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Amplitude Preserved Least-squares RTM Gathers

Y. He[1], F. Hao[1], S. Dong[1], B. Wang[1]*

[1] TGS

Summary

Least-squares reverse time migration (LSRTM) mitigates the illumination problems caused by complex geologic structures, nonuniform acquisition geometry and limited recording apertures. It is theoretically accurate in producing image gathers more suitable for amplitude versus offset (AVO) analysis. We apply image-domain LSRTM in the gather domain with nonstationary matching filters to generate LSRTM gathers with amplitude better preserved. The proposed flow can be applied on both offset and angle gathers with a flat AVO response demigration followed by a remigration. First, we use an acoustic synthetic example to illustrate the idea and verify the results. Then it is applied to a wide-azimuth (WAZ) survey in the Gulf of Mexico.

Introduction

Image-domain LSRTM originated from the inverse or deconvolution operator (Hanisch et al., 1997) that was applied to the Hubble space telescope. Hu et al. (2001) first introduced a deconvolution operator in poststack migration to improve the migration spatial resolution and reduce the artifacts by approximating the inverse of the Hessian in geophysical exploration. Rickett (2003) only approximated the diagonal elements of the Hessian matrix to calculate the illumination compensation. The method estimated the illumination from the ratio between the initial reference model and migrated synthetic data. Guitton (2004) illustrated that the inverse Hessian can be approximated by a bank of nonstationary matching filters, which can be estimated by matching the real data migration image and the remigration image. Symes (2008) has demonstrated how to construct an approximate acoustic linear inversion from RTM by filtering and scaling the migration output. The estimation of the scale factor involves an additional demigration step followed by a second migration, plus some minor additional computations. Fletcher et al. (2016) estimated the Hessian by point spread functions (PSF), the impulse response of the modeling followed by migration, then interpolated them when applying the inverse Hessian operator to improve the image.

As is well known, the subsurface reflectivity is angle or offset dependent. To provide useful information for AVO analysis, it is meaningful to extend the image-only LSRTM to gather inversion. Thus, the LSRTM needs to be performed in the prestack domain instead of poststack. It is important to generate LSRTM gathers with illumination effects removed so that the gathers can preserve correct angle-dependent information. For data-domain LSRTM, which solves the inversion and updates the reflectivity by iteratively matching the modelling results to the acquired data, demigration based on gathers is an indispensable step in the inversion loop. To match the data from variable offsets, the demigration must be done for each migration offset or angle. However, it is difficult and expensive to implement gather-based demigration because the cost of demigration is prohibitive for offset, angle, time, and space-shifted migration gathers.

Compared to data-domain LSRTM, the image-domain approach recovers the subsurface reflectivity by considering the inverse Hessian operator during inversion. Wang et al. (2016) presented a curvelet-domain Hessian filter to extend the stack-based deconvolution to prestack gathers, which improved the subsalt image. In this paper we propose a practical image-domain method to generate LSRTM gathers, which represent angle or offset dependent reflectivity. First, we use a synthetic test to illustrate that the demigration and remigration method can estimate the correct illumination and recover correct AVO in prestack domain. Then we apply the approach to a wide-azimuth survey to demonstrate that it better preserves the amplitude.

Theory

For seismic inverse problem, the inversion is well known in the following form

$$\mathbf{m^*} = (\mathbf{L}^T\mathbf{L})^{-1}\mathbf{L}^T\mathbf{d}=(\mathbf{H})^{-1}\mathbf{L}^T\mathbf{d} \qquad (1)$$

The linear modelling operator $\mathbf{L}$ describes the modelling process. $\mathbf{d}$ is the acquired data, $\mathbf{H}=\mathbf{L}^T\mathbf{L}$. $\mathbf{m_1}=\mathbf{L}^T\mathbf{d}$ is a standard migration. The inversion result is the standard migration with inverse Hessian applied.

$$\mathbf{m^*} = (\mathbf{H})^{-1}\mathbf{m_1} \qquad (2)$$

Here $\mathbf{H}^{-1}$ can be considered as a deconvolution filter. It has both the focusing effect and amplitude compensation. It consists of the inverse of a combination operator, the forward modelling and migration operators, which fundamentally are determined by the model, the underlying wave propagation method and the acquisition geometry.

