High-resolution reverse time migration with squared excitation amplitude imaging condition

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SUMMARY

Reverse time migration (RTM) can provide superior images in areas with complex subsurface structures. However, it faces several challenges when using the conventional cross-correlation imaging condition, such as low resolution, migration artifacts, amplitude preservation, and large storage requirements. We propose a high-resolution RTM method with squared excitation amplitude imaging condition. We first save the maximum amplitude and the corresponding excitation time for each subsurface image point during source wavefields extrapolation, which is equivalent to the excitation amplitude imaging condition for zero phase source wavelet. Next, we perform a direction-preserved zero-lag autocorrelation on the extrapolated receiver wavefields. Finally, we apply a squared excitation amplitude imaging condition to generate the RTM images. Our new RTM method inherits the benefits of the excitation amplitude imaging condition, such as reducing computer storage requirement. The proposed method could further provide RTM images with higher resolution, which is especially important for the thin layers. There are also fewer migration artifacts in the new RTM images. We demonstrate the effectiveness of the proposed RTM method with a synthetic thin layer model and the Marmousi2 model.

INTRODUCTION

The zero-lag cross-correlation imaging condition (Claerbout, 1971) is widely used in reverse time migration (RTM) due to its implicity and stability. The RTM images are generated by the full-space cross-correlation of the source wavefields and the receiver wavefields over each time step, requiring either saving or recomputing all extrapolated source wavefields for each time step, leading to very large storage requirement as a 50% increase in computation cost. The cross-correlation in full-space also introduces unexpected migration artifacts, which can degrade image quality, and inaccurate image amplitudes (Chattopadhay and McMechan, 2008). Claerbout (1971), and Kaelin and Guitton (2006) indicate that we can obtain images with accurate amplitude scaling of the reflectivity by using the source-normalized cross-correlation imaging condition, which is performed by the normalization of the zero-lag cross-correlation image with source illumination strength.

Chang and McMechan (1986) proposed the excitation time imaging condition to sidestep the storage problem of RTM in the cross-correlation imaging conditions. One-way traveltime (excitation time) is calculated by ray-tracing from source to subsurface grid points, followed by extraction of receiver wavefields where the excitation time is satisfied. Loewenthal and Hu (1991) used a finite-difference extrapolation method to replace this ray-tracing. The excitation time imaging condition is equivalent to a zero-lag cross-correlation between the receiver wavefields and a constant amplitude spike wavefront trajectory source wavefield for all time steps (Chattopadhay and McMechan, 2008). For this reason, it will provide RTM images with incorrect amplitude and migration artifacts. The RTM images from both cross-correlation and excitation time imaging conditions have low resolution.

Nguyen and McMechan (2013) proposed an excitation amplitude imaging condition, which is a stable upgoing-over-downgoing wavefield ratio imaging condition. The receiver wavefield is divided by the maximum source wavefield amplitude only at the locations which satisfy the excitation time. The excitation amplitude imaging condition also sidesteps the storage problem of RTM. There are fewer migration artifacts and higher resolution images compared with cross-correlation and excitation time imaging conditions.

In our study, we propose a high-resolution RTM method using a squared excitation amplitude imaging condition. It inherits the benefits of excitation amplitude imaging condition, but further provides RTM images with fewer migration artifacts and higher resolution.

METHOD

There are three main steps in conventional cross-correlation RTM: forward-time extrapolation of source wavefields and storage, reverse-time extrapolation of receiver wavefields, and application of zero-lag cross-correlation imaging condition.

Our proposed high-resolution RTM method is implemented using a different workflow with the above one. We use a synthetic model with three horizontal reflectors to illustrate the benefits of the proposed method.

First, we extrapolate the source wavefields in the forward-time direction, as one does with the conventional cross-correlation RTM. The excitation time for each subsurface grid point is defined as its maximum amplitude arrival time (Chang and McMechan, 1986). This amplitude is known as the excitation amplitude (Nguyen and McMechan, 2013). We only need to save the excitation time and the excitation amplitude field for each subsurface image point,

$$p_{s\_\max}\left(t_e,\mathbf{x}\right)=max\left\{p_s\left(t_i\Big|_{t_i=0}^{T},\mathbf{x}\right)\right\} \qquad (1)$$

where t_e denotes the excitation time and $p_{s\_\max}$ denotes the excitation amplitude. The function max indicates that we extract the maximum amplitude from all extrapolated source wavefields p_s at each time step t_i for every location $\mathbf{x}$. With a smoothed interval velocity model, the excitation time and the excitation amplitude are calculated and saved.

