DEVELOPING FINITE-FREQUENCY REGIONAL PN VELOCITY MODELS

Zhigang Zhang[2], Yang Shen[2], Li Zhao[3], Xiaoping Yang[1], and Kim Olsen[4]

Science Applications International Corporation[1], University of Rhode Island[2], University of Southern California[3], and San Diego State University[4]

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ABSTRACT

Head waves and Pn waves in particular are important in studying the predominantly layered velocity structure of the Earth and discriminating the seismic sources. Conventional studies of head waves have used high-frequency (ray) approximation in wave propagation. While recent studies have shown the diffractive nature and the three-dimensional (3-D) sensitivities of finite-frequency turning waves, analogs of head waves in a continuous velocity structure, the finite-frequency effects and sensitivity kernels of head waves are yet to be carefully examined. We present the results of a numerical study on the finite-frequency behavior of head waves. A reference model with a low-velocity layer over a high-velocity half-space is used. Velocity anomalies of various sizes are placed on either side of the interface at different locations. A 3-D fourth-order staggered-grid finite-difference method is used to calculate synthetic waveforms, and travel time anomalies are measured by cross-correlations of seismograms for models with and without velocity anomalies. The results show that finite-frequency head waves are sensitive to the 3-D velocity perturbation in a more complex way than predicted by ray theory. The peak travel time sensitivity is located near the two piercing points at which the head wave reaches and leaves the interface. The sensitivity is much smaller elsewhere on the ray path. Fresnel zones can be observed from the pattern of positive and negative sensitivities, with the strongest negative sensitivity in the first Fresnel zone. Unlike turning waves, the head wave has a nonzero sensitivity right beneath the interface along the source-receiver path. But at some distance below the interface, the sensitivity has a local minimum. We are in the process of constructing 3-D full-wave sensitivity kernels from 3-D reference velocity models and compare the measured travel time anomalies with the predictions from the 3-D sensitivity kernels.

This is the beginning of a three-year effort to develop accurate, seamless velocity models in Eurasia at local, regional, and teleseismic scales under a self-consistent theory for finite-frequency seismic waves. We will construct the 3-D Finite-Frequency Seismic Tomography (FFST) velocity model for Eurasia and refine it for selected areas of interest (AOIs) and develop finite-frequency attenuation models for the AOIs. Broadband waveforms and ground truth (GT) data will be collected, and frequency-dependent travel times and amplitude measurements will be obtained from waveform cross-correlation.

OBJECTIVES

Our main objectives are to establish a process for developing refined local velocity models and attenuation structure using a newly developed, fully 3-D, finite-frequency waveform-based approach (Zhao et al., 2005). We will obtain FFST velocity models for Eurasia and refine crustal and shallow upper mantle velocity models for selected AOIs. Combining these two levels of velocity models under the unified finite-frequency theory, we will obtain integrated, seamless, finite-frequency kernel-based velocity models at local, regional, and teleseismic scales. A critical component of this project is to understand the finite frequency behavior of head waves, in particular Pn waves, which provides important information about the velocity structure around the crust-mantle boundary. Tomographic models based on the finite frequency effects of head waves (Pn) will likely provide a new and more accurate 3-D view of the boundaries of the Earth's interior, important constraints not only on the location and discrimination of the seismic sources, but also on the geological processes of the Earth.

