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True-azimuth 3D inverse scattering series method for internal multiple attenuation

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SUMMARY

Removal of internal multiples is a long-standing problem and is still very challenging for the industry. The inverse scattering series (ISS) method is one of the advanced approaches addressing this issue. It is a data-driven approach that can predict all internal multiples without any prior knowledge of subsurface information.

In this paper, we discuss the implementation of a true-azimuth 3D ISS method which takes into account the 3D nature of the earth. It is applicable to both wide-azimuth data (land or marine) and conventional marine streamer data. We apply the approach on a synthetic example as well as real data acquired from the Santos Basin, offshore Brazil. The results show that the 3D approach predicts the multiples well because it takes into account the out-of-plane contributions of the internal multiples. As a result, all the internal multiples are strongly attenuated from the data while primaries are well preserved.

Key words: 3D, Internal multiple, Inverse scattering

INTRODUCTION

Multiple attenuation is a key stage for seismic data processing and required for accurate imaging and interpretation. Surface multiple suppression has been well solved in the industry. In comparison, internal multiple attenuation is a long-standing problem and is still very challenging. This kind of multiple is generated by a series of subsurface impedance contrasts such as coal seams and geological unconformities. Internal multiples are observed in some seismic data, for example, in the Santos Basin of Brazil, whereby the multiples generated between the seafloor and the salt structures have similar traveltime as the reflections from the pre-salt reservoir. This poses significant problems for reservoir identification and characterization.

In the past years, several methods have been developed to address this problem such as Delft's feedback model (Berkhout and Verschuur, 1997), Jakubowicz' convolution-correlation method (Jakubowicz, 1998), model-driven methods (Pica and Delmas, 2008) and the inverse scattering series (ISS) based method (Weglein et al., 1997). The first three methods require some form of subsurface information such as the multiple-generating horizons or seismic velocity for predicting the internal multiples. When several multiple-generating horizons are present in the earth, iterative modelling is often required to attenuate all the multiples. In certain geologic settings, multiple generators can exist laterally for thousands of meters and hence horizon-picking is a challenging task (assuming they can be identified in the first place), especially for complex 3D surveys. In contrast, the ISS based method is a data-driven approach that can predict all internal multiples simultaneously without any prior knowledge of subsurface information. The ISS based method can therefore be an effective approach for internal multiple suppression.

We have implemented 2D ISS and successfully applied it on field data for attenuating internal multiples (Wang et al. 2012). However, 2D ISS is ineffective for survey which has multiple-generating interfaces that have significant 3D effects. For instance, in the Santos Basin the highly undulating salt structures can generate internal multiples with strong out-of-plane components. Extending the method from 2D to 3D is straightforward in theory. However, the lack of data in the crossline direction makes 3D ISS prediction difficult for conventional streamer data. We overcome this difficulty by constructing high-density and wide-azimuth data from the existing streamer geometry, the same approach that was used in 3D SRME (Lin et al., 2004) and 3D internal multiple attenuation (Hung et al., 2013). In this paper, we discuss the implementation of 3D ISS internal multiple attenuation and apply the method on synthetic and real seismic datasets. The synthetic example shows that the 3D method offers improvements compared to the 2D results. The real data example shows that the internal multiples are greatly suppressed using 3D ISS and the migration section is cleaner which is helpful for structure interpretation.