Second, we extrapolate the receiver wavefields in the reverse-time direction. Then we calculate a direction-preserved zero-lag autocorrelation $\mathrm{I}_r\left(t_i,\mathbf{x}\right)$ on these receiver wavefields p_r at each time step,

$$\mathrm{I}_r\left(t_i,\mathbf{x}\right)=\begin{cases} p_r\left(t_i,\mathbf{x}\right)p_r\left(t_i,\mathbf{x}\right), & if \quad p_r\left(t_i,\mathbf{x}\right)\geq 0 \\ -p_r\left(t_i,\mathbf{x}\right)p_r\left(t_i,\mathbf{x}\right), & if \quad p_r\left(t_i,\mathbf{x}\right)<0 \end{cases} \qquad (2)$$

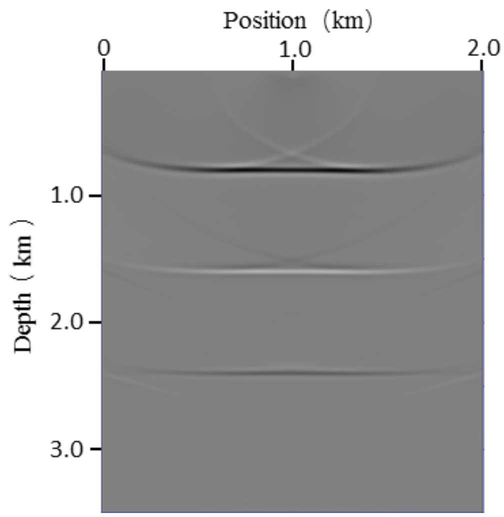
where the zero-lag autocorrelation is performed on the extrapolated receiver wavefields, but the direction is preserved. Direction-preserved zero-lag autocorrelation provides results with higher resolution and fewer migration artifacts, compared with pure receiver wavefields.

Finally, a squared excitation amplitude imaging condition is applied at each time step to provide RTM image,

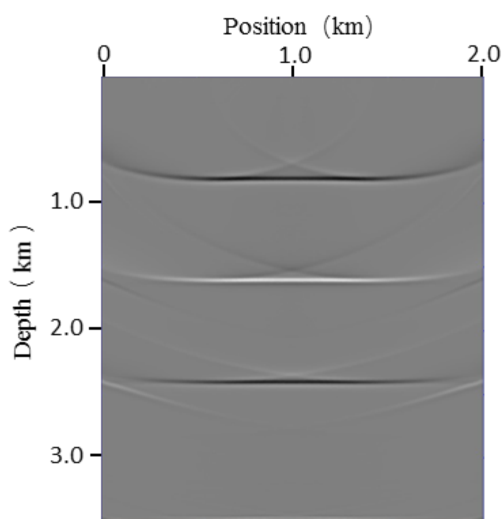
$$\mathrm{I}\left(t_i,\mathbf{x}\right)=\frac{\mathrm{I}_r\left(t_e,\mathbf{x}\right)}{p_{s\_\max}\left(t_e,\mathbf{x}\right)p_{s\_\max}\left(t_e,\mathbf{x}\right)} \qquad (3)$$

The squared excitation amplitude imaging condition is only implemented at the subsurface grid points which satisfy the excitation time t_e. Only the most energetic part is imaged while other events are effectively filtered, which assures stability and minimize migration artifacts. Since the source is a spike, the resolution is higher. The squared excitation amplitude imaging condition is a variation of the upgoing-over-downgoing wavefield ratio method (Claerbout, 1971), providing properly scaled amplitude. Summation over all times and all sources provides the final stacked RTM images.

We compare the single source RTM images of the synthetic model with three horizontal reflectors by using the cross-correlation method (Figure 1a), excitation amplitude method (Figure 1b), and our proposed method (Figure 1c). The cross-correlation result has lowest resolution and most migration artifacts. The excitation amplitude method improves the resolution and reduces artifacts. Our proposed method provides RTM image with least migration artifacts and highest resolution among these three results.