RESEARCH ACCOMPLISHED

Previous Studies

Usually as the first arrival at regional distances, Pn waves are of prime importance in determining accurate locations of seismic events, source mechanisms, as well as the physical and chemical states of the uppermost mantle. There have been numerous tomographic studies of Pn velocity structure at various scales and localities (e.g., Hearn et al., 1991; Hearn, 1996; Ritzwoller et al., 2002; Liang et al., 2004). In previous Pn tomographic studies, the sensitivity of Pn waves to the velocity structure beneath the Moho is collapsed vertically and horizontally to a ray path right beneath the Moho under high-frequency (ray) approximation. Although many researchers recognize that the real Pn wave usually dips deeper into the mantle as epicentral distances increase and correct for the propagation distances empirically (e.g., Ritzwoller et al., 2002), the inversion is usually parameterized as a 2-D problem in latitude and longitude variations. Yet as all observed seismic waves, the Pn wave has a finite frequency range and may be sensitive to the 3-D structure surrounding the geometric ray path. Understanding the finite-frequency sensitivity of Pn waves is important for improving Pn tomography and related source location and discrimination. While recent studies have shown the diffractive nature and the 3-D sensitivities of finite-frequency turning waves (Dahlen et al., 2000; Hung et al., 2000; Zhao et al., 2000; Zhao et al., 2005; Tromp et al., 2005), analogs of head waves in a continuous velocity structure, the finite-frequency effects and sensitivity kernels of head waves are yet to be carefully examined.

At the regional and global (mantle) scales, the 3-D "banana-doughnut" travel-time sensitivity kernels (Dahlen et al., 2000; Hung et al., 2000; Zhao et al., 2000) represent a major advance from the conventional ray theory as the finite-frequency kernels account for wavefront healing and other diffractional effects. The "banana-doughnut" kernels have been used in global (Montelli et al., 2004) and regional (Hung et al., 2004; Shen and Hung, 2004; Yang et al., 2006) tomographic studies. The use of fully broadband seismic records has shown a significant improvement in the resolution of the velocity structure compared to ray-based models (Hung et al., 2004). We note that the kernels used in these studies are constructed using a 1-D reference Earth model due to computational constraints with respect to the scales of the studies. These tomographic inversions are performed under the assumption that the velocity perturbations are relatively small. This assumption is reasonable at regional and global (mantle) scales as demonstrated by the results of the initial finite-frequency tomographic studies.

At local (crustal) scales, large and sharp velocity variations are common and the 1D reference approach becomes inadequate. It is thus necessary to use a 3-D velocity model as the reference to calculate the sensitivity kernels for further improvement of the velocity model. Constructing 3-D sensitivity kernels from 3-D reference velocity models (hereinafter, fully 3-D kernels) is made possible by the ever-increasing power of computation and recent advances in seismic algorithms (Tromp et al., 2005; Zhao et al., 2005). This new approach eliminates both the high-frequency (ray) and structural averaging approximations and provides a powerful tool to further refine 3-D velocity structure. Furthermore, the new approach provides a straightforward way to utilize any segment of the waveform, and thus the rich information in the broadband waveforms. This is particularly important for small events, which are often recorded by only a few stations. In contrast, the traditional approach for tomography model and source studies depends heavily on the first arrivals due to the difficulties in unambiguously identifying later phases.

We report the initial results of a numerical study of the finite-frequency behavior of head waves. A 3-D finite difference code (Olsen, 1994) is used to simulate wave propagation. Traveltime anomalies are measured by cross-correlations of seismograms for models with and without velocity anomalies. The results indicate that finite-frequency head waves are sensitive to the 3-D velocity perturbation in a more complex way than predicted by ray theory. We are also calculating 3-D full-wave sensitivity kernels from 3-D reference models using the method of Zhao et al. (2005). The measured travel time anomalies will be compared with the values predicted by the 3-D sensitivity kernels.

Preliminary Results

In this initial waveform simulation study, we use a simple reference model with a low-velocity layer overlying a high-velocity half space (Figure 1). The same approach can be applied to 3-D reference models. We use an explosive source, a Gaussian derivative function with a dominant period of 1.2 seconds, in the simulations. A cylindrical velocity anomaly with a radius of 3.2 km and height of 1.6 km is placed in various locations within the high velocity layer. Table 1 shows the velocity parameters of the two layers and the anomaly. The grid spacing is 400 m, and the time length is 20 s with time interval of 0.02 s. Pn travel time delays are measures by cross-correlating Pn waveforms for models with and without the velocity perturbation (Figure 2).

