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Static corrections in mountainous areas using Fresnel-wavepath tomography

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ABSTRACT

We propose a 3-D Fresnel-wavepath tomography based on simultaneous iterative reconstruction technique (SIRT) with adaptive relaxation factors, in order to obtain effective near-surface velocity models for static corrections. We derived a formula to calculate the optimal relaxation factor for tomographic inversion to increase the convergence rate and thus the efficiency of the Fresnel-wavepath tomography. A forward method based on bilinear traveltime interpolation and the wavefront group marching is applied to achieve fast and accurate computation of the wavefront traveltimes in 3-D heterogeneous models. The new method is able to achieve near-surface velocity models effective in estimating long-period static corrections, and the remaining traveltime residuals after the tomographic inversion are used to estimate the short-period static corrections via a surface-consistent decomposition. The new method is tested using 3-D synthetic data and 3-D field dataset acquired in a complex mountainous area in southwestern China.

1. Introduction

Statics of seismic data refer to distortions in the arrival time of recorded seismic waves due to near-surface complexities such as variations in elevation and the thickness of the low-velocity weathering layers. Statics have been recognized as a major source of risk for land seismic exploration (e.g., Cox, 1999), particular in desert and mountainous areas. The long-wavelength variations of statics distort the structural timing of reflection events in seismic imageries, while the short-period variations in statics degrade the continuity of stacked events. In traditional seismic data processing, the long-period static corrections are estimated using near surface velocity models based on first arrivals. After correcting the long-period statics, the short-period (residual) statics are estimated by cross-correlating the neighboring traces on CMP gathers and stack sections.

Since 1990s first-arrival traveltime tomography has been recognized as an effective way to estimate near-surface velocity models and associated static corrections, though it has to deal with many challenges especially since seismic inversion is intrinsically an ill-posed problem (e.g., Chang et al., 2002; Stefani, 1995; Zhou and Li, 2012; Zhu et al., 1992). One limitation of the first-arrival traveltime inversion is the high-frequency ray theory assumption that the traveltime of first arrival is a line integral of the slowness along the raypath between the source and receiver. However, rays are deflected around low velocity anomalies, resulting in a biased sampling of high velocity regions. To reduce this bias, we may use the Fresnel volume to represent the path of a seismic wave at a specific frequency, equivalent of the first Fresnel zone in which constructive interference of seismic energy takes place (Cerveny and Soares, 1992; Husen and Kissling, 2001). A traveltime observed at a receiver contains the propagation information of seismic wave in the Fresnel volume. A wave of seismic bandwidth can be more realistically represented by a Fresnel volume than a ray of zero volume.

Several geophysicists used Fresnel volume rays or fat rays in the seismic traveltime tomography. Zhou (1994) and Vasco et al. (1995) proposed Fresnel volume tomography, assuming that traveltime is a weighted volume integral over the earth's velocity field. They calculated the Fresnel volume based on paraxial ray approximation. Wang and Zhou (1997) compared Fresnel volume tomography with conventional ray tomography using 2-D synthetic traveltimes. Watanabe et al. (1999) applied the Fresnel volume to represent wave propagation in an experiment of 3-D synthetic traveltime tomography. They proposed a numerical definition of Fresnel volumes, characterized by a weighting function in terms of the definition of the first Fresnel zone. Husen and Kissling (2001) presented a local earthquake tomography using fat ray. Their synthetic tests showed that fat ray tomography yields significantly better inversion results than conventional ray tomography. Grandjean and Sage (2004) presented 2-D seismic tomography software based on Fresnel wavepaths and a probabilistic reconstruction. The software yielded a higher resolution velocity model from 2-D synthetic borehole traveltime data. Xu et al. (2006) used reflection fat rays to enhance the resolution of 3-D velocity model for migration imaging. Liu et al. (2009)

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proposed the sensitivity kernels for Fresnel volume tomography and concluded that it is practical to replace the band-limited sensitivity kernel with a few selected frequencies or even the single dominant frequency for Fresnel volume tomography. Mendes (2009) combined Monte-Carlo optimization with simultaneous iterative reconstruction technique (SIRT) for Fresnel volume tomographic inversion. Gance et al. (2012) applied a high-resolution tomography of first-arrival traveltimes using Fresnel wavepaths to characterize subsurface of landslides. We also introduced Fresnel volume ray into the first-arrival tomography for building near-surface velocity models (Ke et al., 2007; Zhang, 2009).

We propose a SIRT-based, modified Fresnel-wavepath tomographic method. Several published Fresnel-wavepath tomographic studies are based on SIRT inversion (e.g. Grandjean and Sage, 2004; Mendes, 2009; Watanabe et al., 1999; Zhang, 2009). SIRT is a very suitable technique for inverting large sparse linear systems. It treats one equation at a time, hence avoids the storage of the entire inversion kernel matrix in RAM memory. A parallel algorithm of seismic tomography can be easily implemented based on SIRT. However, SIRT-type algorithms always have a slow convergence. Sometimes a relaxation factor is necessary to speed up the convergence, though it is often given empirically.