METHOD

The ISS based method assumes that the input data are free of coherent noise such as source and receiver ghost events, direct waves and surface-related multiples. As shown in Equation (1), an internal multiple D_{IM} is predicted by selecting parts of the odd inverse subseries which is associated with removing multiply-reflected energy (Weglein et al., 1997),

$$D_{IM}\left(k_g, k_s, \omega\right) = \left(-2iq_s\right)^{-1} \sum_{n=1}^{\infty} b_{2n+1}\left(k_g, k_s, q_g + q_s\right) \quad (1)$$

where q is the vertical wavenumber and k is the horizontal wavenumber (including two components along the x and y

direction for the 3D case). The wavenumbers q and k satisfy the relationship $k_x^2+k_y^2+q^2 = (\omega/c_0)^2$, where ω is the angular temporal frequency and c_0 is the reference velocity (water velocity for marine surveys). Subscripts g and s stand for geophone/hydrophone and source, respectively. More attenuators, expressed by b_{2n+1}, are included in Equation (1) for a more accurate prediction of the multiple. The first attenuator b_3 is used for attenuating the first order internal multiples. For the 3D case we have a 5D data volume, which is shown in Equation (2).

$$\begin{aligned} & b_3\left(k_{gx}, k_{gy}, k_{sx}, k_{sy}, q_g + q_s\right) \\ & = \int\int_{-\infty}^{\infty} e^{-iq_1\left(z_g - z_s\right)} dk_{1x} dk_{1y} \int\int_{-\infty}^{\infty} e^{iq_2\left(z_g - z_s\right)} dk_{2x} dk_{2y} \\ & \times \int_{-\infty}^{\infty} e^{i\left(q_g + q_1\right)z_1} b_1\left(k_{gx}, k_{gy}, k_{1x}, k_{1y}, z_1\right) dz_1 \\ & \times \int_{-\infty}^{z_1+\varepsilon} e^{-i\left(q_1+q_2\right)z_2} b_1\left(k_{1x}, k_{1y}, k_{2x}, k_{2y}, z_2\right) dz_2 \\ & \times \int_{z_2+\varepsilon}^{\infty} e^{i\left(q_2+q_s\right)z_3} b_1\left(k_{2x}, k_{2y}, k_{sx}, k_{sy} z_3\right) dz_3 \end{aligned} \tag{2}$$

In this equation, $b_1(k_{gx}, k_{gy}, k_{sx}, k_{sy}, z)$ is the pseudo-migrated data using the reference velocity from $b_1(k_{qx}, k_{qy}, k_{sx}, k_{sy}, q_s+q_q)$, which is defined in terms of input data D in the frequency domain by Equation (3).

$$\begin{aligned} & b_1\left(k_{gx}, k_{gy}, k_{sx}, k_{sy}, q_g + q_s\right) \\ & = -2iq_s D\left(k_{gx}, k_{gy}, k_{sx}, k_{sy}, \omega\right) \end{aligned} \tag{3}$$

Here z is a variable in pseudo depth, z_s and z_q are source and receiver depths, respectively. As shown in Figure 1, z_1 and z_3 should always be greater than z_2, which is called "low-high-low" relationship (Nita and Weglein, 2007). In practice, ε is slightly longer than the source wavelet.

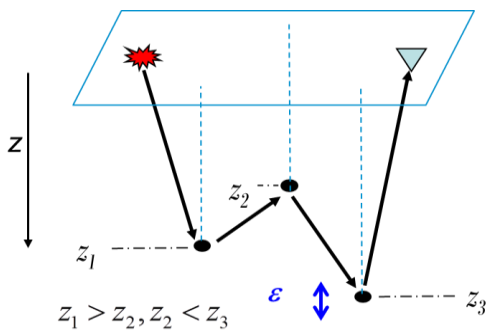

Figure 1: Low-high-low relationship for internal multiple prediction in the 3D pseudo depth domain.

Higher-order attenuators b_n (n = 5,7 …∞), can be formulated in a similar way for internal multiple prediction. The first attenuator b_3 can predict the first-order internal multiple with correct travel-time and less accurate amplitude. Including higher-order attenuators in the prediction can enhance the amplitude accuracy but at the expense of longer computational time. Therefore, our strategy is to use only the first attenuator b_3 in the prediction and then rely on adaptive subtraction to handle the amplitude difference between the actual internal multiples and the predicted ones.