Figure 3a shows the Pn travel time anomalies determined from waveform cross-correlation for models with a low-velocity anomaly right beneath the interface. Positive values indicate travel time delays. The two horizontal axes are the horizontal coordinates of the model. Because of the symmetry about the source-receiver path, calculations are carried out for only half of the model. The travel time delays (sensitivities) have two local maxima near the points where the theoretical ray of the head wave enters and leaves the interface. The asymmetry between the source and receiver sides is attributed to the fact that the source is closer to the interface than the receiver. Unlike turning waves, the travel time anomaly is nonzero along the ray path beneath the interface. Interestingly, there is a local minimum near the piecing point at the receiver side. Such a feature is not observed at the source side because the source is closer to the interface than the receiver and the near-field effects at the source dominate. Figure 3b shows the results for the perturbations with the upper surface of the input anomaly 1.6 km below the interface. The most notable difference is that there is now a local minimum near the center of the source-receiver path, which is analogous to the “doughnut” hole in the sensitivity kernel of the turning wave.

The pattern of positive (delay) and negative (early arrival) travel times and the amplitude variations are consistent with the calculated Fresnel zones (Figure 4). Within the first Fresnel zone, velocity perturbations contribute significantly to the travel time delays as measured by cross-correlation.

Table 1. Reference velocity model and input anomaly

	Vp (m/s)	**Vs (m/s)**	**Attenuation**
Upper layer	5207	3189	no
Lower layer	9058	5307	no
Anomaly	8500	5100	no

