand 3D data acquired in Offshore East Canada. We choose the center cable for the test. As shown in Figure 3(a), the water bottom, the volcanic layer (pointed by the blue arrow) and layers in between can act as strong reflectors for internal-multiple generation. Figure 3(b), (c) and (d) shows the internal multiple models predicted by the Jakubowicz, ISS and Marchenko-based method, respectively. In the Jakubowicz method, the water bottom is used as the internal-multiple generator. To save computation cost, the ISS internal-multiple model is calculated up to 30 Hz. In the Marchenko method, we choose the horizon slightly below the volcanic layer. Figure 4 shows the stack section of the data before and after internal multiple removal with adaptive subtraction. As mentioned, the multiple model we obtained from the Jakubowicz method is only using water-bottom as a generator, hence, the multiple model is not 'complete' in the sense that internal multiples with generators below the water-bottoms are not predicted (see e.g., comparisons highlighted by yellow arrows in Figure 3). Therefore, there are residuals after adaptive subtraction with Jakubowicz model in Figure 4b. For the ISS result, we notice some high-frequency internal-multiple residual in the ISS case because the ISS model is only up to 30 Hz to reduce computational cost. With the inclusion of more internal-multiple generators in the Jakubowicz model and the high-frequency component in the ISS model, both the internal-multiple models and adaptive subtraction result should be improved. The Marchenko method predicts all the multiples with generators above the horizon and arrival times below the horizon in one pass.

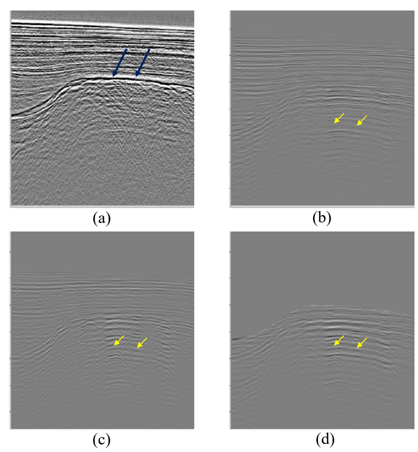

Figure 3: Common channel gather of input data (a), internal multiple model by Jakubowicz method (b), ISS method (c), and Marchenko-based method (d).

In the next example, we use 3D Atlantic Margin South data acquired in Norwegian Sea (see Figure 5(a) for a common channel gather plot). We are interested to predict and remove internal multiple that can obscure primaries below the red dashed curve in Figure 5. These multiples are associated with in intrusive volcanic sill. Hence, the Marchenko method is selected and the dashed curve is used as the horizon in this method. Figure 5(b) show the predicted multiple model. We notice the predicted multiple model kinematically match well with the suspected multiples in the data (see yellow circles in Figure 5). For the adaptive subtraction, we first apply Kirchhoff depth migration to the data and internal-multiple model separately and then, the internal multiples are adaptively subtracted from the data in the image domain using curvelet subtraction, see Figure 6. The application of internal multiple removal removes a lot of internal-multiple energies in the imaging result (see blue circles in Figure 6) and improve the structural interpretability of reflectors beneath the sill. There are multiples residuals left (red arrows) due to the conservative adaptive subtraction.

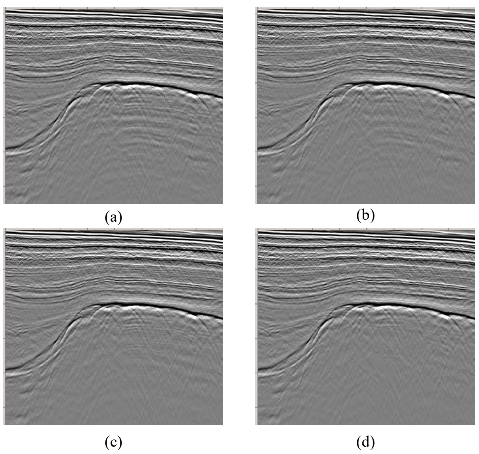

Figure 4: Stack section of data before internal multiple removal (a), and after internal multiple removal with internal multiple model by Jakubowicz (b), ISS (c), and Marchenko (d).

DISCUSSION AND CONCLUSION

We have analyzed similarities and differences among three data-driven approaches for internal multiple removal. Jakubowicz method provides a method to predict internal multiples associated with a specific generator, and a top-down approach is used to remove internal multiples due to different internal-multiple generators. When it is difficult to pick the internal-multiple generators, the ISS method can be used to automatically predict all possible internal multiples. The Marchenko-based method can be used in a target-oriented way to remove internal multiples depending on the users' area of interest.

Field data examples show these methods provide correct kinematics for multiples they predicted. Adaptive subtraction is needed to remove the internal multiples, either in data domain before the migration or in image domain after the migration.

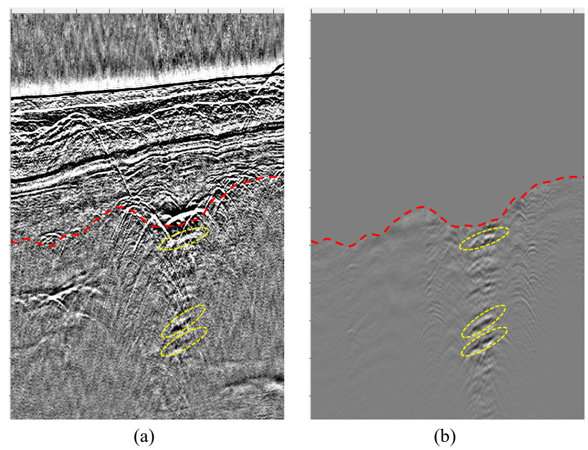

Figure 5: Common channel gather of input data (a) and predicted internal multiple model (b).

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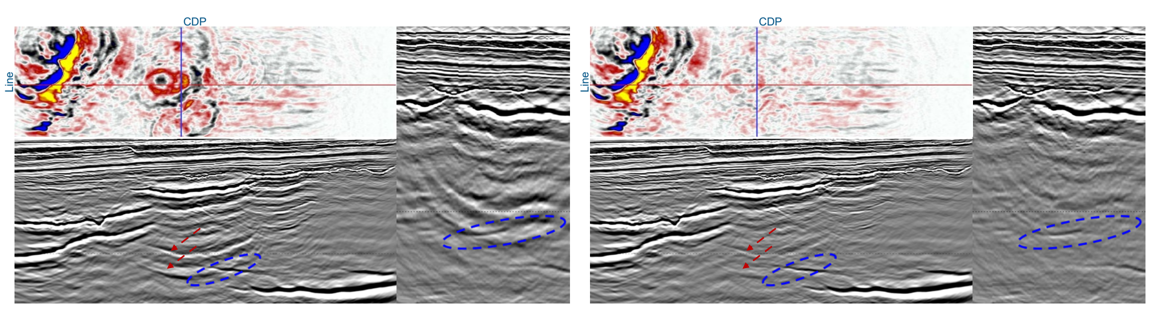

Figure 6: Kirchhoff depth imaging result of data with (a) and without internal multiple (b). In (a) and (b), plots on the upper left are the time slice, plots on the lower left are along inline direction, plots on the right are along crossline direction. The adaptive subtraction of internal multiples is carried out in post-migration stage.