Broadband least-squares reverse time migration for complex structure imaging

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Summary

We propose a practical solution to overcome the frequency band limitation of conventional reverse time migration (RTM) through a least-squares migration approach. We first generate a high-frequency depth image by migrating deghosted marine seismic data using one-way wave equation migration (WEM). Then we use this high-frequency image as the initial model of band-limited least-squares reverse time migration (LSRTM) and refine the image to enhance the low-frequency components and gradually recover the weak energy from complex structures. The original high-frequency components on the WEM image are maintained. Misplaced steep dips on the WEM image due to wide-angle approximation are also corrected after LSRTM. The final output image contains not only high-frequency and high-resolution horizons but also clear complex structures with sharp geologic boundaries. Compared to the method that directly computes broadband RTM images with high frequencies (greater than 40 Hz), our broadband LSRTM approach is more computationally affordable. We demonstrate the effectiveness of the proposed broadband LSRTM work flow with 2D and 3D real data examples.

Introduction

The resolution of seismic reflection data is limited by the wavelength due to the existence of the Fresnel zone. For band-limited discrete seismic signals, extending the spectrum squashes the corresponding time-domain wavelet towards a spike (Dirac delta function), thus improves the resolution and facilitates the seismic interpretation. This simple Fourier transform wisdom is the motivation of the current widely-employed broadband seismic acquisition and processing techniques in the seismic industry. Seismic imaging benefits from broadband input data and creates high-resolution depth images to delineate the geologic structures in great detail.

Reverse time migration (RTM) is the predominant imaging technique among all production-available prestack depth migration (PSDM) methods due to its virtues of imaging complex structures such as steeply dipping faults and subsalt overhangs (Zhu and Lines, 1998). However, the computation cost of RTM is much higher than many other imaging algorithms such as Kirchhoff and Beam migration. Routine production RTM jobs typically restrain the frequencies no more than 40 Hz, thus, provide limited resolution compared to ray-based imaging algorithms. Broadband imaging using RTM seems still unaffordable on presently available hardware platforms.

Least-squares reverse time migration (LSRTM) is an inversion-based imaging method which refines the image of conventional RTM towards true reflectivity (Dong et al., 2012). Each iterative step of LSRTM involves a combination of two-way RTM-based demigration and migration procedures to update the image. It usually enhances the low-frequency end of the image spectrum to suppress the side lobes of the wavelet and improves the spatial resolution (Dai et al., 2013). Due to the frequency band limitation of the initial model, the LSRTM image usually contains insufficient high frequencies. Directly forcing the initial RTM and the LSRTM iterations to work in the high-frequency band will tremendously increase the computation cost thus is not practical for any real 3D projects. Replacing the RTM engine with wavefield extrapolation migration (WEM, aka. one-way wave equation migration [Ristow and Ruhl, 1994]) during the inversion will reduce the computation cost, but will also sacrifice the image quality for complex structures that are commonly related to reservoirs. Obtaining broadband RTM images with enriched both low and high frequencies is in great demand but remains challenging.

Here we propose a practical solution to overcome the high-frequency limitation of conventional RTM so that the final output image contains both low and high frequencies to present a broadband effect. We start from the high-frequency WEM image that migrated from deghosted input data and use it as the initial model for LSRTM. In the subsequent LSRTM iterations, we use the two-way wave equation for the demigration and migration computation to obtain fully two-way gradients and recover the missing events on the WEM image due to angle limitation. To avoid the expensive computation in the high-frequency band, we limit the maximum frequency in LSRTM iterations. With this iterative combination of WEM and RTM, we obtain broadband depth images containing fine horizons and clear steep dips such as faults and fractures with relatively low cost of computation.

Method

The least-squares migration problem can be formulated as

$$m_{mig} = (L^T L)^{-1} L^T d_{obs}, \qquad (1)$$

where m_{mig} is the migration image, L is the forward modeling (demigration) operator, and d_{obs} represents the observed seismic data. The inversion is conducted by minimizing the following objective function:

$$J(m) = \| p_m(Lm) - p_f d_{obs} \|, \qquad (2)$$

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where p_m is a filter applied to match the synthetic data to the observation preprocessed by operator p_f.

The basic idea of the proposed broadband LSRTM work flow is to integrate the advantages of both WEM and RTM through an iterative procedure. WEM method, usually implemented in the frequency domain, is an algorithm that can be easily parallelized due to its frequency-independent nature. Compared to RTM which is usually implemented in the time domain, the computation cost of WEM can be an order of magnitude less than that of RTM. Especially in the high-frequency band (greater than 40 Hz), WEM can produce reliable images at relatively low cost while RTM is almost unaffordable for large 3D projects. However, the imperfect wide-angle approximation in the one-way wave equation for lateral heterogeneous medium induces the fact that many complex structures cannot be imaged as accurately as that in RTM (Mulder and Plessix, 2004). Because of the theoretical limitation of one-way wave equation, any backward propagating waves will be ignored, causing the loss of weak diffraction signals that are usually important to image complex structures. LSRTM can handle the weak diffractions and enhance them iteratively through inversion. If we use a high-frequency WEM image that lacks accurate steep dips as the initial model of LSRTM, we can take the advantage of LSRTM on weak-event recovery so as to obtain a broadband image with accurate complex structure images.