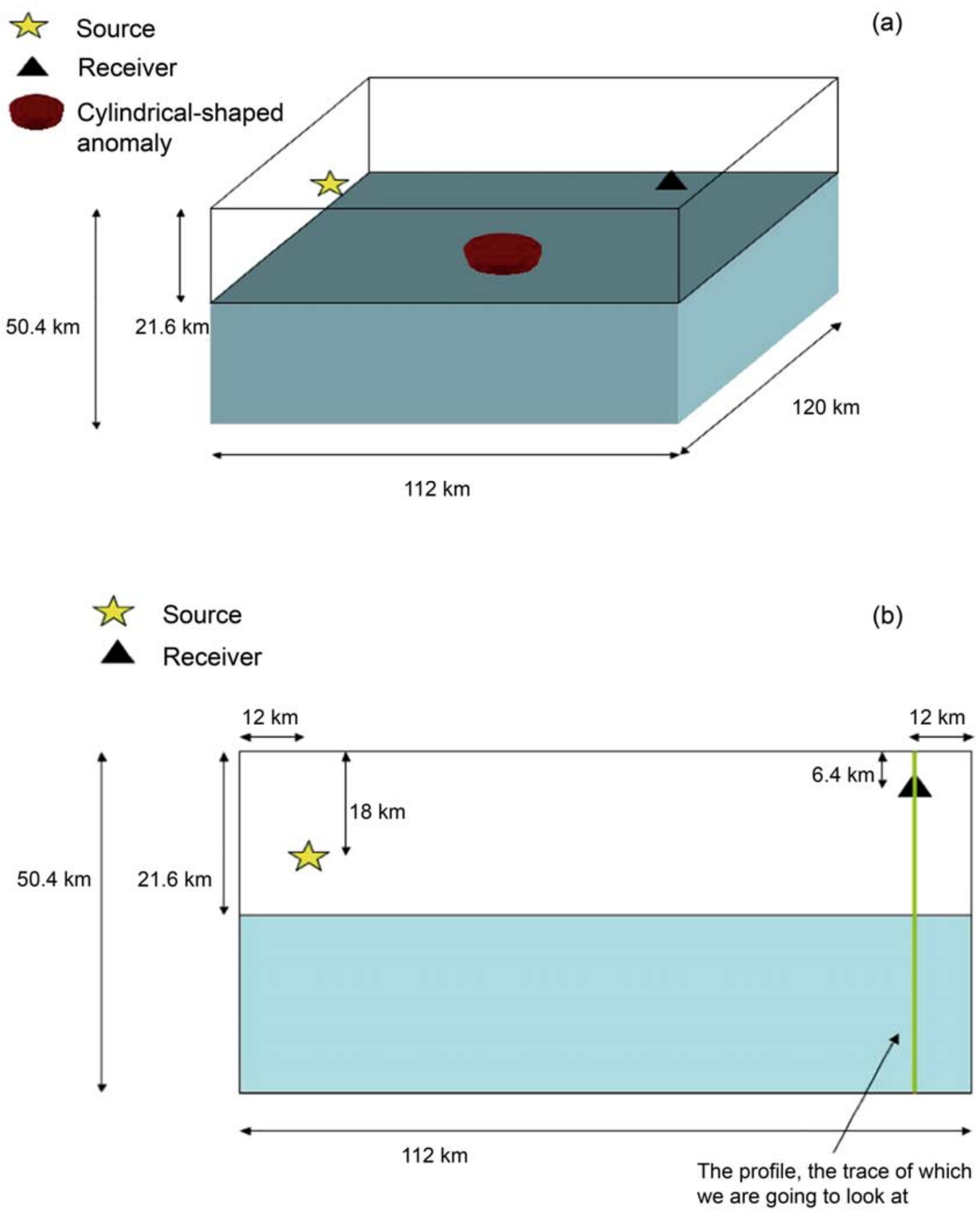

Figure 1. Schematic figure showing the geometry of the 3-D two-layered model. (a) Star represents the explosive source used in wave simulations. Triangle marks the receiver. The red cylindical represents a velocity perturbation beneath the interface. The velocities of the layers can be found in Table 1. (b) The vertical profile containing the source and the receiver. The star presents the location of the source. The black triangle is the location of the receiver. The model and the source-receiver geometry are designed so that the head wave is separated clearly from other phases, including waves reflected from the side and bottom boundaries due to imperfect absorption of seismic energy at the boundaries.

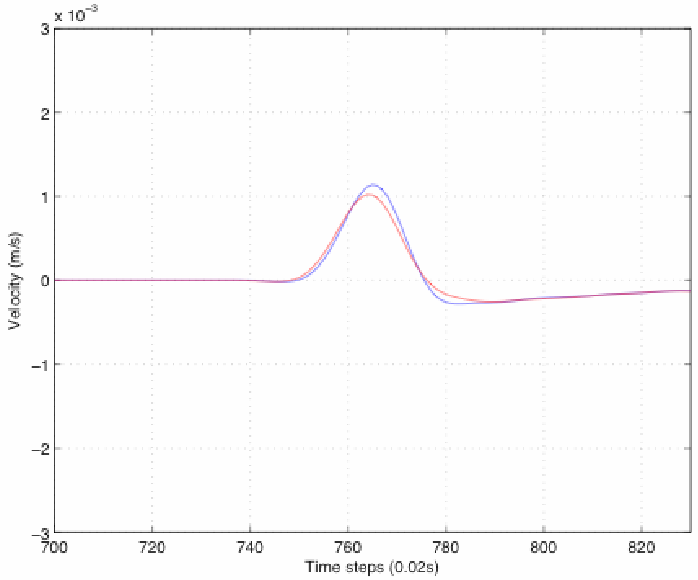

Figure 2. Comparison of the head wave calculated from reference model (red line) and that calculated from a model with a velocity perturbation below the interface in Figure 1 (blue line). The horizontal axis unit is time step with a time interval of 0.02 s. The vertical axis is the velocity.