In this paper, an optimal relaxation factor is estimated automatically at each iteration step to speed up the convergence of the inversion. Based on bilinear traveltime interpolation and wavefront group marching, our fast and accurate 3-D traveltime computation method (Zhang et al., 2011) is adopted into the Fresnel-wavepath tomography. We applied the Fresnel-wavepath tomography to build the near-surface velocity model using first-arrival traveltimes in a mountainous area in southwestern China. The velocity model was used to estimate the long-period static corrections, and the traveltime residuals of the final tomographic velocity model were used to estimate the short-period static corrections. The stacked section after the long- and short-period static corrections shows a significant increase in the continuity of the reflectors, indicating an increase in the reliability of the seismic profile for interpretation.

2. Fresnel-wavepath representation

According to Cerveny and Soares (1992), the Fresnel volume for a pair of source s and receiver r is the region defined by

$$\Delta t_p = t_{sp} + t_{rp} - t_{sr} \le T/2, \tag{1}$$

where t_{sp} denotes the traveltime from s to a variable scattering point p in space, t_{rp} denotes the traveltime from p to r, t_{sr} is the minimum traveltime from s to r, and T is the dominant period of the seismic wave. The dominant frequency will be used for band-limited data. The Fresnel volume becomes wider for lower frequencies and narrower for higher frequencies.

To implement the traveltime computation and tomography, a velocity model is divided into cells defined by a rectangular grid mesh. Using the approach of Watanabe et al. (1999), a numerical Fresnel volume in the discretized model can be represented by weight ω_p at each grid node p,

$$\omega_P = \begin{cases} 1-2\Delta t_P/T, & 0 \le \Delta t_P < T/2 \\ 0, & T/2 \le \Delta t_P, \end{cases} \tag{2}$$

which varies linearly with respect to Δt_p. The weight represents the probability that a model perturbation delays the seismic wave propagation from a source to a receiver by Δt_p. The value of the weight is 1 along the central axis of a Fresnel volume (i.e. the high-frequency ray) and 0 on and beyond its boundary. For each source–receiver pair, the portion of the model space containing all nodes with nonzero weights forms the Fresnel wavepath. The main computation for determining a numerical Fresnel-wavepath is to compute the traveltimes from source s to receiver r and each grid node p, and that from receiver r to each grid node p.

3. Traveltime computation

In computing the Fresnel-wavepaths, we need to find the wavefront traveltimes from every source and receiver to all grid nodes. One of the most popular methods used to compute advancing wavefronts is the fast marching method (FMM) (Sethian, 2001). It uses a narrow band technique and expands the band by selecting only one node with a minimum traveltime in the narrow band as a new source and readjusting outward neighbors. Its computational cost is O (Nlog$N$), where N is the total number of grid nodes in the computational domain. Kim (2002) introduced an optimal variant of FMM called the group marching method (GMM). The GMM expands its narrow band by locating a group of nodes with the traveltimes satisfying certain conditions (Kim, 2002), while maintaining causality and re-computing the traveltimes around their neighbors at one time, and thus costs only O (N).

The traveltime in the FMM and GMM is solved using the finite difference of eikonal equation (Kim, 2002; Sethian, 2001), though the accuracy of this solution decreases with increasing cell size. To improve the accuracy of traveltime computation we derived a closed-form expression to calculate traveltime at an arbitrary point in a hexahedral cell based on a bilinear interpolation of the known traveltimes over the grid nodes in the cell (Zhang et al., 2011). This analytical traveltime solver has a higher accuracy than the finite difference solution of eikonal equation. The combination of the GMM and our 3-D analytical traveltime solver renders a fast and accurate method for traveltime computation in 3-D complex media. We also extended the method for models with irregular cell discretization (Huang et al., 2011).

4. Tomographic algorithm

For large-scale 3-D seismic exploration studies, tomographic inversion always solves a large system of linear equations. In order to avoid the RAM storage of large matrices and to implement a parallel algorithm of the tomographic inversion, we propose a SIRT-based algorithm for Fresnel-wavepath tomography. Following the SIRT algorithm revised by Grandjean and Sage (2004), we propose a set of adaptive relaxation factors based on the weighting values representing the Fresnel wavepaths in grid velocity models. The Fresnel weighting values are calculated and the velocity values are inverted at grid nodes rather than on cells. Let s_j be the slowness at the jth grid node, t_i the traveltime along the ith Fresnel wavepath, and δt_i the traveltime residual, the difference between the observed and calculated traveltimes. According to the SIRT algorithm (Grandjean and Sage, 2004), the slowness perturbation at grid node j due to δt_i can be expressed as

$$\delta s_{ij} = s_j \frac{\delta t_i}{t_i}. \tag{3}$$

The slowness perturbations at different grid nodes within a Fresnel-wavepath may produce different traveltime delays, while the slowness perturbations at nodes within the Fresnel-wavepath i may differ from each other. However, Eq. (3) gives the same back-projected value from δt_i for all nodes of the Fresnel-wavepath i regardless of the node locations. Since the weight ω_p in Eq. (2) accounts for the relative contribution of slowness perturbation at node p to the traveltime residual of a Fresnel-wavepath, we define a weight coefficient applied to the slowness perturbation at node j within the Fresnel-wavepath i with traveltime residual δt_i as

$$p_{ij} = \omega_{ij} / \left(\frac{1}{N_i} \sum_{j=1}^{N_i} \omega_{ij} \right), \tag{4}$$