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Deghosted Least-squares RTM - Image Domain Broadband Solution for Complex Structures

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SUMMARY

We introduce a 3D inversion-based Least-squares Reverse Time Migration (LSRTM) technique combined with a data-based optimum deghosting method. This new LSRTM approach considers the complex features of ghosts, such as frequency dependence and random variation of source and receiver depths. The optimum deghosting part greatly simplifies the data matching and makes the inversion procedure more stable and faster. As an image domain broadband solution, the deghosted LSRTM approach can benefit from both the inversion-based migration operator and data-based frequency-band broadening to provide an uplifted broadband high-resolution image. Working like a 3D deconvolution, this robust LSRTM approach provides a high definition and true-amplitude solution which effectively improves both temporal and spatial resolution of seismic images in complex structure areas.

Introduction

For oil and gas exploration, high-resolution and true-amplitude seismic images are important to interpretation and detailed reservoir monitoring. It is commonly accepted that both low and high frequencies contribute to high-resolution images (Bai et al., 2013). To obtain broadband high-resolution seismic images, several efforts have been made at different data acquisition and processing stages. At the data acquisition stage, many new technologies have been developed to acquire broadband seismic data, such as dual-sensor streamers (Carlson et al., 2007), over-under streamers (Özdemir et al., 2008), and variable-depth streamers (Soubaras, 2010). At the data processing stage, several deghosting technologies have been developed to achieve broadband seismic data on conventional streamer acquisitions. For example, Wang and Peng (2012) proposed a pre-migration deghosting method using a bootstrap approach. Masoomzadeh et al. (2013) introduced a semi-deterministic stage of deghosting operation in plane-wave domain. Zhou (2013) applied deghosting process on conventional towed streamer data. At migration stage, inverse operator-based methods provide broader bandwidth and higher resolution images than the conventional adjoint operator-based migration methods. As an example, Least-squares Reverse Time Migration (LSRTM) can effectively suppress conventional migration artifacts including migration swings, side lobes and acquisition footprints. (Nemeth et al., 1999; Tang et al., 2009; Kaplan et al., 2010; Zhan et al., 2010; Dai et al., 2011; Yao et al., 2012). Meanwhile, successful application of LSRTM for real data remains challenges. In the real world, wavelet changes as wave propagates due to numerous reasons such as attenuation, ghosts and visco-elastic effects. Time and space variant wavelets introduce difficulties to the matching of synthetic and real data. Several methods have been proposed to handle this problem, including the application of a matching filter to the synthetic data (Dong et al., 2012), or the use of cross-correlation based cost function (Zhang et al., 2013).

In this study, we propose a new methodology to combine deghosting with LSRTM. Optimized deghosting and deconvolution are applied on the input data to reduce the wavelet distortion effects before applying LSRTM. The combination of deghosting with the inversion-based imaging method can benefit from both technologies and be able to achieve broadband high-resolution images especially in complex structure areas. In general, the success of conventional LSRTM relies on an accurate source-signature estimation, which is not trivial for real data. Deghosting and deconvolution can relax the dependence on source-signature estimation for LSRTM. However, it is still challenging for conventional RTM with deghosted data in complex-structures imaging such as steep-dip faults and shadow zones due to scattering diffractions and poor illumination. The intrinsic iterative feature of LSRTM can gradually add weak and scattering energies back to the RTM image thus improves the resolution of complex structure imaging and provides a lift to the broadband imaging solution.

Method and theory

The least-squares migration can be formulated by the following equation:

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

where, m_{mig} is the migration image, L represents the forward modeling operator, and d_{obs} is the observed seismic data. An iterative solution can be obtained by minimizing the objective function $J(m)$, which is the misfit between the forward modeled data Lm and the seismic data d_{obs}:

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

where, p_m is a filter applied to match the forward modeled data with the observed data, and p_f is the preprocessing operator applied to the observed field data. Gradient-based iterative solutions are usually employed to solve this equation. Meanwhile, the amplitude matching and the design of matching filter p_m are not easy. For example, conventional synthetic modeling approach cannot simulate ghost accurately. In a real marine seismic operation, both source and receiver depths keep varying due to weather conditions and acquisition limitations. Furthermore, because the sea surface is not a perfect mirror, a downward reflection at the sea surface becomes increasingly imperfect for higher frequencies and ray parameters. Despite of these factors, conventional ghost modeling methods often assume a frequency-independent reflection coefficient. This degrades the data matching between synthetic and real data. In practice, this imperfect matching could lead the iterative inversion process to a divergent state. In this paper we use the deghosting workflow introduced by Masoomzadeh et al. (2013) to remove the ghost effects from input data. In this approach, a ghost function in the τ-p domain is expressed as:

$$1 + r_{(\omega,\tau,p)} e^{i\omega t(p)}, \tag{3}$$

where r is the negative reflection coefficient at the sea surface, which is related to the angular frequency ω. In this method, a stochastic search is performed for the most appropriate set of parameters, including source and receiver depths and effective reflection coefficients on both sides. This deghosting workflow can remove both source and receiver-side ghosts optimally and effectively. The LSRTM combined with this deghosting approach can greatly simplify the process of matching filter design and drive the inversion process to converge faster and more robustly.

