CRUSTAL AND MANTLE STRUCTURE BENEATH EASTERN EURASIA FROM FINITE FREQUENCY SEISMIC TOMOGRAPHY (FFST)

Ting Yang[2], Yang Shen[2], and Xiaoping Yang[1]

Science Applications International Corporation[1] and University of Rhode Island[2]

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ABSTRACT

An accurate, high-resolution 3-D earth model is crucial to the seismic calibration for nuclear monitoring. We use the newly developed Finite Frequency Seismic Tomography (FFST) approach to construct the crustal and mantle structure beneath eastern Eurasia. Traditionally, travel times of seismic waves are calculated based on the ray theory, which is valid strictly for infinite-frequency waves. Observed seismic waves, however, are finite frequency signals. As a result of scattering and diffractive effects, travel times of realistic finite frequency waves are sensitive to 3-D structure around the geometrical rays, and the travel time shifts caused by heterogeneities diminish gradually from the heterogeneities to receivers - a phenomena named the wave front healing. The ray theory ignores this ubiquitous effect of the propagation of realistic seismic waves. Tomographic inversions based on it, therefore, tend to underestimate the magnitudes of heterogeneities. The newly developed FFST utilizes the 3-D Born-Fréchet sensitivity kernels of the travel times of finite-frequency seismic waves. The new method accounts for the wave front healing, off-ray scattering and other non-geometrical diffraction phenomena, and significantly improves the resolution of the velocity heterogeneity.

In addition to the new methodology, we will use a more comprehensive data set than in previous studies to construct the new earth model beneath eastern Eurasia. We will collect data from the publicly accessible sources e.g., Incorporated Research Institutions for Seismology (IRIS), Global Seismographic Network (GSN), the Program for the Array Seismic Studies of the Continental Lithosphere (PASSCAL), and International Monitoring System (IMS) stations. Efforts will also be made to collect data sets from other networks in the region such as the Japanese Broadband Seismograph Network (F-net), the Japanese International Seismic Network (JISNET in Indonesia), and the Taiwan Broadband Seismic Network. Access to other unique sources including permanent and portable seismic stations throughout the study area further improves the station coverage over eastern Eurasia.

This is the beginning of a three-year effort to improve seismic calibration in eastern Eurasia. We will first develop a 3-D FFST velocity model using body waves, along with model uncertainties. Travel time corrections and modeling error surfaces will be derived and applied to relocating ground truth (GT5) events. The final model will be developed using joint body and surface waves. From the 3D velocity models, we will also simulate the full wave propagation in the transition zone. To facilitate data integration, a project database and a web-based tool are being implemented.

OBJECTIVES

We will develop a new generation of high-resolution P and S velocity models that are based on the recent wave propagation theory for realistic, finite-frequency seismic waves using both public and unique data sets. We will derive frequency-dependent travel time corrections and uncertainty estimates for eastern Eurasia, and validate the model and event location improvement using ground truth (GT) data. Three-dimensional (3D) full waveform simulations will be carried out to model wave propagation through the transition zone and seismic anisotropy.

RESEARCH ACCOMPLISHED

Previous Studies

Eastern Eurasia is one of the most tectonically complex regions in the world due to the India-Eurasia collision and subsequent extensive lithospheric deformation. While the evolution history of continental lithosphere has been well recognized (Briais et al., 1993), the fine structure associated with the complicated deformation in this region is far from clear, and deep mantle processes that accompanied shallower lithosphere deformations are poorly understood. An accurate, high-resolution 3D earth model for this region is needed to improve seismic calibration for nuclear monitoring. Efforts have been made in developing and applying regional and teleseismic models for this purpose (Johnson and Vincent, 2002; Antolik et al., 2003; Ritzwoller et al., 2003; Richards et al., 2003; Yang et al., 2004).