(a) Cross-correlation



(b) Excitation amplitude

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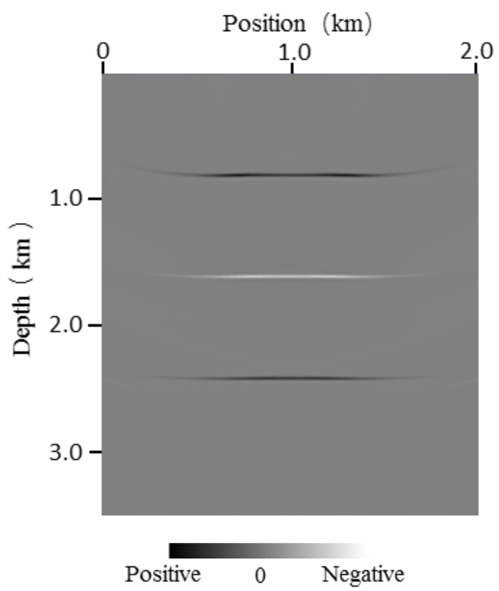


(c) Proposed method

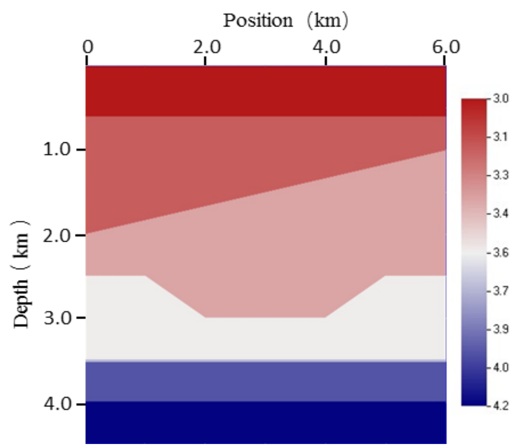
Figure 1: Single source RTM images of synthetic model with three horizontal reflectors using (a) zero-lag cross-correlation imaging condition, (b) excitation amplitude imaging condition, and (c) our proposed method.

EXAMPLES

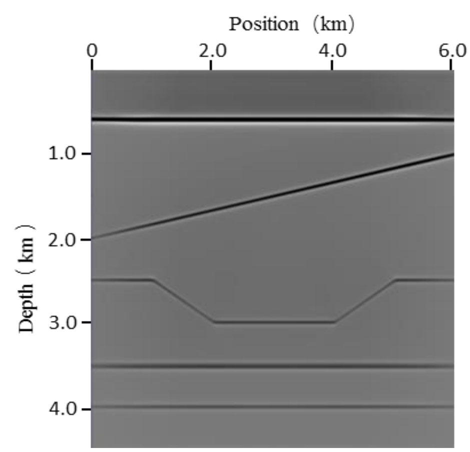
We perform numerical tests with the proposed method on two synthetic model data, including a thin layer model and the Marmousi2 model.

Thin layer model

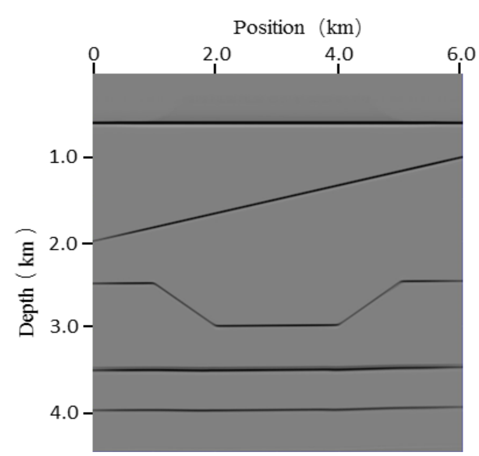
We design a thin layer model (Figure 2a) with a shallow horizontal reflector, a dipping reflector, a sag structure, and especially a thin 10 m low velocity layer at depth 3.52 km. With a smoothed velocity model, pre-stack multi-source stacked RTM images are produced with conventional cross-correlation method (Figure 2b) and our proposed method (Figure 2c). Note the fewer migration artifacts in the shallow part of our result. We enlarge the thin layer part of the velocity (Figure 2d) and the two RTM images (Figure 2e, 2f) around the lateral position 3.0 km. The proposed method provides a RTM image (Figure 2f) with much higher resolution compared with the conventional result (Figure 2e), which makes it easier for us to identify the thin layer. The comparison of the single vertical traces (Figure 2g, 2h) at the lateral location 3.0 km around the thin layer also indicates the improvement of resolution using the proposed method.