To estimate $\mathbf{H}^{-1}$, a reference gather $\mathbf{m_1}'$ is constructed to generate synthetic data $\mathbf{d_1} = \mathbf{L}\mathbf{m_1}'$. Given a constant amplitude gather $\mathbf{m_1}'$, demigration is done once to generate synthetic data for all offsets. It is not as expensive as in data-domain LSRTM since it does not need to demigrate variable amplitude gathers to match the data. There are multiple options for how to do the demigration. One of the popular ways is to directly use the migration stacking image $\mathbf{m_1}$ since it is simple and easy to implement. Another option is to use some forms of delta function, such as PSF, or surfaces. We chose to do the demigration with surfaces, which is simply a reflectivity modelling with the same reflectivity represented in each angle or offset. The surfaces have the same dipping information as the stacking image.

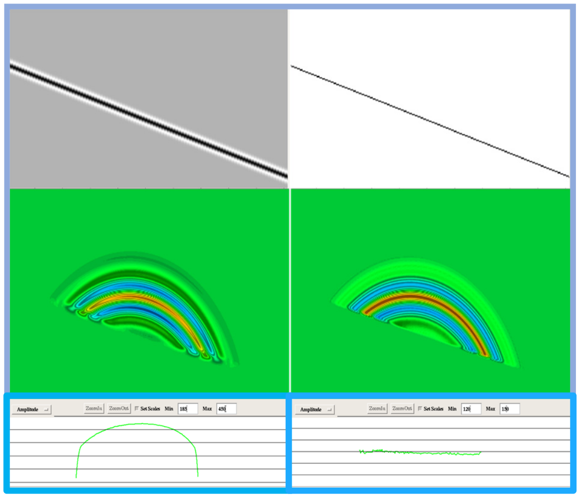

Figure 1 *The wavefield snapshots for a band-limited reflector and a delta function.*

In Figure 1, there is a comparison of the wavefields snapshots reflected from a band-limited image and a delta function. Note that the wavefield reflection is of variable amplitude for a band-limited reflector, while the wavefield magnitude is uniform at all directions with a delta function reflector. The uniform reflection generated from the delta function makes the synthetic data keep constant AVO across the offset or angle domain. It makes the amplitude scaling straightforward and easy to check. If the demigration is based on a band-limited image, the interference effects from adjacent points in the wavelet would generate a synthetic dataset with variable AVO, which distorts the amplitude information.

Following demigration, the synthetic dataset is remigrated to generate a synthetic migration

$$\mathbf{m'}_2 = \mathbf{L}^T\mathbf{d}_1 = \mathbf{L}^T\mathbf{L}\mathbf{m'}_1 = \mathbf{H}\mathbf{m'}_1 \qquad (3)$$

The remigration may not be constant AVO even with a true-amplitude migration algorithm if the acquisition is not uniform or a complicated velocity model causes uneven illumination. Thus $\mathbf{H}^{-1}$ can be estimated by matching $\mathbf{m'}_2$ to $\mathbf{m'}_1$, which is approximated by a bank of filters. Then they can be applied to the original migration results $\mathbf{m}_1$ to generate the inversion result $\mathbf{m}^*$.

Examples

We built an acoustic model with a salt body to demonstrate the idea. Below the salt body, there are a set of reflectors with the same AVO signature, variable in offset, going through the sediment area to the subsalt area. First the migration is done with an incorrect velocity, which results in gathers without flat events, to simulate a realistic situation. From the migration image, a set of reflectivity horizons are generated, and constant AVO reflectivity modelling is simulated to generate a synthetic dataset without AVO variation. Then this synthetic dataset is remigrated. Through the whole process the migration algorithm implemented is the true-amplitude imaging method from Zhang et al. (2014). As is observed in the remigration gathers in Figure 2e, the true-amplitude migration gives correct amplitudes that match the reflectivity (Figure 2d) not only in depth, but also across the offsets in the sediment area.