Many seismic imaging studies have already been conducted in Eastern Eurasia and adjacent west Pacific area. Most of regional studies covering a large area of eastern Eurasia are based on surface wave observations (e.g. Wu et al., 1994; Ritzwoller et al., 1998; Curtis et al., 1998; Zhu et al., 2002; Lebedev and Nolet, 2003). While there are extensive short–period body wave tomographic studies performed along the subduction zone of the pacific plate in western Pacific (Van der Hilst et al., 1991; Fukao et al., 1992; Windiyantoro and Van der Hilst, 1997; Bijwaard et al., 1998; Zhao et al., 2000), only limited body wave travel-time tomographic studies have been conducted within the eastern Asia continent. The resolutions in those studies were limited by the relatively sparse seismic stations in the earlier work (Liu et al., 1989), or only limited to small regional (Pei et al., 2005) and local (Liu et al., 1989; Xu et al., 2001; Huang and Zhao, 2004) areas. There are also several studies using Pn waves to obtain the crustal thickness and uppermost mantle structure beneath the great China region (e.g., Sun et al., 2004; Liang and Song, 2004).

Finite Frequency Seismic Tomography

Almost all global and regional tomographic models, including the ones for Eastern Eurasia, are based on the geometrical ray theory (e.g. Dziewonski, 1984; Grand, 1994; Van der Hilst et al., 1997), which assumes that the seismic waves have an infinite frequency band, and the arrival time of a body wave depends only on the velocity along the geometrical ray path between the source and receiver. In fact, observed seismic waves are finite frequency signals, and their travel times are sensitive to a 3-D volume around the geometrical ray and subjected to wavefront healing, scattering and other diffractive effects. As a result, the travel time shifts are affected by wavefront healing for velocity heterogeneities with dimensions smaller than the width of the Fresnel zone (Nolet et al., 2000; Hung et at., 2000; Baig et al., 2004), and tomography based on ray theory, therefore, tends to underestimate the magnitude of velocity heterogeneities. In contrast, the 3-D Born-Fréchet travel-time sensitivity kernels (Marquering et al., 1999; Dahlen et al., 2000; Hung et al., 2000; Zhao et al., 2000) account for the wavefront healing, off-ray scattering and other non-geometrical diffraction phenomena. By using waveform cross-correlation, the kernel can provide better measurements of the travel time shifts caused by velocity anomaly for finite frequency seismic waves. Thus the seismic imaging technology based on this 3-D sensitivity kernel can significantly improve the resolution of the velocity heterogeneity. The 3-D kernel theory has been successfully applied to regional (Hung et al., 2004; Shen and Hung, 2004) and global (Montelli et al., 2004) seismic tomography. A comparison of the velocity models beneath Iceland showed that the finite-frequency tomography significantly improves the resolution of the velocity structure beneath the Iceland hotspot (Hung et al., 2004).

The general formula for the inverse problem, after parameterization of the model function on a spatial grid of nodes, can be expressed as a concise matrix form for discrete inverse problem:

$$d_i = A_{il} m_l \qquad (1)$$

For teleseismic regional tomography, d_i represents the ith relative travel time delay, and m_l is velocity anomaly at the lth grid node. The difference between ray-based and kernel-based tomography is in A_{il}. In traditional tomography, A_{il} is the difference of the total path lengths throughout a specific volume that contributes to the lth node between the two arrivals in the ith paired relative travel time measurement. In 3-D kernel-base inversion problem, however, A_{il} is the differential value of the integrated volumetric kernels contributing to the lth node (Hung et al., 2004). In order to make the sparse equation solvable, the smoothness regularization is usually needed in the ray-based inversion problem. In finite-frequency seismic tomography (FFST), however, the 3-D broad Born-Fréchet kernel itself provides physical smoothness constraints. So, only a simple norm damping is needed to avoid the *ad hoc* smoothness enforcement.

In FFST, the relative travel-time delays are frequency dependent because seismic waves with different frequency contents sample different volumes of the velocity structure (Dahlen et al., 2000; Hung et al., 2004). To take advantage of the broadband nature of the seismic records, the broadband waveforms can be filtered into several narrower frequency band signals, each of which can constrain a different volume of the velocity heterogeneity, and therefore has different relative travel-time shifts. Figure 1 shows an example of frequency dependent relative travel-time delays at several GSN seismic stations in eastern Eurasia. Another advantage of this feature of FFST is the microseism and other noise having known frequency contents that can be easily isolated from the signals.

