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On the value of frequency-dependent traveltime tomography for surface-seismic data

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Frequency-dependent traveltime tomography does not rely on the high-frequency assumption made in classical (asymptotic ray-theory based) tomography. By incorporating the influence of velocity structures in a nearby region (called 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, improved imaging of the subsurface is expected. Improvements in seismic imaging include the recovery of additional information on the subsurface model, enhanced (model) resolution and better detection and delineation of low velocity zones. It has been argued that finite-frequency effects on traveltimes may be more pronounced in near-surface imaging considering the typical seismic wavelengths and dimensions of heterogeneities compared to global-scale traveltime tomography.

To account for the finite frequency characteristics of seismic data, a so-called fat-ray tomography algorithm was developed. The algorithm forms the sum of source and receiver (adjoint) traveltime fields, calculated by finite-difference modeling of the eikonal equation, to determine the necessary Fresnel volumes and sensitivity kernels for the tomographic inversion. Using different scale surface-seismic synthetic data examples, the imaging capabilities of the fat-ray tomography algorithm were investigated and compared to the results of classical ray tomography. The velocity fields used to generate the synthetic data were chosen to emulate two real field data sets, to which the fat-ray tomography was also applied. The first real data example is a large-scale data set (profile length > 10 km) acquired for hydrocarbon search; the second data set was recorded for high-resolution near-surface imaging of a Quaternary valley (profile length < 1 km). Resolution of the tomograms was assessed on the basis of checkerboard tests and a column sum of the sensitivity matrix.

For the synthetic data examples as well as for the large-scale real data example, it was possible to obtain modest, additional information on the subsurface model when fat-ray instead of classical ray tomography was used. However, for the small-scale field example this was only partly true, because ray coverage was very limited in the deeper parts of the inverted model. By testing different frequencies as input to the fat-ray tomography algorithm, it was found that the choice of the input frequency should not only be based on the frequency characteristics of the source wavelet but also partly on the scale of the experiment. We found that for the large-scale data set an input frequency for the Fresnel volume calculation that is equal to or lower than the dominant frequency of the first arrivals leads to the best results. Conversely, for the small-scale near-surface data set, best results were obtained for frequencies higher than the dominant first-arrival frequency.