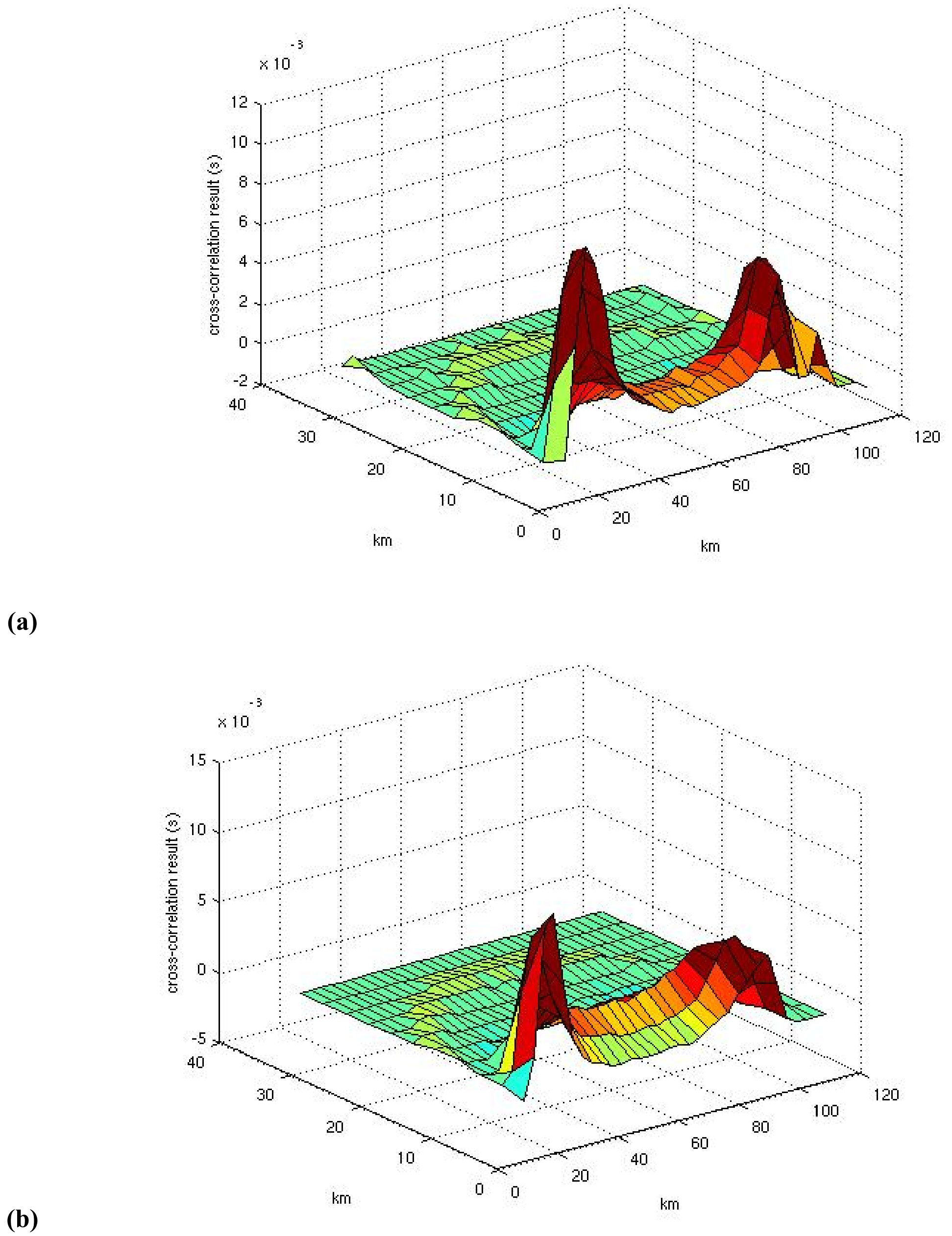

Figure 3. (a) The travel time delays measured by cross-correlation for a moving velocity perturbation right beneath the layer interface with a 5% velocity reduction in a cylinder with a radius of 3.2 km and a height of 4 km. (b) The travel time delay measurements for the same sized velocity anomaly 1.6 km below the layer interface. The x-axis is the distance in the direction of the source and receiver path measured from the side of the model; the y-axis is the distance to the source-receiver plane. The two peaks of the travel time sensitivity are located near the two piecing points of the head wave ray path entering and leaving the bottom layer. Within the first Fresnel zone, velocity perturbations contribute significantly to the travel time delays as measured by cross-correlation. Notice the negative values in the second Fresnel zone and positive values in the third Fresnel zone.