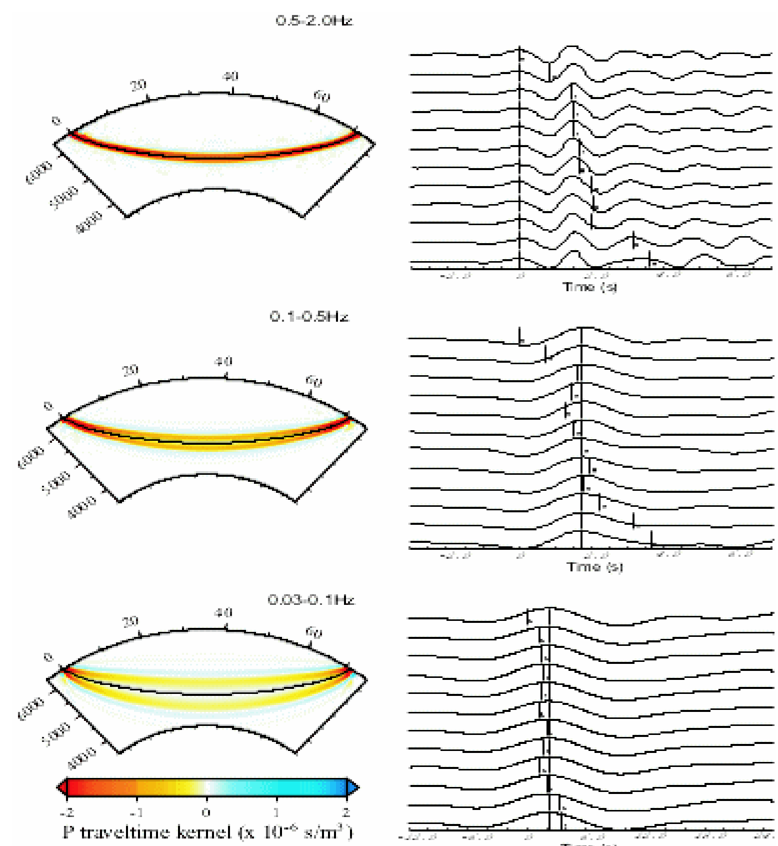

Figure 1. (Left) A comparison of Born-Fréchet kernels for travel-time of teleseismic P phases, measured by cross-correlation of the observed waveforms with the synthetics in three frequency bands: 0.5-2.0, 0.1-0.5 and 0.03-0.1 Hz. (Right) Example of frequency-dependent P arrivals observed at 12 GSN stations from one earthquake. Broadband pulses have been bandpass-filtered at the three frequencies. The waveforms are aligned according to the time picks of the multi-channel cross-correlation method. The vertical bars mark the relative travel-time shifts used to align the waveforms.

Data Set and Inversion

The resolution of seismic models depends on the underlying theory and the data sets used in inversion. In addition to the new seismic imaging technology that integrates realistic, finite-frequency body and surface waves in a self-consistent way, we will collect and utilize a more comprehensive data set than in previous studies to construct the new earth model beneath eastern Eurasia.

As the first step of the three-year effort, we are collecting data from IRIS, GSN, PASSCAL, and IMS stations, the Japanese F-net and JISNET and Taiwan Broadband Seismic Network, as well as unique sources including permanent and portable seismic stations throughout the study area. Figure 2 shows the stations in the study region with broadband data. So far we have obtained an initial data set of broadband waveforms for events in eastern Eurasia since 2000. It includes all GSN stations within the study region in 2000-2004, Taiwan stations in 2000-2004, and JISNET stations in 2000-2001.

