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Research paper

Eliminating the redundant source effects from the cross-correlation reverse-time migration using a modified stabilized division

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ABSTRACT

Cross-correlation reverse-time migration is the kernel of two-way wave-equation migration and inversion. However, it more or less tapers the spectrum of receiver data due to a redundant overlay of the source wavelet, whose amplitude spectrum is usually bandlimited and non-flat. To circumvent this issue, there are two optional strategies: whitening the source directly, or preconditioning the seismic traces by division with the amplitude spectrum of the source in the frequency domain. In this paper, we choose the latter one because the source signature is crucial to illumination compensation and seismic inversion. To avoid division by zero, a modified stabilized division algorithm based on the Taylor-expansion is developed. The modified division is easy to complete with computers and can be extend to any order. Moreover, when simulating 2-D source wavefield, the half-integral effect is also considered. We will demonstrate our proposed scheme using the Sigsbee2b synthetic data and a real field data.

1. Introduction

Cross-correlation reverse-time migration (RTM) is widely used in seismic migration and inversion to map seismic traces from data domain to image domain. Two-way wave equation is deployed to accurately describe wavefield propagation even in complex media. RTM (Whitmore, 1983) promises better imaging of steep dips compared to ray-tracing and one-way migration. Also, cross-correlation RTM is closely related to wave-equation velocity and reflectivity inversion, such as full-waveform inversion (FWI) (Laily, 1983; Tarantola, 1984) and least-squares reverse-time migration (LSRTM) (Nemeth et al., 1999; Dai and Schuster, 2013). If all wave-spreading losses are taken in consideration, RTM can be utilized to develop true-amplitude depth migration (Deng and McMechan, 2007).

Several alternative imaging conditions have been proposed for RTM to improve the image to approach the accurate reflection coefficient, though numerically and dimensionless. The ratio of upgoing and downgoing wavefields at temporal and spatial coincidence (Claerbout, 1971), is the original form of physically definition of reflection coefficient (Lumley, 1989). A hybrid method of ray-tracing for the source extrapolation and finite-difference receiver wavefield exploration (Chang and McMechan, 1986), is utilized as the excitation-time imaging condition in prestack RTM. Loewenthal and Hu (1991) use a finite-difference source extrapolation to calculate the excitation-imaging condition according to the arrival time of the maximum-amplitude primary-wave energy. Normalization of the cross-correlated image by source illumination further improves the physical accuracy of the reflectivity information towards true amplitude (Kaelin and Guitton, 2006). The excitation-amplitude imaging condition (Nguyen and McMechan, 2013) divides the propagating receiver wavefield at the imaging time by the maximum source amplitude at each imaging point.

Although the excitation-time (Loewenthal and Hu, 1991) and excitation-amplitude (Nguyen and McMechan, 2013) imaging conditions are cost-effective and partly free of low-wavenumber artifacts, they cannot handle multi-pathing problem well using a single-valued traveltime. Multi-pathing is usually associated with strong lateral velocity variations, which makes more sense for characterizing the reservoir under complicated structures. Cross-correlation imaging condition implicitly includes multi-pathing because all of the propagating energy is preserved through the accumulation process. Source estimation is an important issue in wave-equation migration and inversion (Pratt, 1999; Shin et al., 2007). However, because the amplitude spectrum of the estimated source is usually bandlimited and non-flat, the imaging resolution of RTM will be inherently degraded. Moreover, in wave-equation inversion, the adjoint method (Plessix and Mulder, 2004) indicates that the gradient can be obtained with the cross-correlation between the incident and residual wavefields. The cross-correlation gradients also suffer from this source effect above.

We attempt to design a source-eliminating scheme so that the

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cross-correlation imaging condition becomes independent of the shape of the source amplitude spectrum. Two strategies are provided: whitening the source directly or preconditioning the receiver traces by division with the source amplitude. We eventually choose the latter one because the first strategy results in an artificial source signature. The estimated source plays important roles in illumination compensation and wave-equation inversion. The source illumination approximates the diagonal of the Hessian (Plessix and Mulder, 2004). In wave-equation inversion, the source wavefield propagating in the forward operator can be used directly to reconstruct the source wavefield in the adjoint operator (Virieux and Operto, 2009). Besides, when propagating source wavefield in 2-D case, it is important to take the half-integral effect into account, because this effect can distort the final imaging waveform.

In the preconditioning step, a division in the frequency domain is performed. To alleviate the introduction of the error caused by a stability factor or the loss of frequency components by the low-cut form (Guitton et al., 2007; Schleicher et al., 2008), we develop a modified stabilized division based on the Taylor-expansion to handle the division-by-zero issue. Specially, our algorithm turns the division issue into a geometrical series which can be easily performed with computers. The order of our Taylor series is flexible, depending on the signal to noise ratio (SNR) of the seismic data. A higher order corresponds to a higher SNR, and vice versa.

The paper is arranged as following: Firstly, we briefly review the conventional cross-correlation imaging condition. Then, we introduce our preconditioner to eliminate the redundant source effects, alternatively, including the half-integral effect in the 2-D source wavefield. Afterward, a modified division algorithm is discussed. Finally, we demonstrate our scheme using the 2D Sigsbee2b synthetic dataset and a real field data.

2. Methods

In this section, we first briefly review the conventional zero-lag cross-correlation imaging condition of RTM; and then propose a preconditioner to enable the imaging condition being independent of the shape of the source amplitude spectrum; alternatively, the half-integral effect implicitly contained in the 2-D wave-equation is discussed. Finally, a modified stabilized division algorithm based on the Taylor-expansion algorithm is used in our preconditioner.