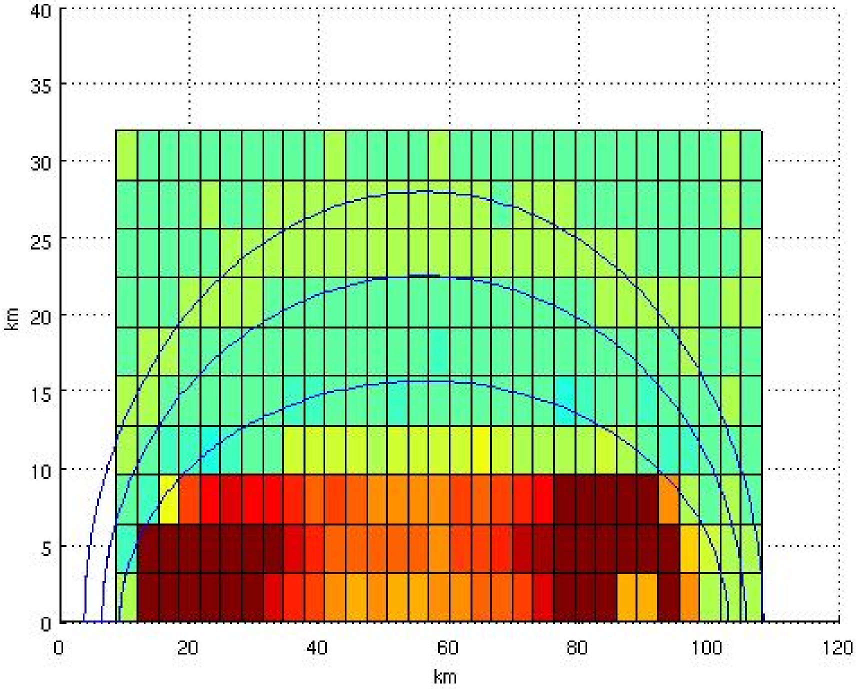

Figure 4. A comparison of the calculated Fresnel zones (blue lines) and the measured travel time delays. The blue lines mark the boundary of the first (innermost), second and third Fresnel zone. The pattern of the travel time sensitivity can be explained by the Fresnel zones.

CONCLUSION(S) AND RECOMMENDATIONS

The travel time anomaly of the finite-frequency head waves measured by waveform cross-correlation is very different from that predicted by the ray theory. While in the ray theory the travel time anomaly is sensitive only to velocity perturbation along the geometric ray path and the sensitivity is the same along the ray path, our results show that realistic head waves with finite frequencies are sensitive to the 3-D structure in a more complex way. The peak travel time sensitivity is located near the two piecing points of the geometric ray of the head wave entering and leaving the interface. The sensitivity is much smaller at other points on the ray path. The pattern of positive and negative sensitivities is consistent with the Fresnel zones, with the travel time anomaly most sensitive to velocity perturbations in the first Fresnel zone. Unlike the turning waves, the sensitivity right beneath the interface is nonzero along the source-receiver path. A few kilometers below the interface, there is a local minimum near the center of the source-receiver path, analogous to the “doughnut” hole in the sensitivity kernels of turning waves.

We are in the processes of constructing 3-D sensitivity kernels for head waves using the method of Zhao et al. (2005) and are exploring how 3-D velocity variations affect the finite-frequency behavior of head waves (Pn waves). The simulations not only help us gain a physical understanding of the finite-frequency behavior of head waves, but also provide us a means to compare the travel time delays measured by waveform cross-correlations and calculations from the sensitivity kernels. We will apply the 3-D Pn sensitivity kernels to image the velocity structure at the selected areas of interest.

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