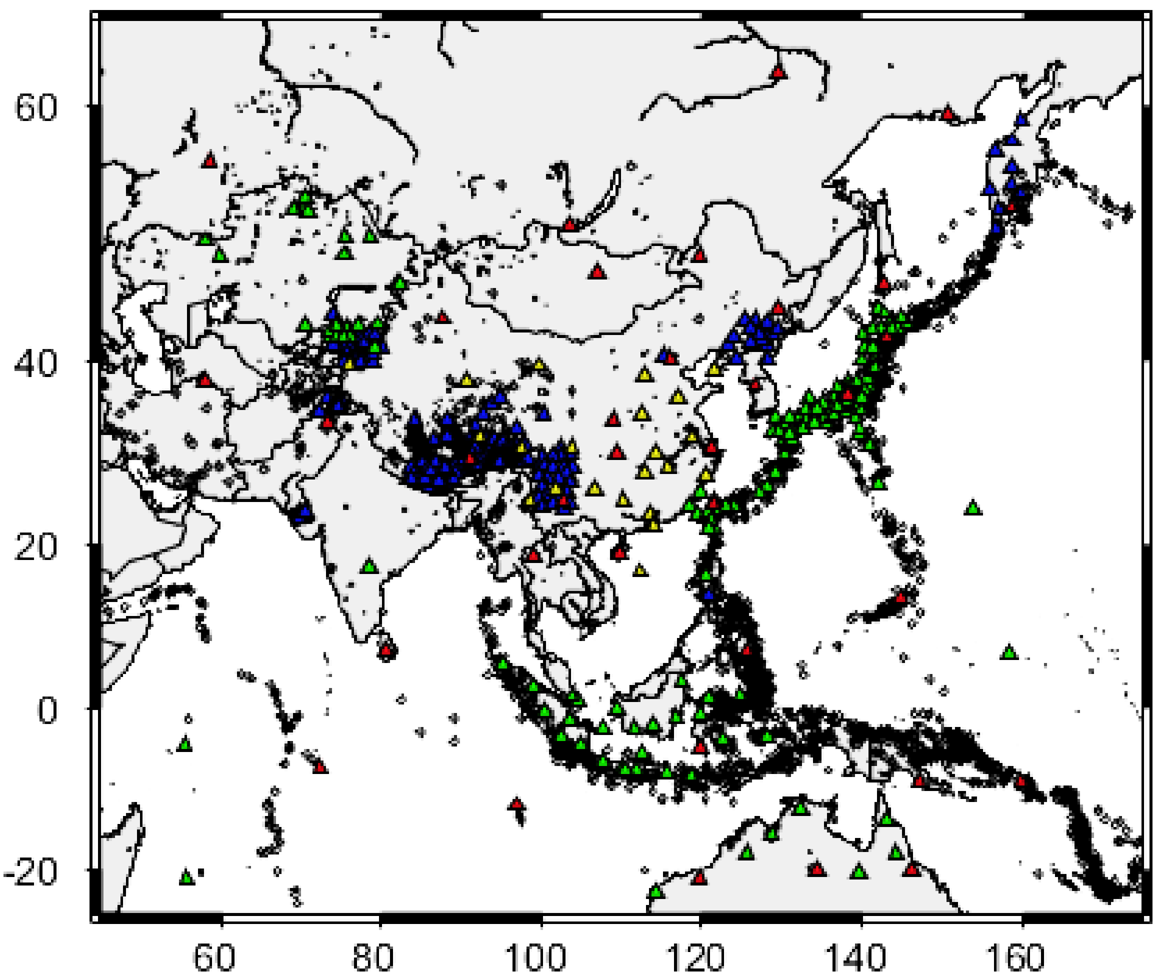

Figure 2. Triangles mark the locations of broadband seismic stations in Eastern Eurasia (red: GSN stations; blue: PASSCAL stations; yellow: part of the CNDSN; green: other permanent or long-term seismic networks). Data from some of the PASSCAL stations will be available only in the later half of this project. Circles represent earthquakes with magnitude greater than 5.0 during the period of 2000-2003.

We have developed an automated waveform cross-correction routine, and processed P waves from global earthquakes (2001-2004) with magnitude greater than 5.5 recorded by the GSN stations in eastern Eurasia and selected stations in Taiwan. In addition to the direct P arrival, we will also use other complementary phases, including the depth phase pP, surface-bounce phase PP (with bouncing point within the study region), and the steeply incident core phases PKP and PKIKP. Figure 3 shows the distribution of global and regional earthquakes used in our preliminary model.

In processing data, to isolate the microseism and utilize the high dynamic range of the seismic records, we filter the broadband waveforms of the P waves in high, intermediate and low frequency bands (0.5-2.0, 0.1-0.5, and 0.03-0.1 Hz, respectively). We specify a threshold value of the signal to noise ratio of 20 for automated data selection in each frequency band and inspect each selected record visually for consistency. The relative travel time delays of the arrivals in each frequency band for each event are measured by multi-channel cross-correlation (VanDecar and Crosson, 1990).