Extending the method from 2D to 3D is straightforward in theory. However, the implementation is more complex as 3D prediction requires an ideal data distribution, a 5D volume as shown in Equation (3). We use an approach on conventional streamer data to satisfy the dense data requirement. The approach is described as follows: (1) generate regularized wide-azimuth data by choosing the appropriate traces from the input data (depending on some selection criteria that minimize the difference in azimuth, offset and midpoint) and then applying differential NMO to correct the discrepancy in offset; (2) perform 3D ISS for internal multiple prediction on the regularized data; then (3) map the internal multiple model to the irregular locations according to actual shot-receiver coordinates. Once having the multiple model, we perform adaptive subtraction to remove the internal multiples from the input data. This technique allows for true-azimuth 3D ISS internal multiple attenuation.

SYNTHETIC AND FIELD DATA EXAMPLES

The 3D ISS method was validated with a synthetic dataset for internal multiple attenuation. A 3D synthetic dataset was generated by acoustic wave modeling. The shallowest two events have significant dip in the crossline direction. Without identifying the multiple-generating interfaces, all the internal multiples are predicted by both 2D and 3D ISS methods. We compare the results from an outer cable which has 200 meters inline distance from the shot line. Figure 2a shows a near-offset section of input data. The blue-dashed lines indicate the exact traveltimes of two strong internal multiples. As a reference, the 2D model is shown in Figure 2b. The 3D ISS multiple model is depicted in Figure 2c. The wiggle displays in the magnified sections (dashed-red box) highlight the extent of matching between the input (colored wiggle) and the predicted multiples (grey wiggle). It can be seen that the 3D model exhibits superior similarity of the traveltime compared with the input than the 2D model. This is because the 2D method does not take into account the out-of-plane reflections that contribute to the generation of the internal multiples. Consequently, it imposes more constraints on the subsequent process of adaptive subtraction. We further check the adaptive subtraction results in Figure 3. Figure 3a shows the input shot gathers. Figure 3b shows the 2D output, which contains residual internal multiples, especially at the locations indicated by the arrows. In comparison, all the internal multiples are strongly attenuated while primaries are well preserved in the 3D output shown in Figure 3c.

Internal multiples are a particular problem in the Santos Basin, offshore Brazil. A series of impedance contrasts above the pre-salt reservoir can be observed such as the water bottom (WB), top of salt (TOS), bottom of salt (BOS) and the layered salt structures as shown in Figure 4a. All these reflectors generate internal multiples which interfere with the reflections from the reservoir. Figure 4b is a crossline view from one location which is indicated by the blue line in Figure 4a. It can be observed that the salt structures have significant crossline dip which introduces strong 3D effects to the generation of the internal multiples. Let us consider the subsalt area which is highlighted by the green box in Figure 4a. The near-offset stack sections of input, ISS subtraction results and their differences are depicted in Figure 5. In this section, the predicted multiples are mainly generated between the seafloor and top of salt as well as from the top of salt and layered evaporites. They are weaker than the primaries, but can still be observed and removed from the input data. The predicted 3D multiples match well to the true ones, leading to good multiple attenuation and primary preservation as shown in Figure 5b and 5c. The improvements from the 3D approach are evident when compared with 2D, which is shown in Wang and Hung, 2014. To observe the effect of internal multiples on migration results, Kirchhoff depth migration was performed on the processed data, which is shown in Figure 6. It can be observed that unreal structures and the migration

swings, which are caused by the IMs, are attenuated after 3D ISS. The clean seismic image is good for the interpretation of the reservoir.

CONCLUSIONS

We have discussed the implementation of the true-azimuth 3D inverse scattering series method for internal multiple attenuation. This approach works for both wide-azimuth data and conventional streamer data. 3D ISS can predict internal multiples produced from all possible generators simultaneously, without requiring any subsurface information. We first applied the method on a synthetic example; the results show that 3D ISS is more effective than the 2D approach becasue it takes into account the strong crossline dip of multiple generators. We also applied this technique on a field dataset acquired in the Santos Basin, offshore Brazil. The unreal structures and migration swings caused by internal multiples are greatly attenuated in migrated sections which helps the structure interpretation.

