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Least-squares reverse-time migration with cost-effective computation and memory storage

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ABSTRACT

Least-squares reverse-time migration (LSRTM), which involves several iterations of reverse-time migration (RTM) and Born modeling procedures, can provide subsurface images with better balanced amplitudes, higher resolution and fewer artifacts than standard migration. However, the same source wavefield is repetitively computed during the Born modeling and RTM procedures of different iterations. We developed a new LSRTM method with modified excitation-amplitude imaging conditions, where the source wavefield for RTM is forward propagated only once while the maximum amplitude and its excitation-time at each grid are stored. Then, the RTM procedure of different iterations only involves: (1) backward propagation of the residual between Born modeled and acquired data, and (2) implementation of the modified excitation-amplitude imaging condition by multiplying the maximum amplitude by the back propagated data residuals only at the grids that satisfy the imaging time at each time-step. For a complex model, 2 or 3 local peak-amplitudes and corresponding traveltimes should be confirmed and stored for all the grids so that multiarrival information of the source wavefield can be utilized for imaging. Numerical experiments on a three-layer and the Marmousi2 model demonstrate that the proposed LSRTM method saves huge computation and memory cost.

1. Introduction

Field data usually suffer from limited recording aperture, coarse sampling, and acquisition gaps; thus, the images produced by conventional migration methods are contaminated by acquisition footprints. Least-squares migration (LSM) is a linear inversion method for seeking the subsurface reflectivity model, which can mitigate footprints (Nemeth et al., 1999) and provide images with higher resolution and more balanced amplitudes (Huang et al., 2014) than standard migration. LSM has been applied to Kirchhoff migration (Nemeth et al., 1999; Duquet et al., 2000; Liu et al., 2005) and the one-way wave equation (Kühl and Sacchi, 2003; Kaplan et al., 2010; Ren et al., 2011; Wang et al., 2013), whereas LSM was recently been combined with RTM to form LSRTM (Plessix and Mulder, 2004; Dai et al., 2010; Dong et al., 2012; Dai et al., 2012; Dai and Schuster, 2013; Dutta and Schuster, 2014; Zhang and Schuster, 2014; Tan and Huang, 2014a; Zhang et al., 2015).

However, the high computational cost of LSRTM is a great challenge. A multisource approach with random- or linear-phase encoding has been used to improve the efficiency of wave equation migration (Zhang et al., 2005, 2007; Liu et al., 2006; Tang et al., 2013; Dai and Schuster, 2013) and LSRTM (Dai et al., 2012; Dai and Schuster, 2013). The main limitation of random-phase encoding is that fixed source-receiver geometry is required (Dai et al., 2012), whereas the plane-wave encoding scheme (Zhang et al., 2005, 2007) is more practice for the moving source-receiver geometry.

To improve the efficiency of LSRTM, we review the RTM implementation strategies, which mainly involve four steps: the forward propagation of a source wavefield, reconstruction of a source wavefield in backward-time, backward propagation of acquired data, and the zero-lag crosscorrelation imaging condition. A source wavefield is usually reconstructed in backward time by two categories of methods, (1) optimal checkpoint methods (Symes, 2007) and (2) boundary wavefield propagation methods (Tan and Huang, 2014b). The second category of methods is usually much more efficient but requires more memory and has the same computation cost as the forward propagation of a source wavefield. For conventional LSRTM, if an acoustic wave equation is solved by using a regular finite-difference scheme and a source wavefield is reconstructed by using boundary wavefield propagation methods, multiple-layer boundary wavefields of all time-steps and snapshots of the last two time-steps should be stored in memory. The source wavefield for the RTM procedure is forward propagated once and must be reconstructed repetitively in backward-time during all

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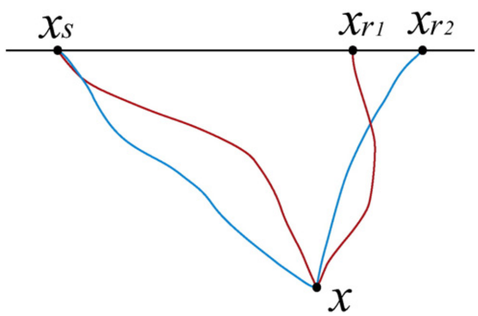

Fig. 1. Multiarrivals at a single subsurface point: The source wavefield forward propagates along different wavepaths and arrives at a subsurface point, x, with different incident angles.

iterations. The same source wavefield for the RTM of different iterations requires huge computation time and large memory.