Synthetic data example

We first conduct a synthetic study on a modified Marmousi model. A constant depth towed streamer acquisition is simulated, assuming sources at 8 m and receivers at 16 m below the sea surface. Ghost-contaminated data are generated with a free surface condition and ghost-free data are generated with an absorbing-boundary condition on the top of the model.

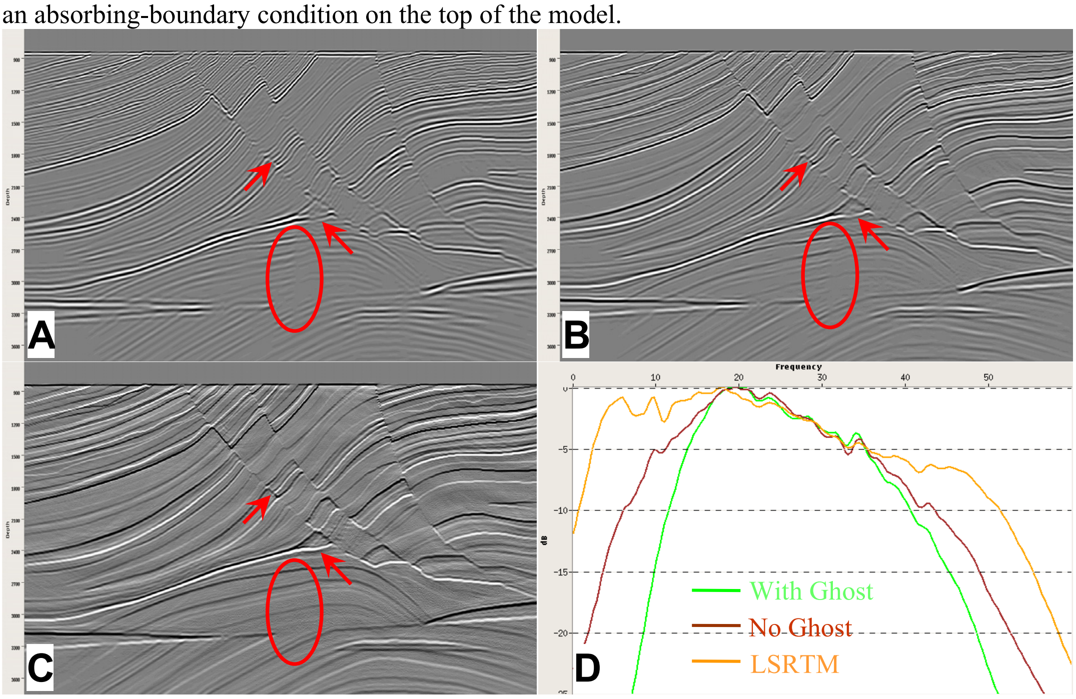

***Figure 1**. (A) RTM image of synthetic data with ghost. (B) RTM image of synthetic data without ghost. (C) LSRTM image of data after deghosting. (D) The depth frequencies of all images.*

The RTM images with and without ghost are shown in Figure 1. The image with ghost (Figure 1A) shows strong side lobes and defocusing effect, which cause the image look blurred especially in fault zones and deep areas. Meanwhile, the image without ghost (Figure 1B) shows weaker side lobes, which makes the faults and deep events much clearer. From the depth image spectrum comparison (Figure 1D), we can see the ghost-free image extend its frequency bands on both low and high ends. Then we apply the LSRTM on the deghosted data. The depth-frequency band of the image is further extended, especially on the low end. The resulting image (Figure 1C) shows further improvements. The faults look much clearer because of better terminations; the deep weak events are boosted up; the image is laterally more balanced, and the smeared reflections in the circled area shown in Figure 1A and 1B now become shaper and continuous. All these improvements benefit from the intrinsic iterative feature of LSRTM: it gradually adds back the weak energies caused by poor illumination and diffraction scatterings and provides an image with well balanced illumination.

Field data example

In the field data example, we use a 2D conventional streamer data acquired in Brazil. We apply conventional RTM on data with and without deghosting, and LSRTM on deghosted data respectively. A comparison of the resulted images is presented in Figure 2. With deghosting only (Figure 2B), the image spectrum is broadened and the side lobes are reduced. With deghosted LSRTM (Figure 2C), the image resolution is further improved. Compared to conventional RTM images, the steep dip faults are significantly better imaged with shaper fault planes and clearer geological termination. The overall amplitudes are more balanced, and the image spectrum is further extended with enriched low frequency information, leading to a sharper image with less side lobes that greatly facilitates further interpretation.