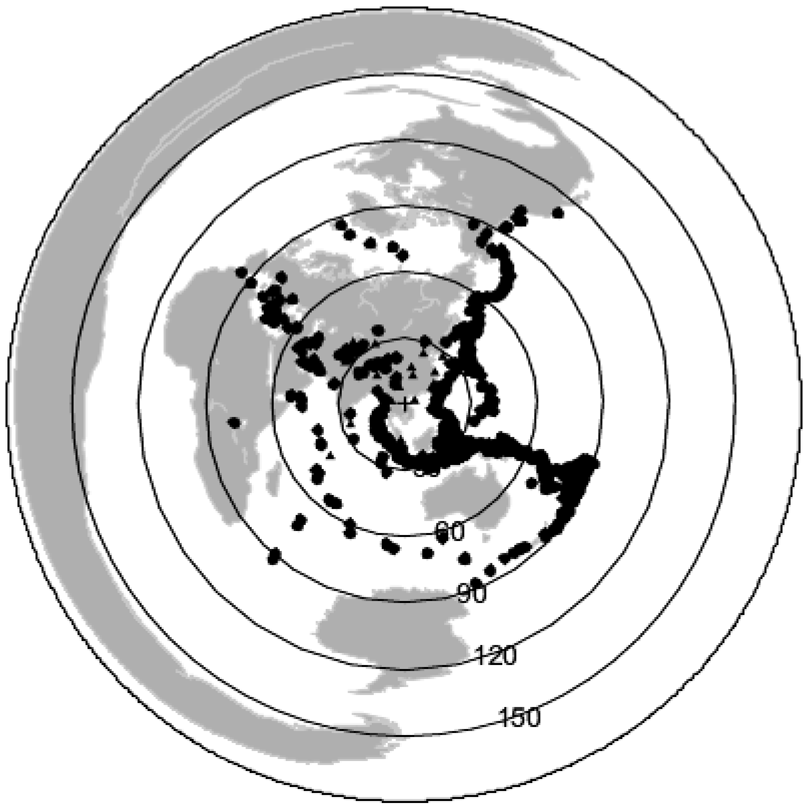

Figure 3. Location of the earthquakes with useful P phases (solid circles) and GSN stations (triangles) in the study region.

The norm damping factor of the inversion is determined by the trade-off analysis of model roughness versus variance reduction (Menke, 1989). An additional free term at each station was added into the inversion to absorb the time shifts due to the lateral variation in station elevation and velocity anomalies at shallow depths, which cannot be constrained due to the lack of crossing rays. The inversion of the massive matrix is approximated by the iterative solution of the LSQR algorithm (Paige et al., 1982).

Preliminary Results

Figure 4 shows the sampling density from high-, intermediate-, and low-frequency P waves from teleseismic earthquakes recorded by the GSN stations. The sampling density is the diagonal values of the product of the Gram matrix in equation 1 and its transpose (Hung et al., 2004). By examining the sampling, we can find where the model space is expected to be well resolved and where additional earthquake-station paths or phases are needed to obtain an adequate sampling of the velocity structure beneath the study region. As shown in Figure 4, direct P arrivals provide a good coverage in the depth range of 400 - 1500 km. There exist large coverage gaps in the shallow upper mantle and crust due to the sparse GSN station distribution.

We note that so far only a small fraction of the available data sets has been used in this preliminary result. The other data sets being collected (e.g., CNDSN, IRIS, PASSCAL, IMS and JISNET) will fill most of the blanks in Figure 4, especially beneath the Eurasia continent. The depths phase pP, surface multiple phase PP, and regional arrivals will provide resolution for the shallow structure. PKP and PKIKP phases will provide coverage in the deep mantle and vertical ray paths that cross with other phases in the shallower mantle. We also note that surface waves, which sample the crust and shallow mantle, will be used in joint tomography of finite-frequency body and surface waves to obtain the 3-D shear-wave velocity structure.