However, in the subsalt area, the amplitude is distorted due to uneven illumination from the complex salt geometry. Since the reflectivity input into the demigration has constant AVO, any AVO variation observed after remigration is considered to arise from the model or the acquisition geometry. We match Figure 2e to Figure 2d by a set of matching filters, which generates Figure 2f. Then the same filters are applied on Figure 2b to generate Figure 2c, which is considered an inversion result. The gathers at the sediment and the subsalt area are compared before and after the filtering in Figure 3. Since a true-amplitude migration algorithm is used, the sediment does not change considerably, which can also be explained by the negligible difference between the gathers in Figures 3d and 3e in the sediment area. However, the gather events in the subsalt area change a lot with the correction, approaching the theoretical AVO curve. One thing we need to note is that the forward modelling operator here is still based on an acoustic assumption since this is an acoustic reverse time migration. Even the density factor is not considered yet. In reality, the waves travel through the Earth with elastic properties and suffer attenuation effects. All these factors that may affect the amplitude are not included in the acoustic algorithm. But this is the best we can do under an acoustic assumption to remove the prestack illumination effects.

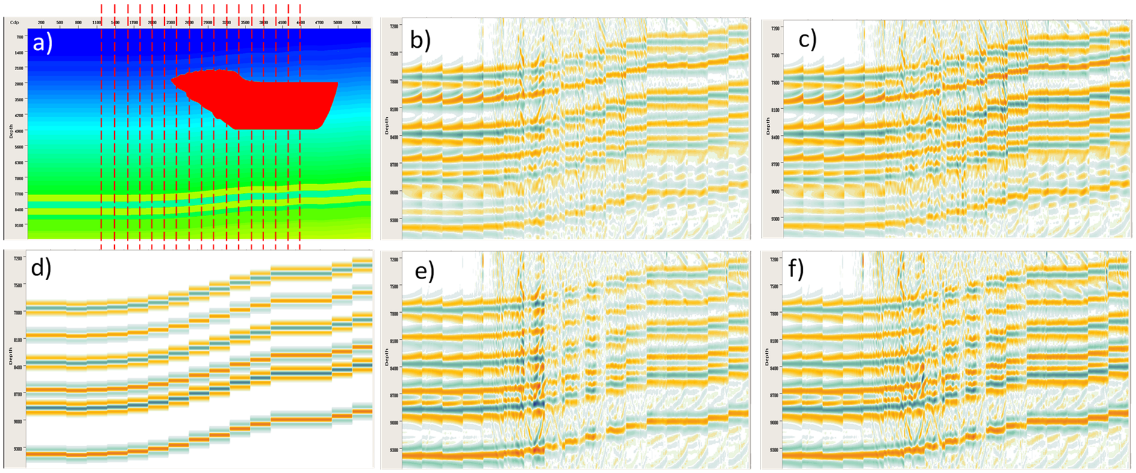

Figure 2 *a). The velocity model with the gather locations marked. b). The migration gathers from the dataset without any correction. c). The migration gathers with correction. d). The reflectivity with constant AVO. e). The remigation gathers. f).The remigration gathers with compensation.*

Another factor is that the velocity structure can cause difficulties, especially with a rugose top salt. When the top salt surface is complicated, it generates multiple arrivals and diffractions which distort the wave amplitude and make the amplitude scaling difficult. Mora and Biondi (2000) showed that a complex overburden distorted the AVO more than a flat layer. Askim et al. (2010) also stated that the division is difficult to accomplish where the illumination is too weak in the subsalt area. To make the amplitude correction stable, proper damping and smoothing of the filters is applied.

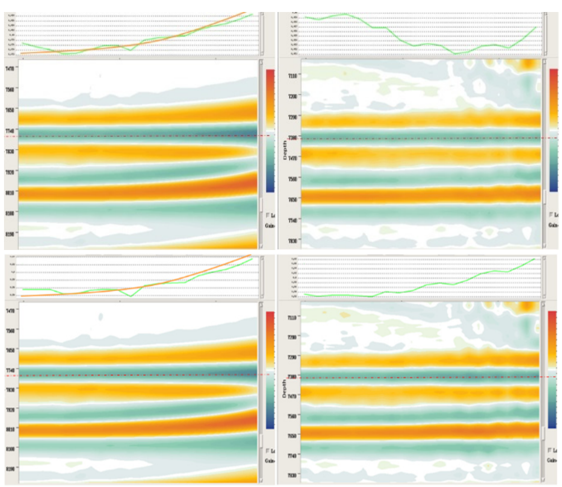

***Figure 3** The top panels show gathers for the sediment and subsalt areas without correction. The bottom shows gathers with correction. The orange curve is the theretical AVO curve.*