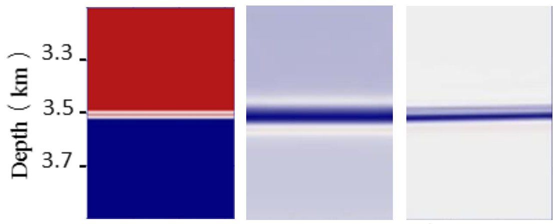
(a) Thin layer model



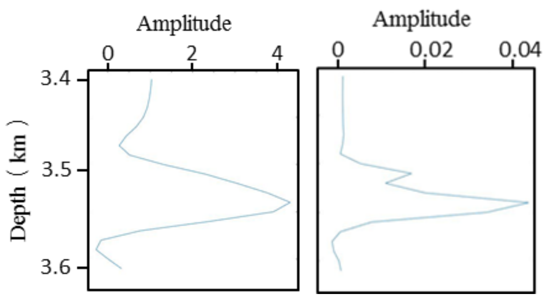
(b) RTM by cross-correlation



(c) RTM by the proposed method



(d) enlarge (a) (e) enlarged (b) (f) enlarged (c)



(g) Cross-correlation (h) Proposed method

Figure 2: Multi-source RTM images of thin layer model by different methods. The proposed RTM method provides images (c, f, h) with higher resolution, which helps identify the thin layer.

Marmousi2 model

We also implement numerical test on a part of the Marmousi2 model including a suite of thin layers. The RTM images by using the conventional cross-correlation imaging condition and the proposed method are shown in Figure 3a and 3b. Our proposed RTM method provides image with more focused energy and fewer migration artifacts. The thin layers are also better resolved due to the higher resolution of the proposed RTM method.

CONCLUSIONS

We have implemented a high-resolution RTM method using a squared excitation amplitude imaging condition. It inherits the benefits of the excitation amplitude imaging condition, sidestepping storage problem and providing stable results. The proposed method further provides RTM images with fewer migration artifacts and higher resolution, which are indicated by the numerical tests on a synthetic thin layer model and the Marmousi2 model. The primary limitation of the proposed method is in dealing with multipathing of the source wavefields. We need to store more arrivals when multipathing is prevalent. The proposed method could play a positive role for thin layer exploration and is naturally extended to 3D case.

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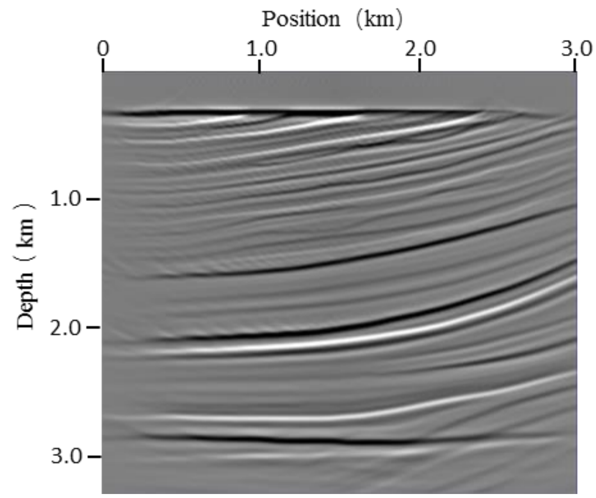
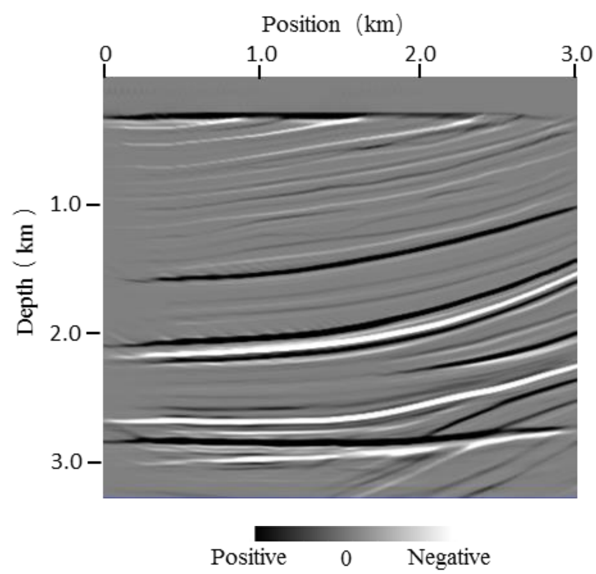


(a) RTM by cross-correlation



(b) RTM by the proposed method

Figure 3: RTM images of part of the Marmousi2 model using (a) conventional cross-correlation imaging condition, and (b) our proposed method.