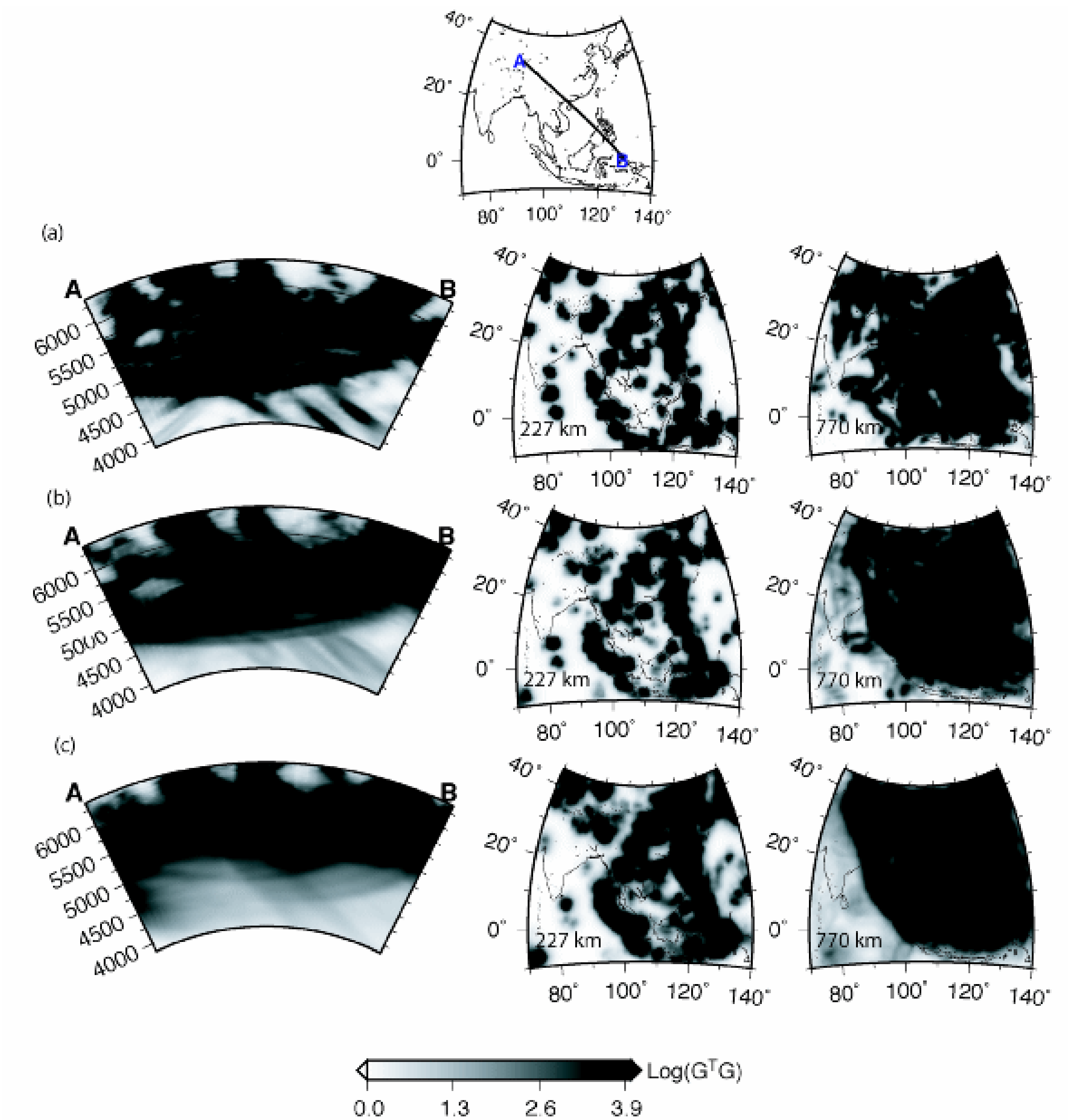

Figure 4. Sampling of the model space by 3D sensitivity kernels of P waves with (a) the high-frequency band (0.5-2 Hz), (b) intermediate frequency band (0.1 -0.5 Hz), and (c) low-frequency band (0.03 -0.1 Hz). The line AB in the map view marks the location of the vertical profile. The horizontal slices are at 227 and 770 km depth.

Because of the relatively narrow "banana-doughnut" sensitivity kernels of high-frequency P waves (Figure 1), the sampling of high-frequency P waves (Figure 4a) resembles that in ray theory. At intermediate and low frequencies, the broad sensitivity kernels provide a more smooth coverage of the structure (Figures 4b and 4c). FFST will combine the sensitivity kernels in all frequency bands.

Project Database and Web-based Tool

We have created a project database to integrate data sets collected for model construction and validation. The database will include a large amount of waveforms as well as ground truth (GT) data with event location uncertainty within 5 km. It is an Oracle relational database using the core NNSA schema with some modifications. We have implemented the fundamental principles of the database management system (DBMS) to obtain an Entity-Relationship diagram (Figure 5).