In the next example, we applied the approach on a WAZ dataset from the Gulf of Mexico, shown in Figure 4. The same scaling factors were applied to the synthetic migration and real data migration. While the synthetic migration is corrected to be constant AVO, the real data migration should be also corrected with better amplitude fidelity in the same way. The RTM angle gathers with correction show a more balanced stacking image with a normalized display at the top salt. The gathers have a higher signal-to-noise ratio and are more continuous with fewer artifacts. The angle coverage is also extended with more energy contribution.

Conclusions

We presented a practical image-domain method to generate LSRTM common-offset and common-angle gathers with demigration-remigration filtering. Without matching the original dataset in time domain, the demigration with constant AVO makes the amplitude scaling straightforward and easy to check in image domain. Though it is under an acoustic assumption, it may remove the uneven illumination effectively and preserve the amplitudes better than standard migration when nonuniform acquisition and velocity complexity exist.

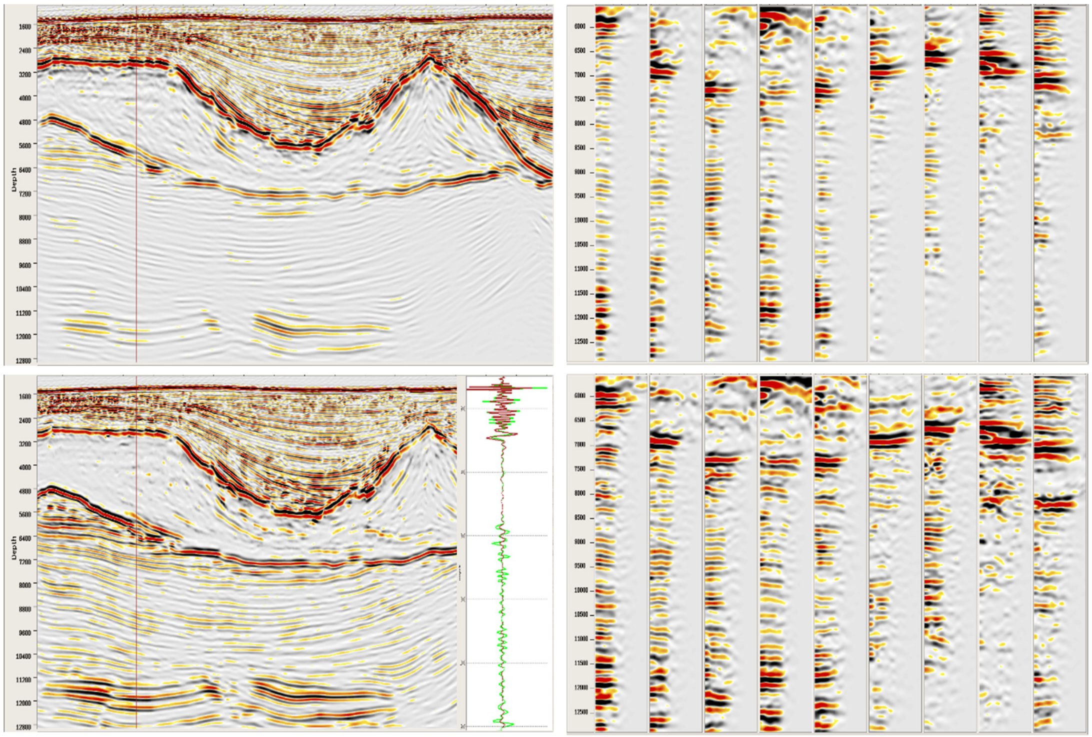

Figure 4 *Results before and after correction for the Fusion WAZ survey in the Gulf of Mexico.*

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