We developed a new LSRTM method based on the modified excitation-amplitude imaging condition. Chang and McMechan (1986) developed RTM with the excitation-time imaging condition, where the excitation-time (i.e., the imaging time) is the first-arrival time computed by ray-tracing. A subsurface image was produced by putting backward propagated receiver wavefield values into discrete image points where the imaging times are satisfied at each time-step. With the excitation-time at a grid point defined as the arrival time of the maximum source-wavefield amplitude (i.e., the excitation-amplitude), Nguyen and McMechan (2013) proposed the excitation-amplitude imaging condition by dividing the backward propagated receiver wavefield by the precomputed excitation-amplitude only at the grid points that satisfy the imaging time, which can be conveniently generalized to elastic RTM (Chen and Huang, 2014; Nguyen and McMechan, 2015). Standard LSRTM computes the gradient of the misfit function using the crosscorrelation imaging condition. We developed a modified excitation-amplitude imaging condition by multiplying the maximum source wavefield amplitude with the corresponding receiver wavefield, which accounts for the strongest energy of the crosscorrelation imaging condition (Nguyen and McMechan, 2013). Moreover, when geology is extremely complex and multiarrivals with different incident angles occur (Gray et al., 2002), 2 or 3 local peak-amplitudes and their traveltimes for all the grid points can be stored in memory and used for migration during all iterations. Our method avoids the repetitive reconstructions of source wavefields for RTM while saving large amounts of memory by only storing 2 or 3 local peak-amplitudes and their traveltimes.

Our method retains the same Born modeling procedure as the standard LSRTM. Born modeling requires the full waveform of the source

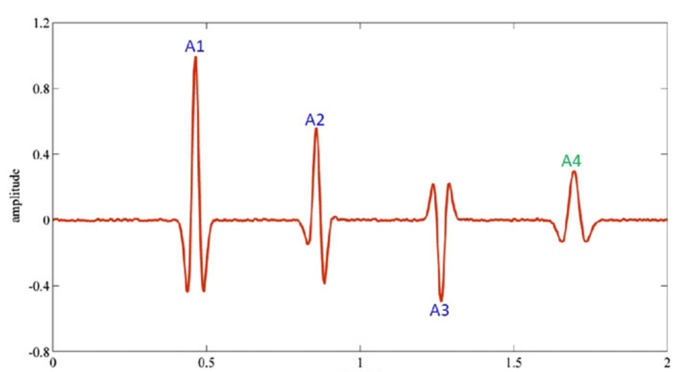

Fig. 2. All of the multiarrivals with different phases are observed at a grid point. Several peak-amplitudes with larger energy can be chosen, e.g., peak-amplitudes A1-A3 and their traveltimes are chosen, and peak-amplitude A4 is neglected. The strongest peak-amplitude A1 is the so-called excitation-amplitude. Instead of the whole waveform, only several stored peak-amplitudes are used for imaging.

wavefield, which varies with different subsurface points, to form the source term of the scattered wavefield. For the accuracy of the waveform of the modeled data, the repetitive forward propagations of the source wavefield for Born modeling of different iterations are difficult to avoid. We have tested our method and conventional LSRTM on two numerical data sets, and our new method relative to the standard LSRTM method saves approximately 25% of the computation cost and most of the memory storage for source wavefield.