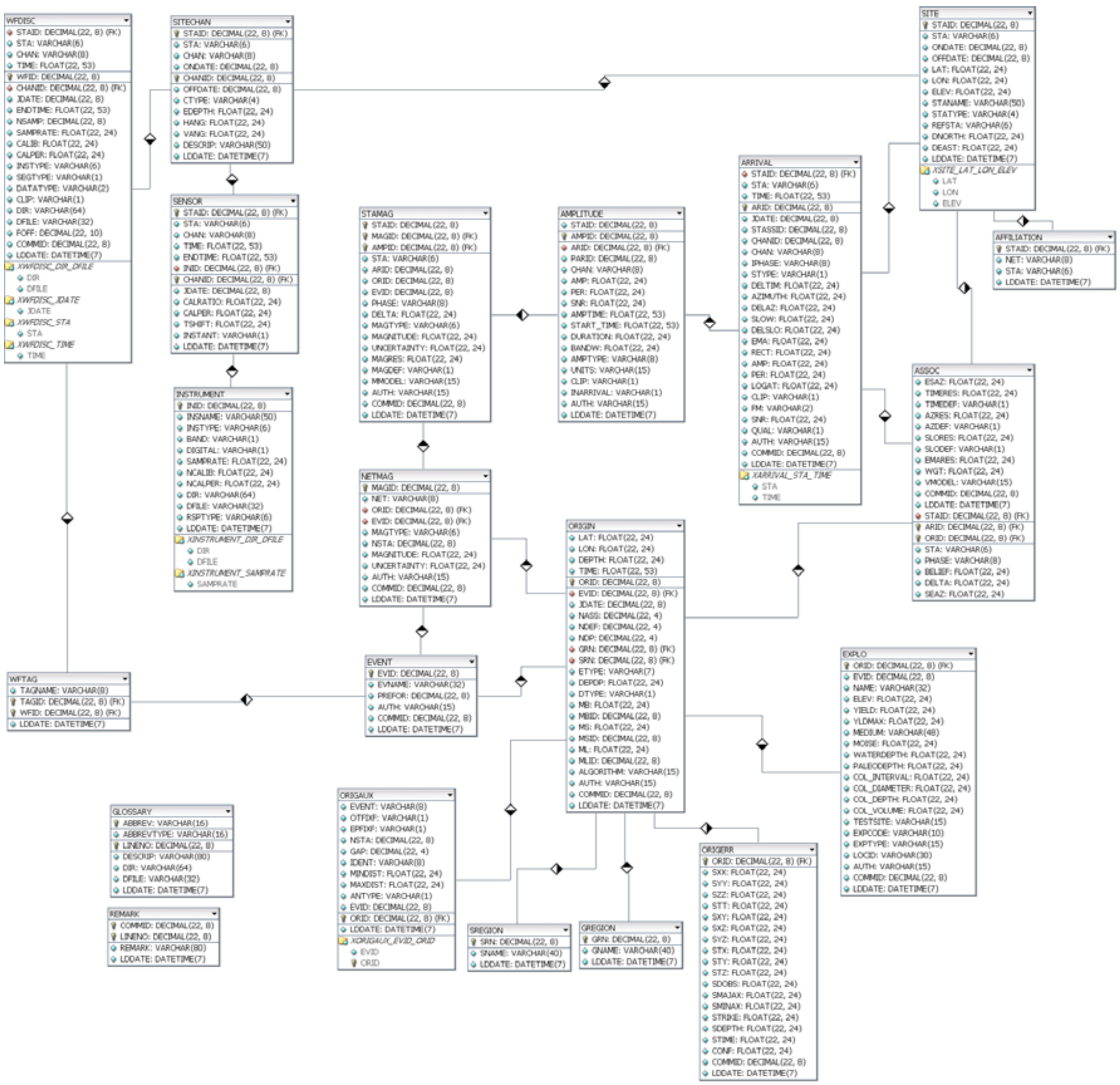

Figure 5. E/R diagram for the project database.

As data are being collected by the team members in this project, they are integrated and stored in the project database. To facilitate efficient data integration and access, a Science Applications International Corporation (SAIC) existing web-based tool is being implemented for use by the project. Figure 6 shows the interface developed under SAIC support. This tool will enable the distributed team members to remotely upload data directly into the database besides other functionalities such as search.