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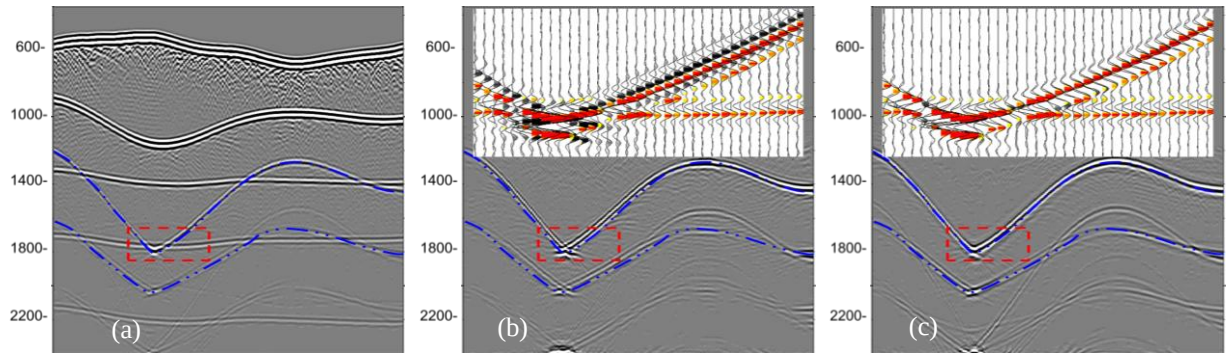

Figure 2: Near-offset section for (a) input data, (b) 2D ISS model, and (c) 3D ISS model. The blue- dashed lines indicate two strong internal multiples, which are drawn from the input section. The wiggle displays show the overlay between the input and the model.

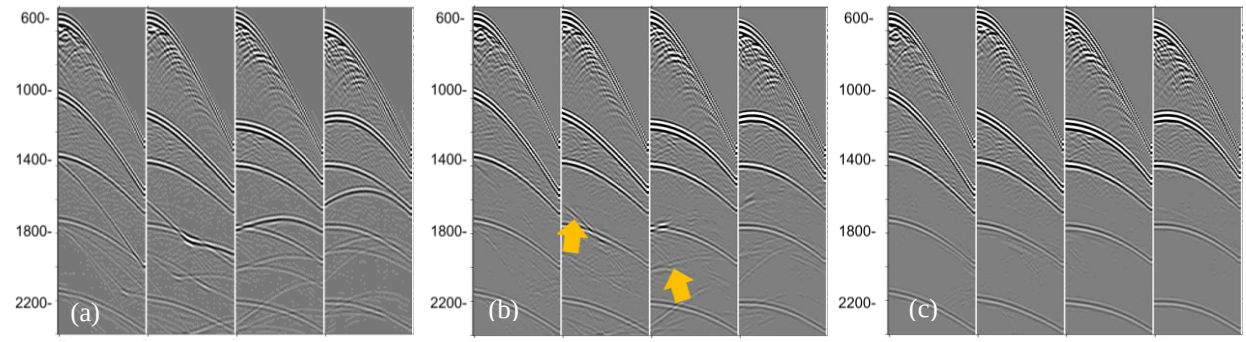

Figure 3: Shot gathers for (a) input data, (b) 2D output, and (c) 3D output. Yellow arrows indicate the residual internal multiples left in the 2D case.