It is worth noting that this iterative combination of WEM and RTM differs from the method that simply merges the independent images of the two algorithms. In the direct merging case, incorrectly positioned events on WEM images (such as a steep salt flank) will still appear on the merged output and smear the true structure images. In our iterative method, images are updated through an inversion procedure which is more mathematically stable and physically reasonable. Other benefits from the inversion include more balanced illumination, suppression of migration artifacts, and true amplitude behaviors. Moreover, the computation cost is limited and practically affordable compared to direct broadband RTM because the iterations work only in the low-frequency band.

Deghosted broadband input data are important to successful applications of the proposed LSRTM work flow. Due to the high cost of the RTM-based forward modeling kernel, the LSRTM inversion is usually implemented via gradient-based local optimization algorithms such as the conjugate gradient method. This introduces a fundamental limitation that the starting model has to be close enough to the true model otherwise the inversion will be risked in local

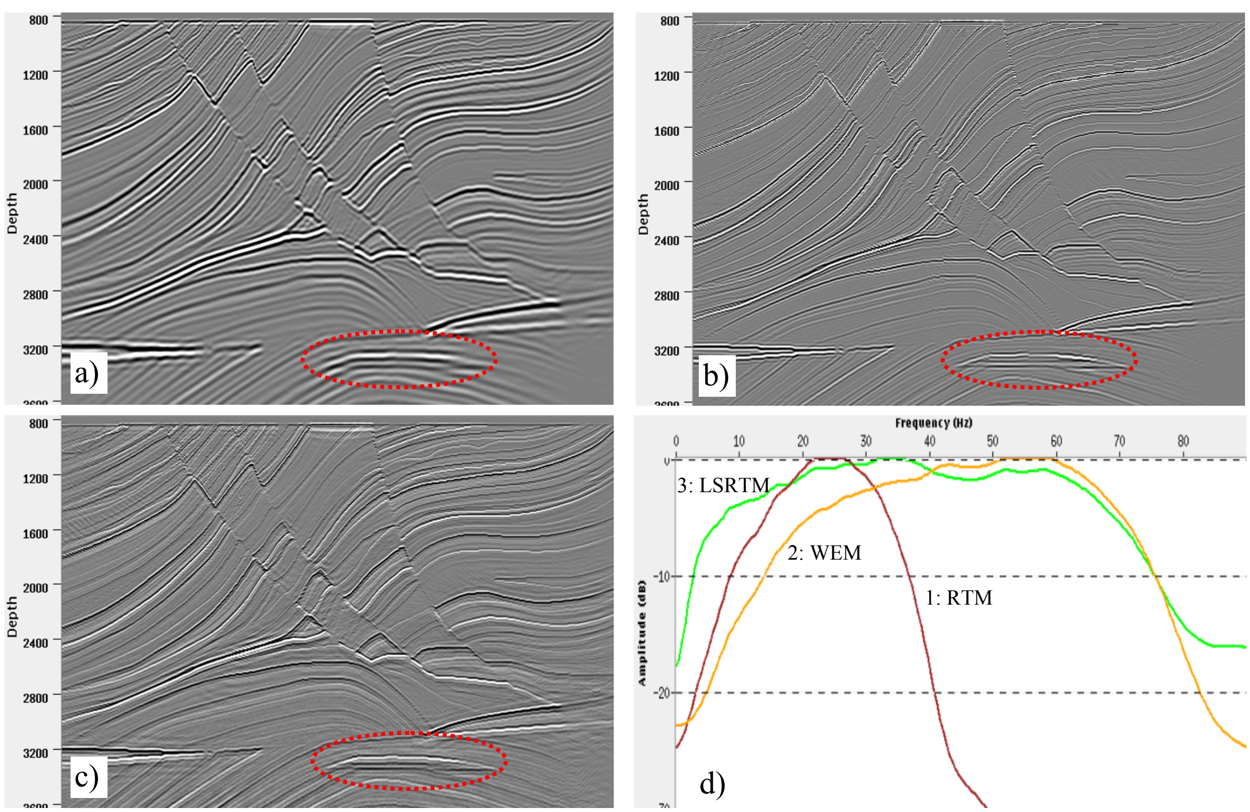

Figure 1. Marmousi image from a) Deghosted RTM, b) Deghosted high-frequency WEM, c) Broadband LSRTM. d) Corresponding spectra, red (1), orange (2), and green (3) curves represent the normalized amplitude spectra of RTM, WEM and LSRTM images, respectively.