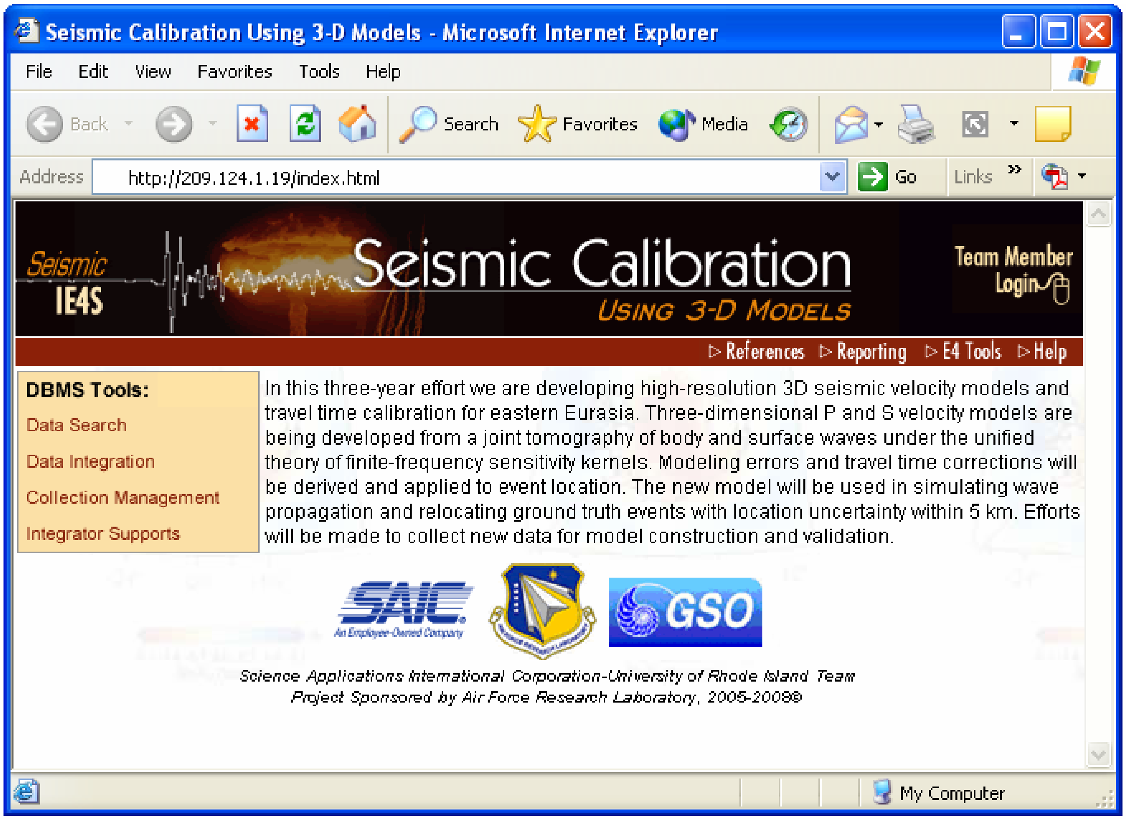

Figure 6. Web-based tool for use in data integration and data access.

CONCLUSIONS AND RECOMMENDATIONS

In this three-year project we will improve seismic calibration for nuclear explosion monitoring in eastern Eurasia using our recently developed FFST. The 3-D, finite-frequency kernels account for wavefront healing and other finite-frequency effect of wave diffraction. In addition to the new methodology, we will use a more comprehensive data set than in previous studies to construct the new earth model beneath eastern Eurasia.

Preliminary tomographic inversions using finite-frequency kernels have demonstrated significant improvement in resolution compared to those based on ray theory. Initial data processing using teleseismic earthquakes recorded by the GSN stations in eastern Eurasia demonstrates that 3-D finite-frequency sensitivity kernels yield a more smooth and uniform sampling than in ray theory, which improves tomographic inversions. The mantle in the 400-1500 km depth range is well sampled by the direct teleseismic P arrivals. The initial results show that additional phases (e.g., pP, PP, PcP, PKP) as well as regional arrivals are essential to imaging the shallow (<400 km depth) and deep (>1500 km) velocity structure.

The 3D velocity models will be used in seismic calibration in Eurasia. We will develop frequency-dependent travel time corrections and uncertainties, and used them in relocating GT events for validating the model and event location improvement. From the 3D velocity model we will also simulate 3D full wavefield for modeling wave propagation through the transition zone.

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