2. Conventional least-squares reverse-time migration

For a 2D model, the scattered data $d(\boldsymbol{x_r},\boldsymbol{x_s},\omega)$ recorded at the receiver$\boldsymbol{x}_r=(x_r,z_r)$ from the source $\boldsymbol{x_s}=(x_s,z_s)$ can be represented under the Born approximation as follows:

$$d(\boldsymbol{x_r},\boldsymbol{x_s},\omega)=\omega^2\int G_0(\boldsymbol{x_r},\boldsymbol{x},\omega)m(\boldsymbol{x})G_0(\boldsymbol{x},\boldsymbol{x_s},\omega)f_s(\omega)\ d\boldsymbol{x}, \tag{1}$$

where ω is the angular frequency, $f_s(\omega)$ is the source signature, $m(\boldsymbol{x})$ represents the reflectivity (a perturbed quantity from the background velocity) at the subsurface point $\boldsymbol{x}=(x,z)$, and $G_0(\boldsymbol{x},\boldsymbol{x_s},\omega)$ and $G_0(\boldsymbol{x_r},\boldsymbol{x},\omega)$ are the Green's functions connecting the source and receiver to the subsurface point, respectively. Because $d(\boldsymbol{x_r},\boldsymbol{x_s},\omega)$ is one element of the vector $\boldsymbol{d}$, Eq. (1) can be compactly represented with vectors as follows:

$$\boldsymbol{d}=\boldsymbol{Lm}, \tag{2}$$

where $\boldsymbol{L}$ is a linear forward modeling operator and $\boldsymbol{m}$ is the reflectivity model vector.

The RTM operator can be regarded as the adjoint of the forward Born modeling and can be represented as (Claerbout, 1992):

$$\boldsymbol{m}_{mig}=\boldsymbol{L}^T\boldsymbol{d}_{obs}, \tag{3}$$

where the superscript T represents the conjugate transpose of the matrices, $\boldsymbol{L}^T$ compactly represents the migration operator, $\boldsymbol{d}_{obs}$ represents the observed data, and $\boldsymbol{m}_{mig}$ represents the migration result. The migration image of one subsurface point, $\boldsymbol{x}$, can be expressed as follows:

$$m_{mig}(\boldsymbol{x})=\iiint\omega^2[G_0(\boldsymbol{x},\boldsymbol{x_s},\omega)f_s(\omega)]^*\ G_0{}^*(\boldsymbol{x_r},\boldsymbol{x},\omega)d_{obs}(\boldsymbol{x_r},\boldsymbol{x_s},\omega)d\omega d\boldsymbol{x_r}d\boldsymbol{x_s}, \tag{4}$$

where the superscript * represents the complex conjugate. Eq. (4) indicates that the crosscorrelation imaging condition is utilized for RTM.

The migrated image is only a good approximation of the subsurface reflectivity if the observed data have infinite aperture and dense sampling. To invert the true reflectivity model, the misfit function

$$f(\boldsymbol{m})=\frac{1}{2}\|\boldsymbol{Lm}-\boldsymbol{d}_{obs}\|^2+\frac{\varepsilon}{2}\|\boldsymbol{m}\|^2, \tag{5}$$

must be minimized (Nemeth et al., 1999), where ε is the damping parameter. The regularization term avoids the generation of large abnormal values in the inverted image.

The gradient descent algorithm

$$\begin{aligned}\boldsymbol{g}^{(k)}&=\nabla f(\boldsymbol{m})=\boldsymbol{L}^T\left(\boldsymbol{Lm}^{(k)}-\boldsymbol{d}_{\text{obs}}\right)+\varepsilon^{(k)}\boldsymbol{m}^{(k)},\\ \delta\boldsymbol{m}^{(k)}&=P\boldsymbol{g}^{(k)},\end{aligned} \tag{6}$$

$$\boldsymbol{m}^{(k+1)}=\boldsymbol{m}^{(k)}-\lambda^{(k)}\delta\boldsymbol{m}^{(k)}, \tag{7}$$