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minima. Marine seismic data suffer from a notorious ghost problem which causes a notch on the frequency spectrum and distorts the seismic wavelet. Deghosted data create more accurate seismic images with recovered frequencies and provide better initial models for LSRTM so that the inversion is more stable (Dong et al., 2014).

Synthetic Test

We examine the proposed broadband LSRTM work flow based on the synthetic data calculated with the Marmousi model. We apply an absorbing boundary on the top of the model to remove the ghost effect so that the synthetic data can be considered perfectly deghosted. An Ormsby wavelet (Ryan, 1994) with maximum frequency of 85 Hz was used to create the broadband input data. Figure 1a displays the corresponding 40 Hz RTM image. We run WEM up to 80 Hz to build a high-frequency image (Figure 1b) as the starting model of the LSRTM iteration. Then we run LSRTM up to 40 Hz to update the image. Compared to the 40 Hz RTM image (Figure 1a), the updated LSRTM image (Figure 1c) shows a significant broadband effect. Figure 1d illustrates the normalized amplitude spectra of the three images. The WEM image spectrum lacks low frequencies and the RTM result lacks high frequencies. In contrast, the spectrum of the LSRTM image covers the full seismic frequency band from about 0.5 Hz to 85 Hz (calculated based on amplitudes of 0 to -15 dB). In addition, the LSRTM image of the target reservoir (dot-circled area) is greatly improved compared to the RTM and WEM images.

Real Data Examples

To investigate the effectiveness of the proposed broadband LSRTM approach for real data, we applied the algorithm to a set of 2D streamer data acquired in Brazil (data courtesy of the TGS/WesternGeco Brazil 2D Data Alliance). The original VTI RTM image obtained from migrating the raw data up to 25 Hz is shown in Figure 2a. Due to the ghost effect, the image is band limited and lacks of both low and high-frequency components. To overcome the ghost problem, we apply a deghosting process to the raw data using the method introduced by Masoomzadeh et al. (2013). Then we applied VTI WEM up to 50 Hz for the deghosted data. The high-frequency WEM image (Figure 2b) is used as the initial model of the subsequent LSRTM inversion. After several iterations, the (VTI) LSRTM image (Figure 2c) clearly presents a broadband effect by enriching the low-frequency components and maintaining the high-frequency information as shown in Figure 2d. Compared to the original RTM image and the high-frequency WEM image, the steeply dipping faults are significantly better imaged with focused fault planes and clearer geologic terminations.

Upon the success of the broadband LSRTM on the 2D real data, we extend our study to a 3D shallow-water streamer data from the Gulf of Mexico (data courtesy of TGS multiclient acquisition). We apply the same work flow as the one in the previous 2D data investigation. Figure 3 compares the deghosted RTM image and the broadband LSRTM result. Thanks to the broadband effect, the LSRTM image exhibits clearer fault planes and much higher resolution horizons compared to those on the conventional deghosted RTM image.

For the 3D data example, each iterative step of the broadband LSRTM takes about 3.5 hours. However, if we directly compute the 60 Hz RTM for the same model and data, the estimated total computation time is around 30 hours using exactly the same computing resources, disregarding the impractical GPU memory requirements. Hence our broadband LSRTM is superior to conventional RTM not only in the image quality but also in the computation cost.

Conclusions

The broadband LSRTM utilizes deghosted marine data and iteratively integrates WEM and RTM methods to produce broadband depth images, with enriched low frequencies as well as high frequencies. The computation cost of the broadband LSRTM is practically affordable compared to directly calculating high-frequency RTM images. The image quality is significantly improved compared to that of either conventional RTM or high-frequency WEM. The high-resolution image produced by the broadband LSRTM greatly facilitates timely seismic interpretation and helps to guide in drilling decisions.

