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Frequency-dependent traveltime tomography using fat rays: application to near-surface seismic imaging

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ABSTRACT

Frequency-dependent traveltime tomography does not rely on the high frequency assumption made in classical ray-based tomography. By incorporating the effects of velocity structures in the first Fresnel volume around the central ray, it offers a more realistic and accurate representation of the actual physics of seismic wave propagation and thus, enhanced imaging of near-surface structures is expected. The objective of this work was to apply frequency-dependent first arrival traveltime tomography to surface seismic data that were acquired for exploration scale and near-surface seismic imaging. We adapted a fat ray tomography algorithm from global-earth seismology that calculates the Fresnel volumes based on source and receiver (adjoint source) traveltime fields. The fat ray tomography algorithm was tested on synthetic model data that mimics the dimensions of two field data sets. The field data sets are presented as two case studies where fat ray tomography was applied for near-surface seismic imaging. The data set of the first case study was recorded for high-resolution near-surface imaging of a Quaternary valley (profile length < 1 km); the second data set was acquired for hydrocarbon search (profile length > 10 km). All results of fat ray tomography are compared against the results of classical ray-based tomography. We show that fat ray tomography can provide enhanced tomograms and that it is possible to recover more information on the subsurface when compared to ray tomography. However, model assessment based on the column sum of the Jacobian matrix revealed that especially the deep parts of the structure in the fat ray tomograms might not be adequately covered by fat rays. Furthermore, the performance of the fat ray tomography depends on the chosen input frequency in relation to the scale of the seismic survey. Synthetic data testing revealed that the best results were obtained when the frequency was chosen to correspond to an approximate wavelength-to-target depth ratio of 0.1.

1. Introduction

Seismic traveltime tomography is a popular and widely used tool to image the Earth's internal structure on a variety of scales. Classical ray-based traveltime tomography uses picked traveltimes of seismic waves to invert for a subsurface seismic velocity distribution. The method relies on the high frequency assumption of asymptotic ray theory that the wavepath is infinitely thin and does not take into account diffraction and other effects caused by velocity variations away from the pencil ray (Woodward, 1992). Typical applications include crosshole experiments (e.g. Fehler and Pearson, 1984; Vasco et al., 1995; Doetsch et al., 2010), studies of the near-surface zone in engineering and environmental investigations (Lanz et al., 1998; Heincke et al., 2006; Zelt et al., 2006), exploration of the uppermost crust for orebodies and hydrocarbons (e.g. Chiu and Stewart, 1987; Schmelzbach et al., 2008) and seismological studies at the regional and global scales to image the deep structure of the Earth's interior (e.g. Kissling, 1988; Lippitsch et al., 2003; Zhao, 2004).

Instead of only using picked traveltimes, full waveform inversion (Pratt, 1999; Fichtner et al., 2008; Virieux and Operto, 2009) of the complete seismic record is in principle ideal for obtaining high-resolution subsurface velocity models. It provides theoretically superior resolution but lacks robustness when compared to classical traveltime tomography.

Frequency-dependent traveltime tomography (FDTT) is a compromise between classical ray-based traveltime tomography and full waveform inversion, taking into account the finite frequency characteristics of wave propagation, yet maintaining the robustness of classical traveltime tomography. In the literature mainly two different FDTT approaches can be found: Fresnel volume tomography (Yomogida, 1992; Snieder and Lomax, 1996; Jocker et al., 2006; Liu et al., 2009) and fat ray tomography (Watanabe et al., 1999; Husen and Kissling, 2001; Bai et al., 2013). Both approaches aim at taking into account the influence of the first Fresnel volume around the central ray on seismic wave propagation. Fresnel volume tomography is based on wave-equation tomography (Luo and Schuster, 1991; Woodward, 1992) and requires finite-

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difference wave-equation forward modelling. The finite frequency characteristic of seismic wave propagation is introduced in the tomographic inversion by calculating band-limited amplitude and traveltime sensitivity kernels using the first order Born (or Rytov) approximation (e.g. Marquering et al., 1999; Dahlen et al., 2000; Hung et al., 2000). In fat ray tomography the first Fresnel volume is determined from the source and receiver (adjoint source) traveltime fields. In this paper we use the approach of fat ray tomography and focus especially on its application to real data sets from surface seismic surveys.

So far only a few studies have been published where FDTT is applied to surface seismic surveys at scales typical for civil engineering (source-receiver offsets <0.5 km) and oil exploration (source-receiver offsets <5 km) investigations. Benxi et al. (2007) applied fat ray tomography to a data set recorded over rough topography in a mountain area. Zelt et al. (2011) tested an FDTT algorithm in comparison with FWI over a known near-surface target (tunnel). Gance et al. (2012) used FDTT for imaging velocity and attenuation structures inside a landslide.

We present two examples where fat ray tomography is applied to surface seismic data at civil-engineering and at oil-exploration scale. These data were acquired (1) for near-surface imaging of a Quaternary valley in northern Switzerland (profile length < 1 km; source-receiver offsets <250 m) and (2) for hydrocarbon exploration in a karstified area in the Middle East (profile length > 10 km; source-receiver offsets <5 km). Our 2D fat ray tomography algorithm follows the approach described by Husen and Kissling (2001) and Bai et al. (2013) and is directly implemented in the ray-based traveltime tomography algorithm of Lanz et al. (1998). Before application to real data, the fat ray tomography algorithm is tested on synthetic data with scales comparable to the field data sets. All results of fat ray tomography are compared against the results of classical ray-based traveltime tomography. The choice of the input frequency to the fat ray tomography algorithm in relation to the scale of the survey is examined, leading to the conclusion that the choice of the single input frequency should not only be based on the frequency characteristics of the source wavelet but also partly on the scale of the experiment.