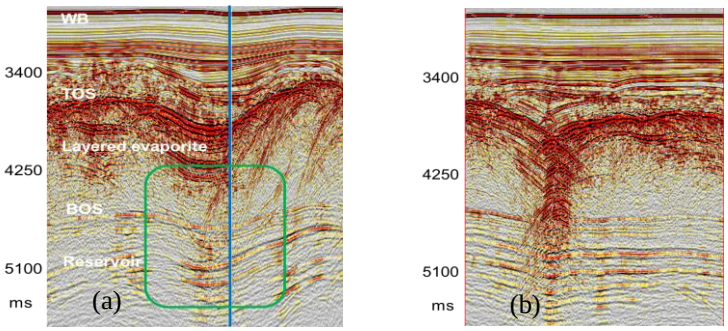

Figure 4: (a) Common-offset section from Santos Basin, Brazil which includes strong reflections such as water bottom (WB), top of salt (TOS), bottom of salt (BOS) and layered salt structures. (b) Crossline view from the location indicated by blue line in (a), which shows the strong crossline dip of the salt structures.

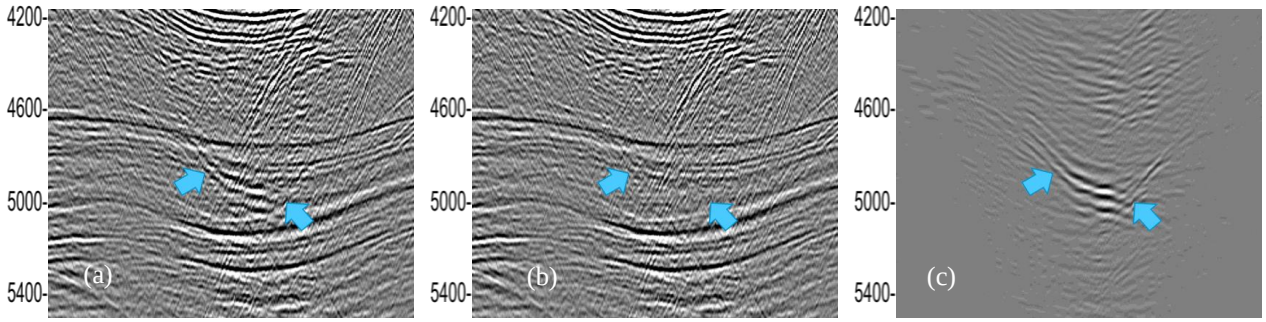

Figure 5: Near-offset NMO stack sections of zoomed area (green box in Figure 4a). (a) Input, (b) 3D ISS output, and (c) difference. Blue arrows indicate the major internal multiples which are attenuated in 3D ISS.

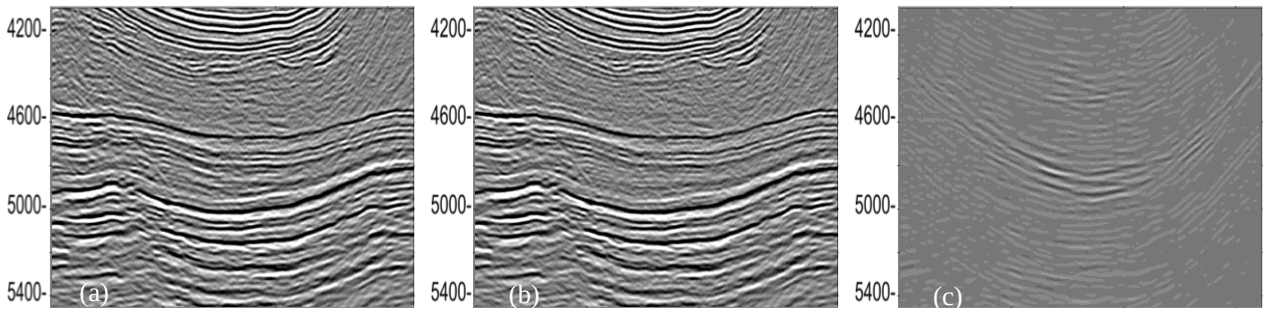

Figure 6: Near-offset depth migration stack sections of zoomed area (green box in Figure 4a). (a) Input, (b) 3D ISS output, and (c) difference.