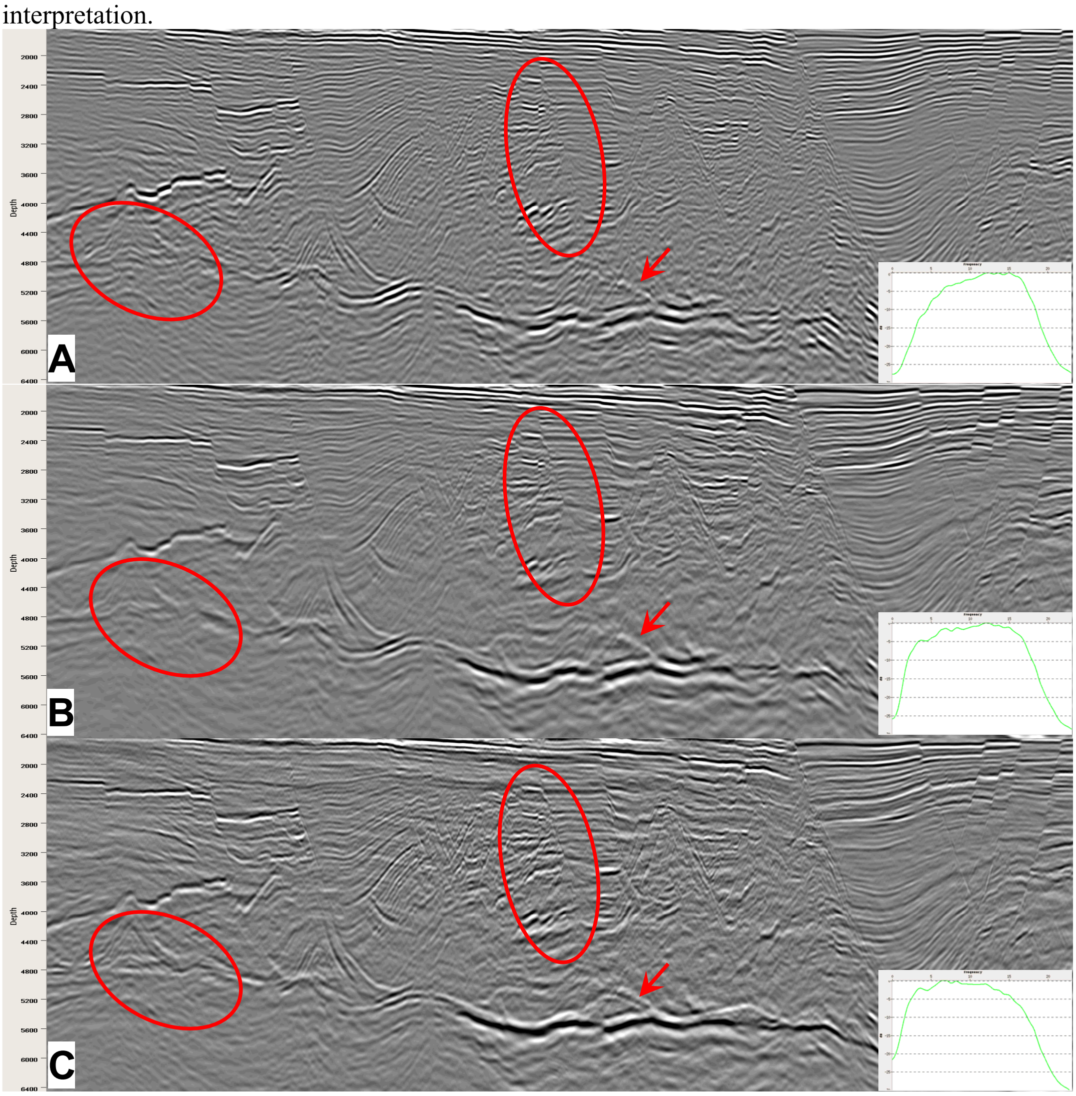

***Figure 2**. 2D marine data images: (A) RTM image of input data without deghosting. (B) RTM image of input data with deghosting. (C) LSRTM image of input data with deghosting.*

For LSRTM we assume the source signature is unknown, therefore we insert a band limited flat spectrum wavelet without a prior knowledge of the exact source wavelet. Without incorporating the deghosting and deconvolution, the LSRTM process would pose a risk of heading to a non-convergent state after several iterations. This is mainly caused by the wavelet mismatch between synthetic and real seismograms. The deghosting and deconvolution steps suggest that the resulting wavelet is expected to be time and space invariant. Therefore the data misfit is truly dominated by the differences between the image and the real earth reflectivities with minimal interference of the inaccuracy of forward modelling process. The deghosting stage helps the LSRTM to be more robust and capable of picking up the inaccurately migrated weak events and subtle features, and compensating them back to the initial image.

Conclusions

The LSRTM combined with an optimum deghosting workflow can significantly stabilize and simplify the inversion process. This approach can benefit from both the inversion-based migration operator and data-based frequency-band broadening to provide an uplifted broadband high-resolution image. Working like a 3D deconvolution, this robust deghosted LSRTM approach can effectively improve the complex structural images to provide a high-definition and true-amplitude solution for detailed reservoir imaging and interpretation.

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