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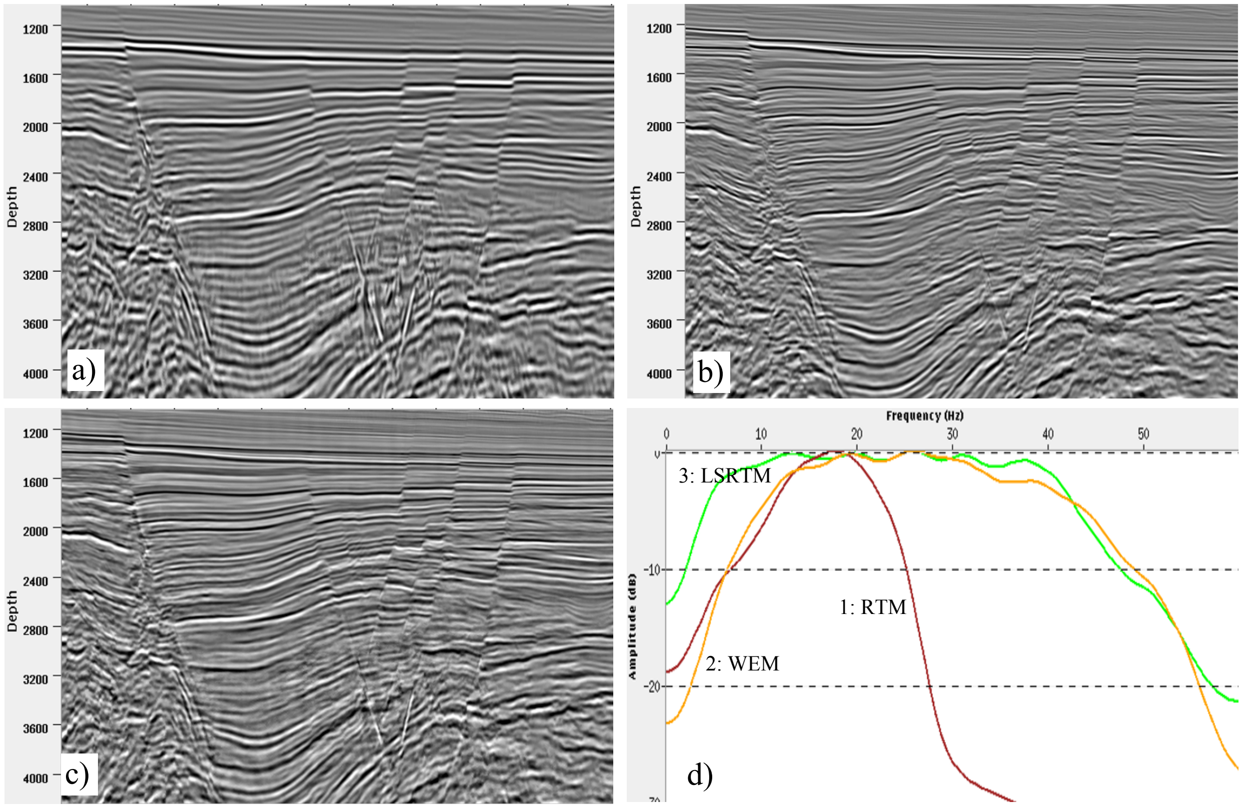

Figure 2. a) Conventional RTM image, b) Deghosted high-frequency WEM image, c) Broadband LSRTM image migrated from the 2D streamer data in Brazil. d) Corresponding spectra, red (1), orange (2), and green (3) curves represent the normalized amplitude spectra of RTM, WEM and LSRTM images, respectively. Spectra are obtained via depth to time conversion.

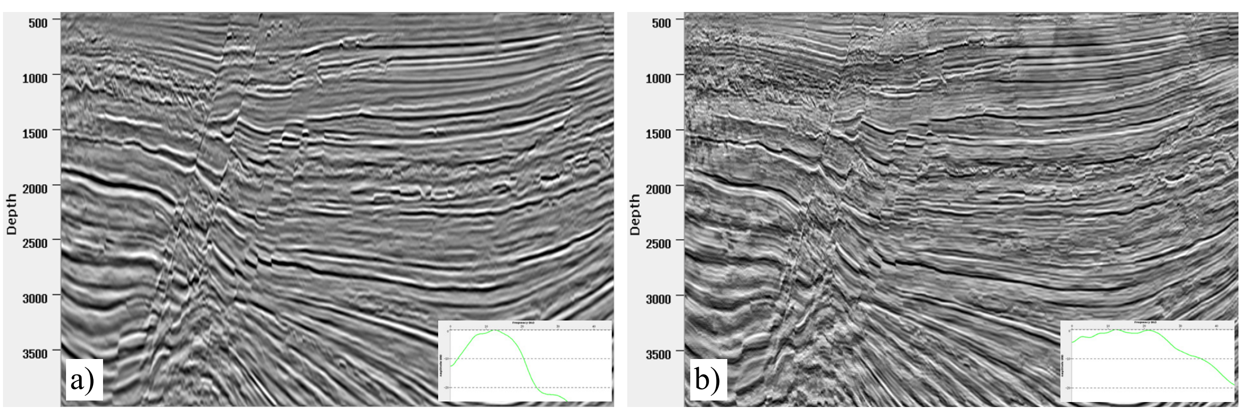

Figure 3. a) Deghosted RTM image, and b) Broadband LSRTM image migrated from the 3D streamer data in the Gulf of Mexico. Corresponding spectra are shown in lower right corner for comparison.

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