2.1. Conventional cross-correlated RTM imaging condition

The conventional zero-lag cross-correlation RTM imaging condition reads

$$I(\mathbf{x}) = \iint p_S(\mathbf{x}, t; \mathbf{x}_s) p_R(\mathbf{x}, t; \mathbf{x}_s) dt d\mathbf{x}_S, \tag{1}$$

where $p_S(\mathbf{x}, t; \mathbf{x}_s)$ denotes the forward propagation of source wavefield, and $p_R(\mathbf{x}, t; \mathbf{x}_s)$ denotes the backward propagation of receiver wavefield, with the shot at $\mathbf{x}_s$. Eq. (1) is governed by the following system:

$$\begin{cases} \left(\dfrac{1}{v(\mathbf{x})^2}\dfrac{\partial^2}{\partial t^2} - \nabla^2\right) p_R(\mathbf{x}, t; \mathbf{x}_S) = 0, \\ p_R(\mathbf{x}_R, t; \mathbf{x}_S) = D_R(\mathbf{x}_R, t; \mathbf{x}_S), \\ \left(\dfrac{1}{v(\mathbf{x})^2}\dfrac{\partial^2}{\partial t^2} - \nabla^2\right) p_S(\mathbf{x}, t; \mathbf{x}_S) = s(t; \mathbf{x}_S), \end{cases} \tag{2}$$

with $v(\mathbf{x})$ the migration velocity, $s(t; \mathbf{x}_S)$ the source signature at $\mathbf{x}_S$, $D_R(\mathbf{x}_R, t; \mathbf{x}_S)$ the observed receiver data at $\mathbf{x}_R$, and ∇^2 the Laplacian operator. Note that $D_R(\mathbf{x}_R, t; \mathbf{x}_S)$ are imposed as boundary conditions. In our scheme, we assume the knowledge of the source signature.

If the Green's function is defined as

$$\left(\frac{1}{v(\mathbf{x})^2}\frac{\partial^2}{\partial t^2} - \nabla^2\right) G(\mathbf{x}, t - t'; \mathbf{x}_S) = \delta(\mathbf{x} - \mathbf{x}_S)\delta(t - t'). \tag{3}$$

The imaging condition in Eq. (1) can be rewritten as

$$I(\mathbf{x}) = \iiint G_S(\mathbf{x}, \omega; \mathbf{x}_S) W_S(\omega) \left[G_R(\mathbf{x}, \omega; \mathbf{x}_R) D_R(\mathbf{x}_R, \omega; \mathbf{x}_S) \right]^* d\omega d\mathbf{x}_R d\mathbf{x}_S, \tag{4}$$

where the superscript * denotes the conjugate transpose, ω is the angular frequency, $W_S(\omega)$ denotes the spectrum of the source, $D_R(\mathbf{x}_R, \omega; \mathbf{x}_S)$ denote the spectra of the receiver data, $G_S(\mathbf{x}, \omega; \mathbf{x}_S)$ and $G_R(\mathbf{x}, \omega; \mathbf{x}_R)$ denote the Green's functions of the source and receiver wavefields, respectively. The backward propagation in the time domain is indicated by the conjugate operator in the frequency domain. The phase of $W_S(\omega)$ can be assumed to be either zero phase or minimum phase, or even mixed phase, depending on the wavelet embedded in the receiver data $D_R(\mathbf{x}_R, \omega; \mathbf{x}_S)$. Because of the conjugate operator *, the cross-correlation imaging condition will produce an image where each reflector is represented as zero-phase bandlimited singular functions with the peak positioned at the reflector. For simplicity, we assume that both the source wavelet and the wavelet embedded in seismic data are rotated to zero-phase.

The estimated source wavelet may behave better than an arbitrary artificial source in RTM and seismic waveform inversion (Pratt, 1999; Shin et al., 2007). In practice, even after being processed carefully, the seismic traces are still slightly mixed-phase. The amplitude spectrum of the estimated source $|W_S(\omega)|$ is usually non-flat and band-limited. In this case, $|W_S(\omega)|$ may act as a filter, tapering the spectra of $D_R(\mathbf{x}_R, \omega; \mathbf{x}_S)$. A deal of valid frequency information is suppressed. The level of suppression depends on the shape of the source amplitude spectrum. Assuming the same signature of the source and receiver wavelets, for example, a Ricker wavelet, the cross correlation of source and receiver wavefields has a cross-reflector width of approximately double the wavelength of each, as shown in Fig. 2c and d, and is a function of incident angle (Tygel et al., 1994). The simplified versions of RTM, such as the excitation-time imaging condition assuming a spike source wavelet (Chang and McMechan, 1986) and excitation-amplitude imaging condition assuming a deconvolution condition (Nguyen and McMechan, 2013), cannot handle the multi-pathing problem well. Even the source-normalized imaging condition (Kaelin and Guitton, 2006), which just corrects for the amplitude scale, has the same resolution as that of the cross-correlated image.

2.2. A preconditioner for source elimination

Now we attempt to eliminate the tapering effect of the bandlimited source from the cross-correlated RTM. There are two options: whitening the source directly or preconditioning the seismic traces by division with the source amplitude spectrum. If we chose the first strategy, regardless of the phase spectrum, the processed source signature approaches some specified wavelets, such as the Ormsby or Klauder wavelet. As a result, the source illumination (Kaelin and Guitton, 2006), which approximates the diagonal of the Hessian (Plessix and Mulder, 2004) to compensate for the wave-spreading loss, is produced by an artificial source. Moreover, because the cross-correlation RTM can be considered as the adjoint operator in wave-equation inversion (Virieux and Operto, 2009), the source wavefield propagated in the Born operator can be directly used to crosscorrelate with the receiver wavefield to produce a gradient. Finally, we choose the second strategy. In this way, the cross-correlation imaging condition can