2. Theory

In seismic first-arrival traveltime tomography, the data $\boldsymbol{d}$ (i.e., first arrival traveltimes), are related to a set of model parameters $\boldsymbol{m}$, (i.e., P-wave velocities or their reciprocals, slownesses), through the equation:

$$\boldsymbol{d} = g(\boldsymbol{m}) \tag{1}$$

which is generally referred to as the forward problem and g is the forward operator used to calculate synthetic or predicted traveltimes from an underlying seismic velocity distribution. Here, the finite-difference solver of the eikonal equation of Podvin and Lecomte (1991) is used to calculate first-arrival traveltimes.

The inverse problem, i.e. estimating a set of model parameters from observed data, is solved using the regularized, iterative inversion scheme of Lanz et al. (1998). A slowness model estimate $\boldsymbol{m}^{est}$ is obtained by solving a system of equations of the following form (adapted from (Lanz et al., 1998):

$$\begin{pmatrix} \boldsymbol{W}_D\left(\left(\boldsymbol{d}^{obs} - \boldsymbol{d}^{pred}\right) + \boldsymbol{Jm}\right) \\ \alpha_S \boldsymbol{m}^{ini} \\ 0 \end{pmatrix} = \begin{pmatrix} \boldsymbol{J} \\ \alpha_S \boldsymbol{I} \\ \alpha_X \boldsymbol{W}_X \end{pmatrix} \cdot \boldsymbol{m}^{est} \tag{2}$$

where $\boldsymbol{d}^{obs}$ and $\boldsymbol{d}^{pred}$ are the observed and predicted traveltimes, respectively, $\boldsymbol{m}^{ini}$ is the initial slowness model, I is the identity matrix, $\boldsymbol{W_D}$ is a data weighting matrix, $\boldsymbol{W_X}$ is the smoothing matrix, and α_s and α_x are damping and smoothing factors, respectively. $\boldsymbol{J}$ is the sensitivity or Jacobian matrix containing the partial derivatives $\boldsymbol{d}t_i/\boldsymbol{d}s_k$, where t_i is the traveltime of the i-th ray and s_k is the slowness in the k-th cell of the subsurface model. The ray paths needed to setup the sensitivity matrix are found by following the traveltime gradient from a receiver back to the source. The initial model and the employed damping and smoothing factors are the free parameters in finding a solution to the inverse problem. The damping factor controls how much the model estimate deviates from the initial model or the model of the previous iteration (Marquardt, 1970) whereas the smoothing factor controls the model roughness and is needed to combat the iunder-determined nature of the inverse problem (Constable et al., 1987). There are various ways to choose these parameters. For our inversion experiments, we chose combinations of free parameters that allowed reducing the RMS value of the traveltime residuals (i.e. difference between observed and calculated traveltimes) to the estimated data uncertainty. The general consensus in the geophysical community is that this is a sensible and justifiable approach (e.g., Zelt, 1999).

2.1. Fat ray tomography

Following the approach described in Husen and Kissling (2001) and Bai et al. (2013), fat ray tomography was directly implemented in the ray-based traveltime tomography of Lanz et al. (1998). The first Fresnel volume is defined in terms of traveltimes (Červený and Soares, 1992) as:

$$|t_{sx} + t_{rx} - t_{sr}| \le \frac{T}{2} \tag{3}$$

where $T = 1/f$ is the dominant period of the seismic wave having a dominant frequency f, t_{sr} is the shortest traveltime between a source located at s and a receiver at r, t_{sx} and t_{rx} are source and receiver traveltime (adjoint source) fields, respectively. Eq. (3) effectively states that any part of the medium at position x between source and receiver within the first Fresnel volume surrounding the ray will contribute to the first half cycle of the arriving wave.

The concept of using adjoint sources for determining the dimensions of the fat rays (Fresnel volumes) from Eq. (3) is illustrated in Fig. 1. Fig. 1a and b show the traveltime fields calculated from the true and adjoint source (receiver) positions, respectively, to all points in the medium. The traveltime fields were obtained through finite-difference modelling of the eikonal equation. The underlying (or background) velocity function has an initial constant gradient, increasing from 600 m/s at z = 20 m to 3200 m/s at z = 150 m. For greater depths the velocity gradient is reduced, such that a maximum value of 5000 m/s is reached at z = 500 m. Setting the left hand side of Eq. (3) equal to $T/2$ yields the contour of the fat ray for a specific frequency ($f = 1/T$). In Fig. 1c the contours of three fat rays, each having a different frequency, are superimposed on the summed traveltime field. From Eq. (3) it is seen that the area (volume) covered by the fat ray decreases with increasing frequency.

The main difference between the classical ray-based and fat ray tomography approaches is the calculation of the sensitivities. For ray tomography the sensitivities effectively are the lengths of the ray segments within the respective model cells. In the fat ray tomography scheme the sensitivities are calculated using fat rays without resorting to ray tracing (Bai et al., 2013; Husen and Kissling, 2001).

The traveltime tomography algorithm uses two differently spaced grids. The grid for the finite difference modelling (forward grid) needs to be sufficiently fine to allow for an accurate traveltime computation whereas the slowness model for the inversion step is defined on an invariably coarser grid to stabilize the inversion (inversion grid).

For a 2D fat ray in a discretized medium the sensitivity of the traveltime t_i with respect to a change in slowness s_k is given by (Eq. (17) in Bai et al. (2013); reformulated here for slowness):

$$\frac{\partial t_i}{\partial s_k} = \frac{a_k^i}{A_i} \cdot \frac{t_i}{s_k} \tag{4}$$